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**Federal Railroad
Administration**

Passenger Train Equipment Review Report

Office of Research
and Development

Washington, D.C. 20590

Volume 2. Propulsion System Components and Future Train Energy Consumption

FRA/ORD-81/45.2

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MAY 1981

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16. Abstract

Early in 1977, the Federal Railroad Administration, Office of Research and Development, initiated the Improved Passenger Equipment Evaluation Program (IPEEP), which was designed as a detailed systematic review of advanced passenger trains and equipment throughout the world that could possibly be used in the United States. During the course of this program, the members of the IPEEP Train System Review Team prepared 24 technical papers, in addition to the basic set of IPEEP reports covering baseline data and individual train reviews and a separate report on train performance methodology.

These 24 technical papers have been arranged in six volumes under the main title, Passenger Train Equipment Review Report. The volume subtitles are Volume 1. Advanced Propulsion Systems and Propulsion Systems Requirements, Volume 2. Propulsion System Components and Future Train Energy Consumption, Volume 3. Suspension and Guidance Systems, Volume 4. Braking Systems, Volume 5. Banking Systems and Train Articulation, and Volume 6. Car Body Construction and Crashworthiness.

This volume of six papers covers traction motor drives, modern slip detection and control systems for electric locomotives and multiple-unit cars, onboard high-voltage switchgear for electric locomotives and multiple-unit cars, high-voltage protection and switching control for Northeast Corridor vehicles, pantographs, and the energy consumption of future passenger trains.

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PREFACE

The Improved Passenger Equipment Evaluation Program (IPEEP) constitutes a major research effort undertaken by the Federal Railroad Administration, Office of Research and Development, Office of Freight and Passenger Systems, to evaluate advanced passenger train technology throughout the world. The goal of this program is to provide the technical data and detailed analysis needed for the definition of an advanced passenger train system for future use on intercity passenger lines in the United States, especially in the heavily traveled Northeast Corridor (NEC) between Boston and Washington, D.C.

Between 1977 and 1980, an extensive technology evaluation effort was undertaken by the IPEEP Train System Review Team, consisting of Battelle Columbus Laboratories; Carnegie-Mellon University, Transportation Research Institute; Louis T. Klauder and Associates; J. W. Marchetti, Inc.; and Unified Industries Incorporated. The review team prepared a basic nine-volume set of IPEEP reports covering baseline data (volume 1) and individual train reviews (volumes 2 through 9), plus an additional report on train performance methodology. These documents may be ordered from the National Technical Information Service.

During the same period, the members of the review team also prepared 24 working papers and criteria papers on various aspects of advanced passenger train technology. These technical papers have been arranged in six volumes (of which this is one) under the following titles:

Passenger Train Equipment Review Report: Volume 1. Advanced Propulsion Systems and Propulsion System Requirements.

Passenger Train Equipment Review Report: Volume 2. Propulsion System Components and Future Train Energy Consumption.

Passenger Train Equipment Review Report: Volume 3. Suspension and Guidance Systems.

Passenger Train Equipment Review Report: Volume 4. Braking Systems.

Passenger Train Equipment Review Report: Volume 5. Braking Systems and Train Articulation.

Passenger Train Equipment Review Report: Volume 6. Car Body Construction and Crashworthiness.

These six volumes are being published to serve as a supplement to the basic IPEEP reports and to thereby provide the U.S. railroad community with additional technical information on a wide variety of passenger train technology issues.

All the papers in these volumes, together with the names of the authors and the original dates of completion, are given in the appendix included in each volume. All six volumes are available from the National Technical Information Service.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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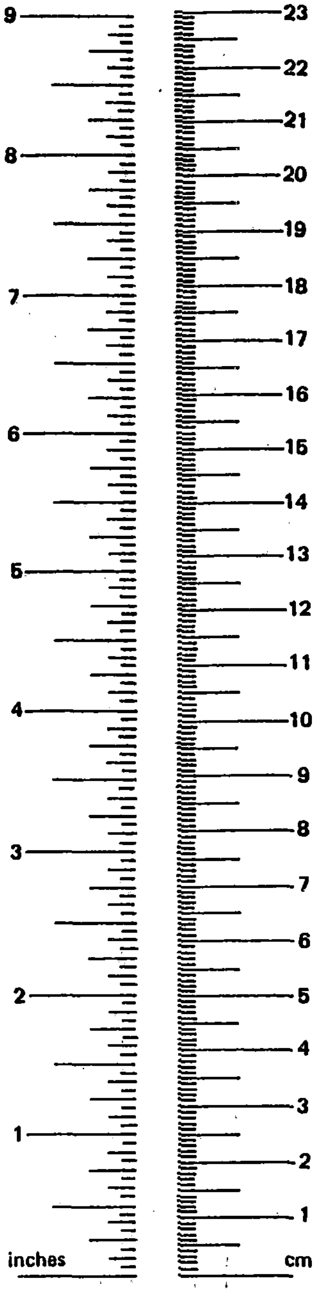
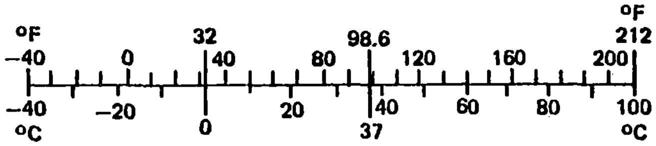
*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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PART 1. TRACTION MOTOR DRIVES

Louis T. Klauder
and Associates

1 - CONCLUSIONS

The lapse in interest in intercity passenger trains in the U.S. during the 1950's and 1960's has restricted development of rail passenger equipment to transit and commuter trains. Multiple unit electric cars and diesel locomotive hauled trains have been designed which operate satisfactorily at the moderate speeds involved.

Because of the market for freight equipment, diesel and electric locomotive development has been directed toward freight designs with an emphasis placed on adhesion for maximum pulling capacity but limited concern for riding and tracking qualities commensurate with the moderate speed requirements. In the interest of economy, electric locomotives have shared traction motors and truck designs with diesel electric locomotives.

With the current resurgence of interest in high speed passenger service in the NEC and other corridors, Amtrak has acquired passenger locomotives with available freight locomotive components such as three-axle trucks. Riding and tracking qualities of these locomotives at passenger train speeds have been unacceptable on existing track and speed restrictions have been imposed.

There is a need to evaluate both vehicles and track to arrive at a compatible design, giving consideration to the forces produced by vehicle suspensions at the wheel/rail interface and the role played by traction motor drives in reducing the unsprung mass of powered axles.

It has been easy to regard the conventional axle hung traction motor as simple in design and easily maintained, without regard for its detrimental effect on track, and consequential requirement for increased maintenance to the track. With mixed traffic of passenger and freight at a variety of speeds, it is almost impossible to identify the specifics of vehicle design features that affect the track. Thus it is difficult to present an economic argument for more complex traction motor drives. Freight cars of 100 ton capacity with conventional "three-piece" trucks have been shown to degrade the "Fast" test track at Pueblo, however, no corresponding data is available on high speed passenger equipment.

Several other countries, notably Japan, France, and Italy have undertaken the construction of exclusive high speed passenger rights-of-way and the Japanese have had considerable service experience. The French have run an extensive developmental program and are presently constructing a new high speed TGV network for 160 mi/h operation. Extensive prototype testing in France has reinforced theory dictating a reduction in unsprung mass as a key requirement in the design of traction motor drives.

The degree of sophistication and complexity of drive required are heavily influenced by the intended speed of service. At high speeds the stresses produced by inertia forces and the effect of these forces on the tracking characteristics of the vehicle require that complex drives be employed. There are four basic criteria which must be considered in the design of a traction motor drive for high speed service:

- Isolation of the traction motor from the shocks to which the wheel-axle assembly is subjected.
- Reduction in unsprung mass of the wheel-axle assembly and the damaging effects on both wheel and rail caused by inertia forces.
- Reduction of forces applied to the primary suspension by axle driving torque.
- Prevention or minimization of axle steering due to inertia forces resulting from any offset in the mass of attached motor and drive components from a vertical plane through the axle.

Passenger locomotives with reasonably high speed capability are not new in the U.S. but the lessons of history in the development of locomotives in the U.S. at times seem to have been forgotten. The GG-1 locomotive of the former Pennsylvania Railroad was the product of a competitive development project between two major electrical equipment suppliers supervised by the railroad's engineering department. The GG-1 proved to have superior tracking performance as measured by impact recording instrumented ties (a crude but effective early substitute for instrumented wheels).

Early difficulties with riding and tracking qualities of locomotives experienced by the former New York Central and Pennsylvania railroads in their development of electric locomotives, and the more recent problems experienced by Amtrak with six-axle diesel and electric locomotives indicate that there has been no change in the problem over the years. The patterns of passenger equipment development in Europe and Japan, when contrasted with most U.S. practice, confirm this point. The two most important objectives in high speed passenger equipment design are the reduction in unsprung mass and proper guidance of axles; both of which are strongly influenced by the design of traction motor drive.

2 - INTRODUCTION

The designs used for coupling electric traction motors to driving wheels encompass a great variety of mechanical arrangements and gearing. In reviewing the history of electric traction, the drives employed have changed greatly in detail as materials have improved while the basic mechanical principles remain unchanged.

The mechanical arrangements of motors and drive couplings may be loosely grouped according to the degree to which motor and transmission gear masses are isolated from the axle to reduce unsprung weight.

- Motor and gears directly connected to axle.
- Motor and gears shock mounted to axle.
- Motor on truck frame (primary suspension), gear unit on axle.
- Motor and gears on truck frame (primary suspension), coupling to axle.
- Motor on body (secondary suspension) with gearing and shafts to axle.

Within the variety of gear arrangements and couplings which have been used to achieve the various degrees of isolation, there is a general distinction between right angle drives and parallel drives. Another distinction is made between coupled axles and separately driven axles. With truck mounted traction motors the parallel drive configuration permits a very compact arrangement within a truck for fairly large traction motors mounted in a low position under the vehicle floor. It permits the motor to be placed between the axle and the truck's center transom, but does not interfere with the center pivot. This permits the center pivot and carbody reaction point of the truck to be placed as low as possible, thus minimizing weight transfer between axles. Mounting the motor as low as possible in the truck also serves to keep the center of gravity low.

Right angle drives are more common when two or more axles are to be coupled together with a single motor, as with the single motor drives of light transit vehicles. There are also examples of coupled axles using a parallel drive arrangement and (from a historical standpoint) axles coupled with side rods as with steam locomotives.

Both geared and gearless drives have been used. The gearless drive, in which the traction motor rotates at axle speed, can generally be dismissed from present consideration because of the low power output developed for a given mass of motor. Specific power output of an electric motor generally is proportional to motor speed. At the other extreme, a very high speed motor would require an extemely high gear ratio which would require a gear unit so large as to negate the effect of reduced motor size.

3 - EARLY DRIVES

With the need for electric locomotives capable of hauling trains of the size handled by steam locomotives, came the need for traction motors and drives of considerably greater proportions than those applied to street cars and interurban cars. Street cars in the early 1900's had modest power requirements of approximately 25 horsepower per axle while the larger, faster interurban cars had as much as 60 horsepower per axle. Steam locomotives by contrast developed over 500 horsepower per axle and were rapidly approaching the 1000 horsepower level. A steam passenger locomotive typically would develop about 2500 horsepower, usually on 3 axles.

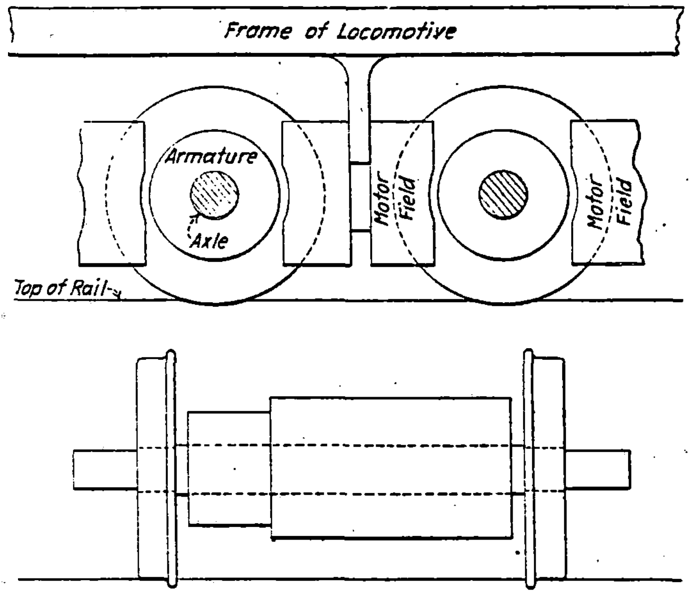
Weight and bulk of traction motors were key issues. Traction motors in the early 1900's weighed approximately 18 lbs. per horsepower for direct current motors while commutating alternating current motors weighed 22 1/2 lbs. per horsepower. This contrasts with 9 1/2 lbs. per horsepower for common direct current traction motors today. Thermal limitations in early insulation materials severely limited continuous power output. For these reasons, locomotive sized traction motors had to be very large thus different designs of traction motor drives had to be developed to overcome the space and weight shortcomings of the basic axle hung, geared drive of the trolley car. Several unusual alternative configurations resulted.

Bipolars

The first group of "main line" electric locomotives designed to handle steam locomotive sized trains was built in 1906 for the New York Central as part of the electrification for Grand Central Station. Direct current electrification was selected using an underrunning third rail distribution system at 600 V. The locomotives have four driving axles in a rigid frame with a guiding truck at each end. (Originally single-axle guiding trucks were used (1-D-1) but this was later changed to a two-axle arrangement (2-D-2) because of tracking instability.)

The prototype locomotive, built in 1904, was followed by two classes of production locomotives. Several class S2 locomotives are still in service as switchers in Grand Central Station after more than 73 years of service.

The most interesting feature of these locomotives is the traction motor drive in which the four motor armatures are mounted directly on the axles while the field poles and brushes are carried on the frame of the locomotive. This introduces a large amplitude vertical movement between the rotor and the stator because of the locomotive's suspension. As a result only one set of field poles (located fore and aft of the axle) can be provided for each motor. This is the basis for referring to locomotives of this type as "bipolars."



Gearless Drive—Armature on the Axle. *

The unsprung mass of each axle including suspension components is approximately 11,000 lbs. While significantly greater than the effective unsprung mass (approximately 8,200 lbs. per axle) of recent diesel-electric locomotives, it is lighter than the unsprung mass of steam locomotives of the early 1900's. Considering the lower service speed of 60 mi/h for the electric vs. 80 mi/h for steam, the inertia forces at the rail were still less severe.

One of the unique features of the "S motors" is that the path of magnetic flux of the four traction motors is in series. The return path of flux between the two end motors is carried in a frame member across the top of the four motors. This provides inherent protection against motor overspeed in the event of wheelslip in that the slipping motor is prevented from overspeeding by the high field strength of the other three motors.

Other designs of bipolar locomotives were built with the same basic axle mounted motor drive but widely differing wheel arrangements. The later class T locomotives of the New York Central had 8 motors in four trucks while the Milwaukee Road bipolars had 12 motors in a four-part articulated frame with a unique three-part carbody. All of the bipolars provided successful performance for their time.

In an overview of bipolars, the unsprung mass of the axle mounted armature would appear to be quite high by current standards, however it was no greater than that of contemporary steam locomotives. The magnetic flux density was necessarily low because only one pair of field poles could be used, (located ahead of and behind each axle) and the field pole faces were flat

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*COURTESY OF SIMMONS-BOARDMAN, "RAILROAD ELECTRIFICATION AND THE ELECTRIC LOCOMOTIVE", 1923.

to accommodate relative movement of the armature. This limited the power of the motor, but the sheer mass of the motor components provided a heat sink which afforded high short time overload capacity when starting, in spite of the thermal limits imposed by the primitive insulation materials of the day.

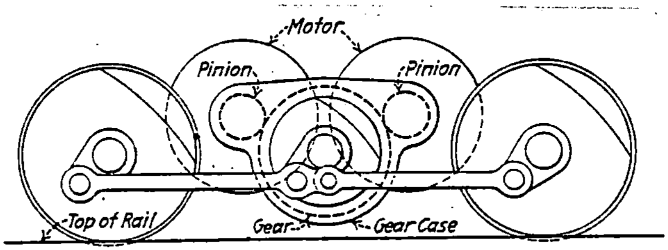
Rod Drives

Some early electric locomotives employed drives such as side rods (as on a steam locomotive) which may appear bizzare today. Such arrangements were quite logical when considering the large size of motors required to develop the desired power and the economy of using as few motors as possible to achieve this end. There is also an obvious advantage to isolating the motors from mechanical shocks to which axle mounted components are subjected. With rod connected drives, the locomotive frame construction and side rods were conventional to steam locomotive practice and therefore presented no unusual or special maintenance requirements at the time. Electrical components such as motors and switch groups were often of modular construction to facilitate building and heavy maintenance.

In the rod driven locomotive, steam locomotive type (cranked) driving wheels were connected by side rods to a frame mounted crank shaft called a jack shaft. The jack shaft in turn was driven by either geared or direct drive motors. The cranks on opposite sides of the locomotive were 90° apart, as on a steam locomotive, to permit continuous torque transmission without a "dead" center position. The rod drive permitted the motors to be carried on the frame of the locomotive and isolated from axle accelerations by the suspension of the locomotive, while driving forces were transmitted longitudinally by the crank and rod linkage.

Numerous rod drive arrangements were used in the United States by the Pennsylvania, the Virginian, and the Norfolk and Western railroads as well as one New Haven experimental unit. In Europe, the German and Swiss railroads made extensive use of rod drives.

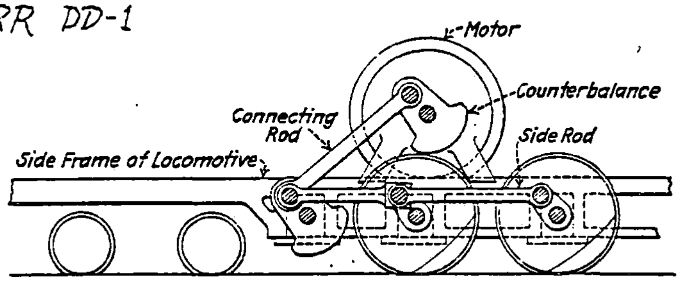
N&W electric



Combined Gear and Side Rod Drive.

COURTESY OF SIMMONS-BOARDMAN, "RAILROAD ELECTRIFICATION AND THE ELECTRIC LOCOMOTIVE", 1923.

PRR DD-1



Arrangement of Parts When Side-Rod Drive is Used.*

An interesting example of a rod locomotive is the DD1 class developed by the Pennsylvania Railroad. Shortly after the New York Central began its program for electrification of Grand Central Station, the Pennsylvania Railroad began the Penn Station project in New York. Direct current electrification at 600 volts was also selected, but an overrunning third rail was used. Because of the need to operate heavy trains at speeds up to 50 mi/h on the grades in the tunnels under the rivers, a locomotive of 4000 horsepower was envisioned.

The DD1 consisted of two locomotive sections of an asymmetrical wheel arrangement coupled back to back by a fixed drawbar. Each section had a single large motor (weighing 42,000 lbs.) which operated at driving axle speed and had a short time rating of 2000 horsepower. A total of 4000 horsepower per locomotive distributed over only four driving axles made the DD1 the equivalent of a steam locomotive. Each motor was mounted on the frame above the drivers and was coupled to a jack shaft by an additional pair of side rods. Two driving axles with 72 inch diameter wheels were located in the frame toward the non-cab end of each section of the locomotive and a two-axle guiding truck was provided under the cab end (2-BxB-2).

The maximum tractive effort transmitted by each drive was 25,000 lbs. producing 12,500 lbs. tractive effort per axle. This can be compared with the starting tractive effort of the Virginian class EL-3A freight locomotives which had geared traction motors and transmitted 39,390 lbs. tractive effort to two-axles in each of six drives for 19,695 lbs. tractive effort per axle.

One of the potential advantages of rod connected drives (which holds true for all coupled axle drives) is attenuation of wheel slip at high levels of tractive effort. The distribution of motor torque between two or more axles also overcomes the effect of weight transfer between the axles and reduces the effect of rail contamination on adhesion of the lead driving axle.

A decided disadvantage was the need for weights on the wheels to counterbalance the mass of the side rods. This balance weight was purely unsprung mass. Because the side rods and wheel counterbalance weights do not rotate in the same vertical plane,

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*COURTESY OF SIMMONS-BOARDMAN, "RAILROAD ELECTRIFICATION AND THE ELECTRIC LOCOMOTIVE", 1923.

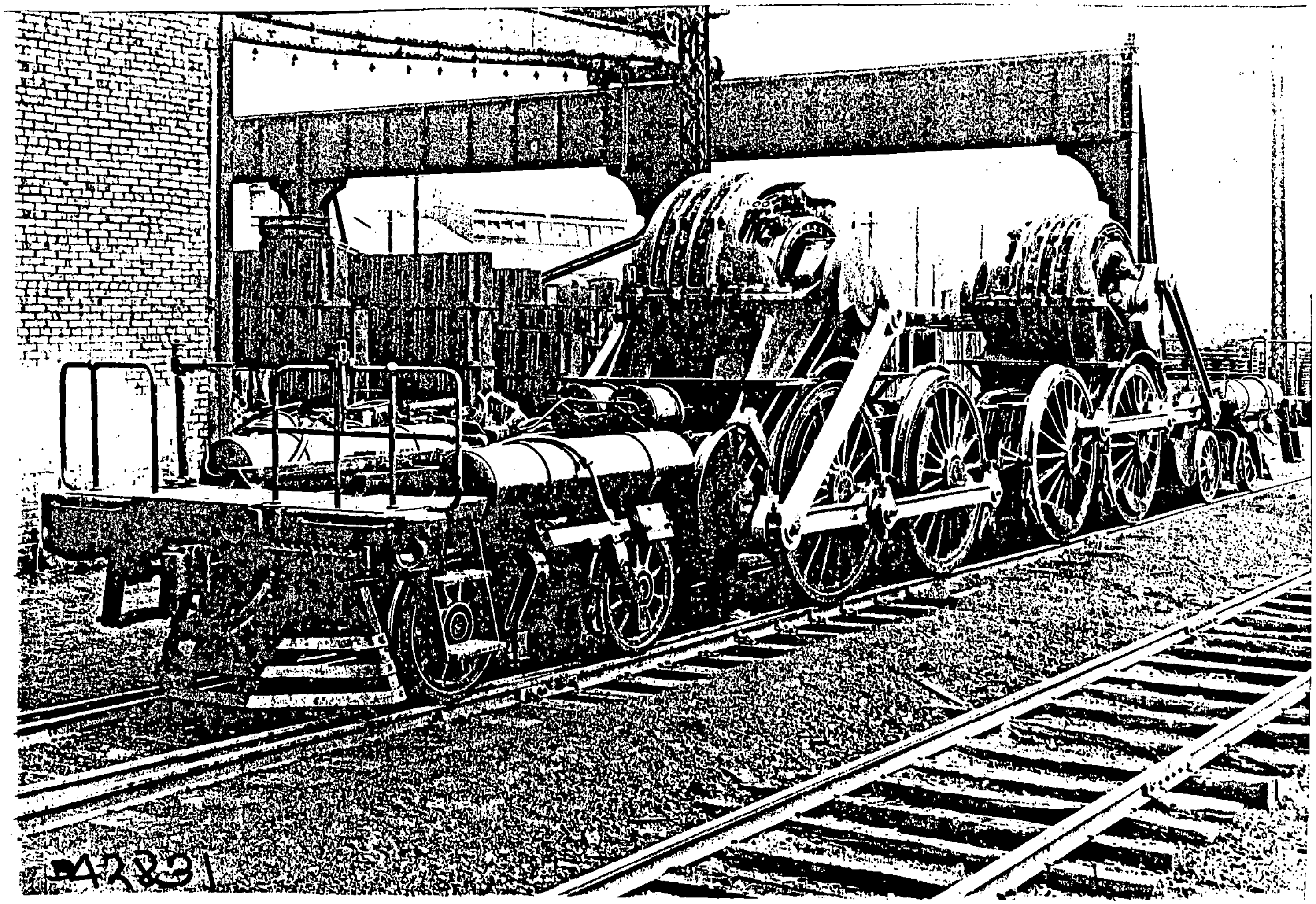
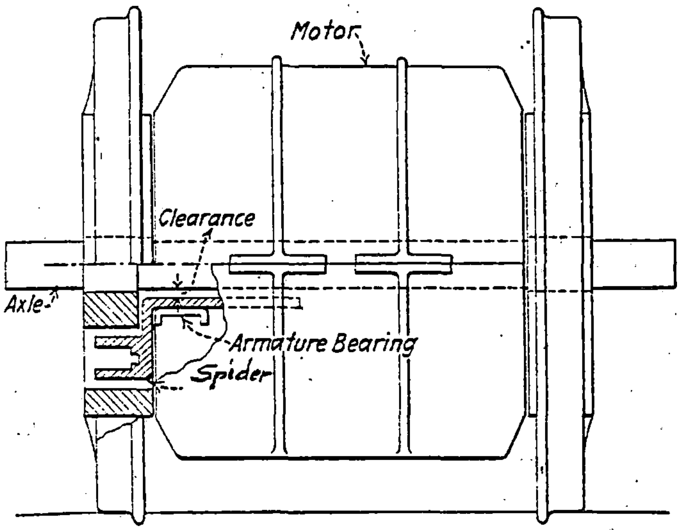


FIGURE 3 – 1
PENNSYLVANIA RAILROAD DD-1 LOCOMOTIVE
WITH CARBODIES REMOVED

COURTESY OF R. B. WATSON'S HISTORICAL PRR FILE some degree of cross counter balancing was also necessary, further increasing the unsprung mass.

Gearless Quill

Another early drive arrangement used on the first electric locomotives built for the New York, New Haven, and Hartford Railroad was the gearless quill drive. In this arrangement the motor shaft is a hollow tube or "quill" which surrounds the driven axle. A "spider" (flange) with fingers which project between the spokes of the driving wheels is mounted on each end of the quill. The spider is coupled to the spokes with springs which accommodate relative movement. The motor is carried on the locomotive frame with spring mounts which further isolate the drive components.



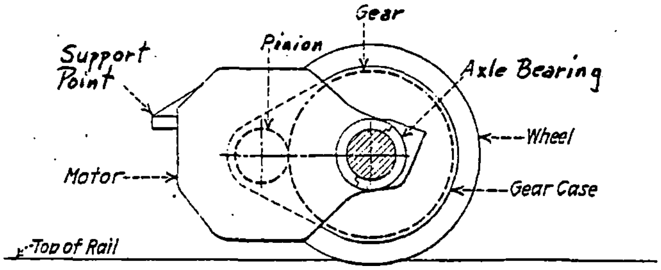
Gearless Drive—Armature on a Quill. *

While reducing the unsprung mass, this arrangement had the disadvantage of low motor speed and quickly gave way to geared quill drives in the interest of more power for a given motor mass.

*COURTESY OF SIMMONS-BOARDMAN, "RAILROAD ELECTRIFICATION AND THE ELECTRIC LOCOMOTIVE", 1923.

4 - AXLE HUNG PARALLEL DRIVES

The conventional axle hung gear drive employed on all U.S. built diesel-electric locomotives and many of the more recent electric locomotives is little changed from the mechanical principle employed by Sprague in electrifying horse drawn street cars in 1885. The motor is oriented with its shaft parallel with the axle and has two bearing on the side of the motor frame which rest on axle journals between the wheels. In this manner the motor is hung from the axle so that its shaft and axle are held in parallel alignment and a simple pinion and gear arrangement can be used. The opposite side of the motor frame (nose) is supported by a spring or shock mount from a cross member of the truck frame. This arrangement has been referred to as a "wheel barrow" or "nose" suspension.



Arrangement of Parts for Direct-Geared Drive.

COURTESY OF SIMMONS-BOARDMAN, "RAILROAD ELECTRIFICATION AND THE ELECTRIC LOCOMOTIVE", 1923.

Variations in gearing are possible using either single or double reduction stages or a single reduction stage with an idler gear to increase the distance between the traction motor and the axle. Locomotive and early street car drives have spur gearing while more recent multiple unit car drives employ helical gearing for noise reduction. The disadvantage of helical gearing is the development of lateral force which requires the use of thrust bearings and a substantial gear box. In contrast, spur gears need only a light weight cover to keep dirt out of the gears.

Axle hung motor arrangements have three fundamental drawbacks, the most notable of which is the high unsprung mass. The effective unsprung mass of the axle hung traction motor can be taken as the mass of the wheels, axle, gear, and bearing assemblies plus one half of the mass of the motor and pinion, and one half of the mass of the primary springs. For the GE type 780 B1 traction motors applied to the Amtrak E-60CP locomotive and rated at 1000 horsepower, the approximate unsprung mass per axle is 8,325 lbs. The EMD type D77 traction motors applied to the Amtrak F40PH locomotive and rated at 750 horsepower are significantly lighter, with an approximate unsprung mass of 7,475 lbs. per axle.

Because of the impact forces to which axle hung motors are subjected, components such as shafts and bearings must be of ample proportions and capacity to provide adequate service life. This reinforcement of components increases weight which tends to be self defeating as the increase in inertia, in turn, increases the forces elsewhere.

An example of the problems with impact forces and armature shaft deflection occurred in recent years on some locomotives having high axle loads. The motor armature shafts deflected in service causing misalignment of the straight roller bearings. This overloaded the ends of the rollers, leading to premature bearing failure. The problem was overcome by changing to a self aligning bearing to accommodate a limited degree of misalignment.

The second drawback is that the driving torque must be reacted by vertical forces on the motor suspension mounts and the primary suspension. This is not a serious problem with two-axle trucks because the change in primary spring deflection does not change the weight distribution between the two axles. However, in the case of three axle trucks with both end motors inboard of their respective axles, the forces on the primary suspension will be in one direction on the two axles with the same motors orientation while the forces will be in the opposite direction on the third axle with its motor oriented on the opposite side of the axle. This action produces a weight bias between the three axles, which will adversely effect the tractive effort of the locomotive by reducing the available adhesion on some axles.

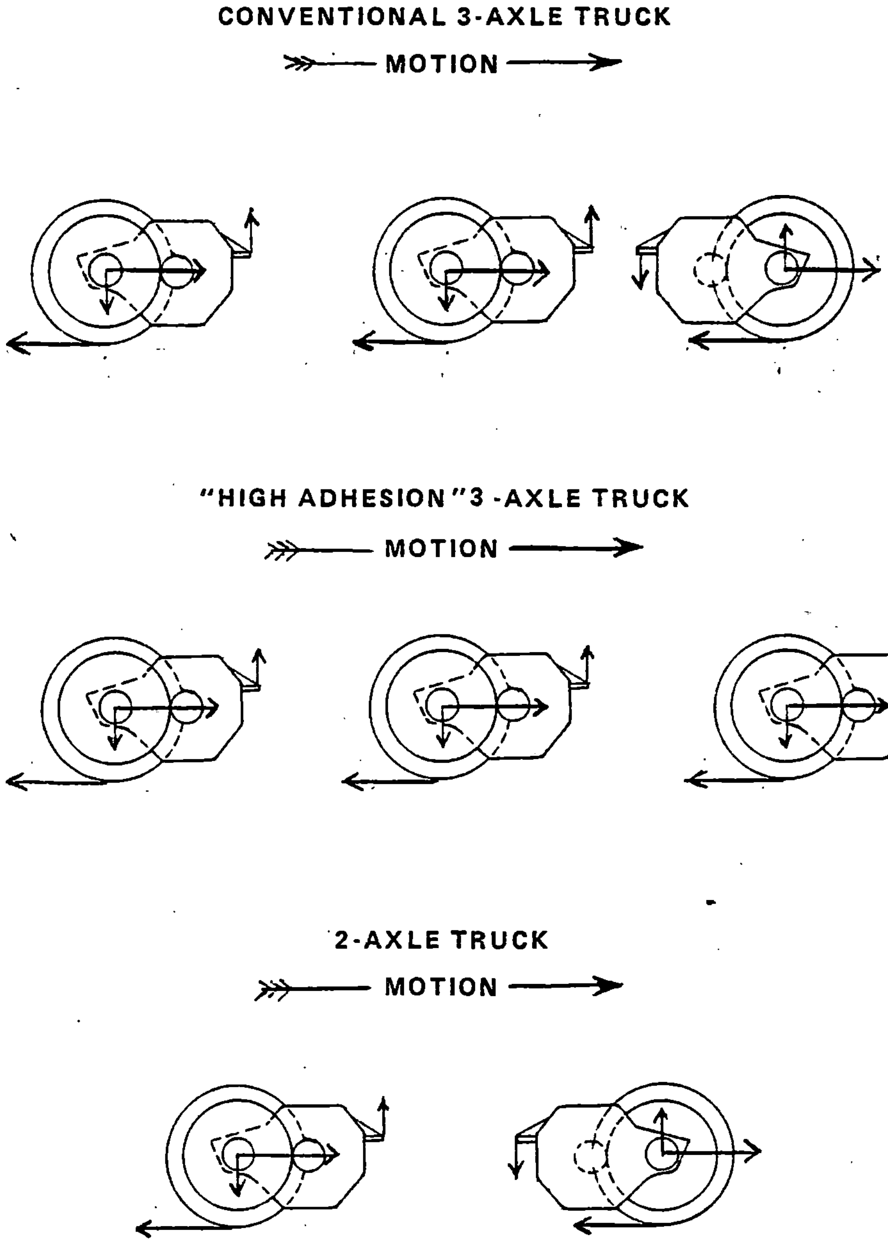
To overcome this weight transfer situation, three and four axle trucks have been offered with all motors oriented on the same side of their respective axles. This produces a uniform bias on the primary suspension and precludes weight transfer due to motor torque alone. Figure 4-1 contrasts these arrangements. The problem with this configuration is that it may lead to undesirable truck steering cause by lateral inertia forces, which is the third drawback to be discussed here.

The third drawback of the axle hung motor is that the location of the motor ahead of or behind the axle longitudinally offsets the center of mass of the motor and axle assembly. Any lateral accelerating force at the wheel/rail-interface therefore results in a moment about a vertical axis through the center of mass which produces a steering effect. Lateral movement in the motor suspension bearings on the axle will attenuate this effect to some degree. Stiffness in the lateral restraint of the axle journal bearings will limit the yawing or steering movement of the axle with respect to the truck frame. Closing of either of these lateral tolerances will limit axle movement which can occur before the mass of the motor and truck frame both become a part of the lateral unsprung mass of the wheel axle assembly. This combination in turn will increase the lateral forces between wheel and rail.

FIGURE 4 – 1

ORIENTATION OF NOSE SUSPENDED MOTORS IN TRUCKS

ARROWS SHOW FORCES EXERTED ON RAILS AND ON TRUCK
THROUGH AXLE BEARINGS AND MOTOR SUPPORTS
BY MOTOR/WHEEL/AXLE ASSEMBLIES



COURTESY OF LTK&A

Several modifications to the axle hung motor have been used to provide vibration isolation for the motor. One of the earliest configurations was the introduction of a torsionally flexible gear on the axle to attenuate the torsional shocks and attendant forces between gear teeth. The toothed ring of the axle gear was mounted in a supporting flange plate on the axle and leaf or coil springs were employed to couple the two parts. The inherent damping of leaf spring stacks offered an advantage to their use.

The second basic change was the introduction of shock mounts and resilient couplings which are discussed in succeeding sections. All of the multiple unit commuter cars presently operating in the NEC have some variation of shock mounted motors rather than direct nose suspended motors.

Table 4-1 compares current U.S. made locomotives with axle hung motors. The list includes both diesel electric and straight electric locomotives and gives the starting tractive effort and horsepower for each. In the case of electric locomotives, the continuous tractive effort is also given. These data are also expressed in a per-axle basis for comparison with other forms of traction motor drives.

The tractive effort characteristics of diesel locomotives as a function of speed generally follow a constant horsepower curve because of the limited output of the diesel engine. Their starting tractive effort is generally limited by adhesion although locomotives geared for higher speeds (such as the Amtrak F40PH) have a motor current limit at low speeds.

Straight electric locomotives of the types listed have the same basic design of d.c. traction motors as the diesel locomotive and are limited in power output by motor (and transformer) voltage and current characteristics. The expected duty cycle and continuous thermal capability may result in widely differing tractive effort curves. Passenger locomotives such as the E60CP have tractive effort curves which are constant up to nearly half of the maximum rated speed, and then decline on a constant voltage curve. The short time accelerating power level may be 190% of the continuous power capability of the locomotive at any given speed. Freight locomotives are often restricted to relatively low short time overloads to prevent thermal overloading.

COMPARISON OF U.S. LOCOMOTIVES W

TYPE	TRACTIVE EFFORT		HORSEPOWER
	STARTING	CONTINUOUS AT SPEED	NOMINAL
Diesel			
U23B	78,000 lbs.		2,250 hp
U23C	117,000 lbs.		2,250 hp
U36B	84,000 lbs.		3,600 hp
U36C	120,000 lbs.		3,600 hp
LRC	29,200 lbs.		3,100 hp
GP38-2	79,000 lbs.		2,000 hp
SD38-3	100,000 lbs.		2,000 hp
DD40A	172,000 lbs.		6,000 hp
GP40-2	86,500 lbs.		3,000 hp
F40PH	60,000 lbs.		3,000 hp
Electric			
E25B	78,000 lbs.	55,000 lbs. at 15 mi/h	2,500 hp
E50C	117,000 lbs.	73,000 lbs.	5,000 hp
E60C	120,000 lbs.	78,000 lbs. at 25 mi/h	6,000 hp
E60CP	75,000 lbs.	34,000 lbs. at 58 mi/h	*6,000 hp

* Maximum short time horsepower of 9,800 hp at 52 mi/h

TABLE 4-1

ITH AXLE HUNG MOTORS

	PER AXLE RATINGS	
NO. AXLES	STARTING T.E.	NOMINAL H.P.
4	19,500 lbs.	563 hp
6	19,500 lbs.	375 hp
4	21,000 lbs.	900 hp
6	20,000 lbs.	600 hp
4	7,300 lbs.	775 hp
4	19,750 lbs.	500 hp
6	16,667 lbs.	333 hp
8	21,500 lbs.	750 hp
4	21,525 lbs.	750 hp
4	15,000 lbs.	750 hp
4	19,500 lbs.	625 hp
6	19,500 lbs.	833 hp
6	20,000 lbs.	1,000 hp
6	12,500 lbs.	1,000 hp

5 - SHOCK MOUNTED DERIVATIONS OF AXLE HUNG PARALLEL DRIVES

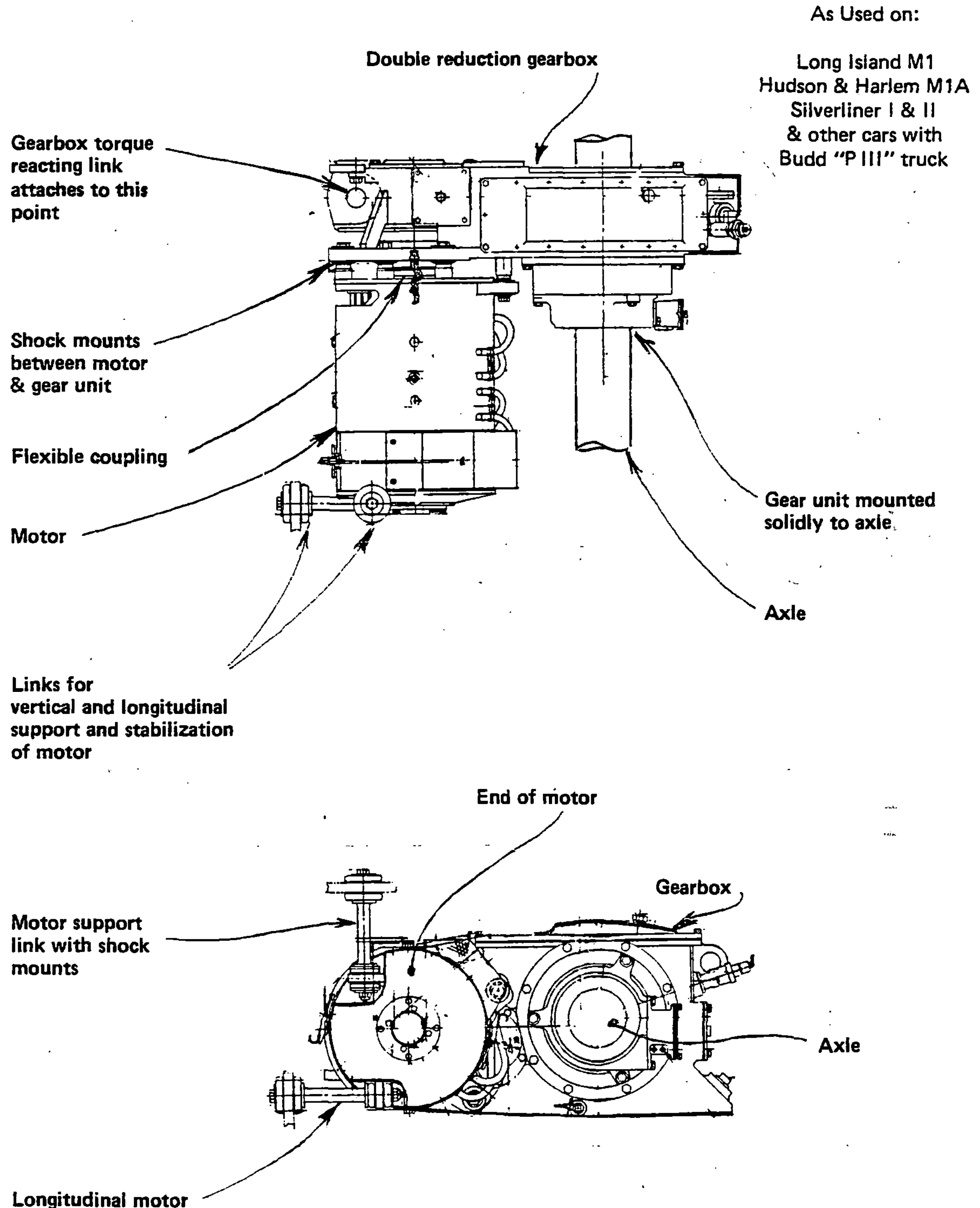
The next step in reducing the unsprung mass of axle hung parallel drives is the isolation of the motor mass from the gear box or the entire motor and gear unit from the axle by some arrangement of shock mounts. These mounts are usually rubber composites using deflection of the rubber in shear and compression to provide spring action and take advantage of the inherent damping characteristics of the rubber. The absence of wear surfaces is also advantageous in the dust filled environment under a train. A number of variations in this approach have been taken and are illustrated by the various multiple unit car propulsion systems, on the Westinghouse equipped Metroliners, and on the various commuter car types operating in the NEC. The two General Electric equipped Metroliners upgraded by a research and development project for the FRA also had an arrangement of this type.

Shock Mounted Motors

One of the simplest shock mount arrangements for the traction motors is used on the Septa Silverliner II and Silverliner III car and on the MTA's M1 and M1A cars on the Long Island Rail Road and Hudson and Harlem division. This arrangement has an axle mounted gear unit with a torque reacting support to the truck frame. The motor is in turn supported by the gear unit with shock mounts at the driven end (which also serve to react motor torque), and a separate set of rubber bushed suspension links at the other end. A flexible coupling connects the motor and input shafts to accommodate the relatively small displacement of the shock mounts. This arrangement results in a minimum of supporting members on the gear unit and is particularly well suited to the Budd "P III" type articulated truck frame, which has no conventional center transom to which motor and gear units could be attached. Figure 5-1 is an illustration of this type of motor and gear unit.

Another design of shock mounted traction motor has been applied to the two Research and Development upgraded General Electric equipped Metroliners, the MTA's New Haven division M2 cars, Septa's Silverliner IV, and NJDOT's Jersey Arrow II and III multiple unit cars. This design is referred to as a "trunion mount" and is illustrated in Figure 5-2. The gear unit is mounted solidly to the axle and has a single mounting and torque reaction point to the truck frame located along the centerline of the truck. The motor is, in turn, shock mounted to the gear unit at two major support points or trunions on the sides of the motor frame and coupled to the gear unit input shaft with a flexible coupling.

Smaller shock mounts between the motor and gear unit at the shaft coupling end serve to keep the shafts in approximate alignment and minimize coupling distortion. The trunion supports



As Used on:

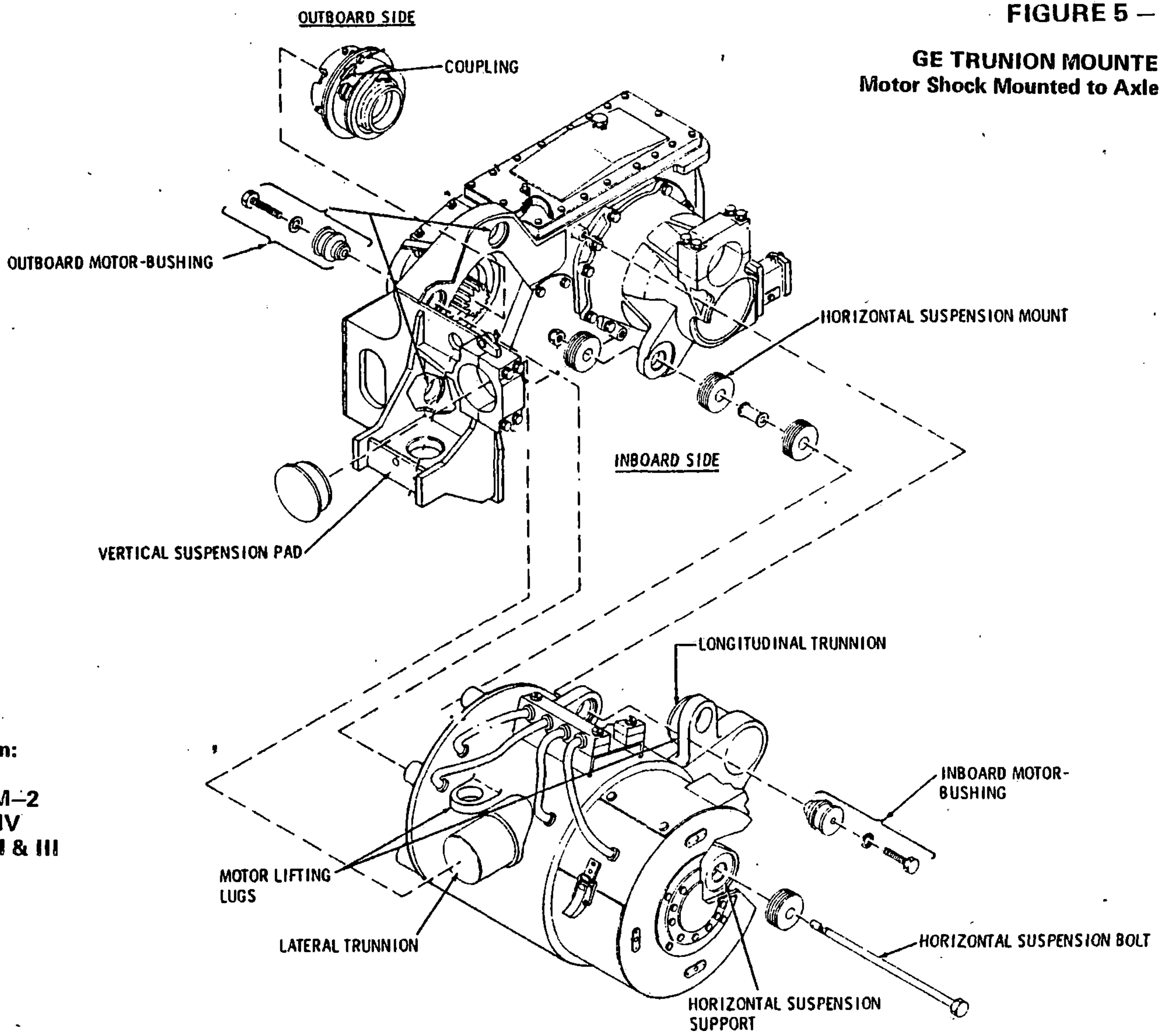
Long Island M1
Hudson & Harlem M1A
Silverliner I & II
& other cars with
Budd "P III" truck

FIGURE 5 – 1
AXLE MOUNTED GEAR UNIT
WITH
SHOCK MOUNTED MOTOR

COURTESY OF GE MAINTENANCE MANUALS ON M1 AND DRPA CARS

FIGURE 5 – 2

GE TRUNION MOUNTED MOTOR
Motor Shock Mounted to Axle Hung Gear Unit



As Used On:

New Haven M–2
Silverliner IV
Jersey Arrow II & III

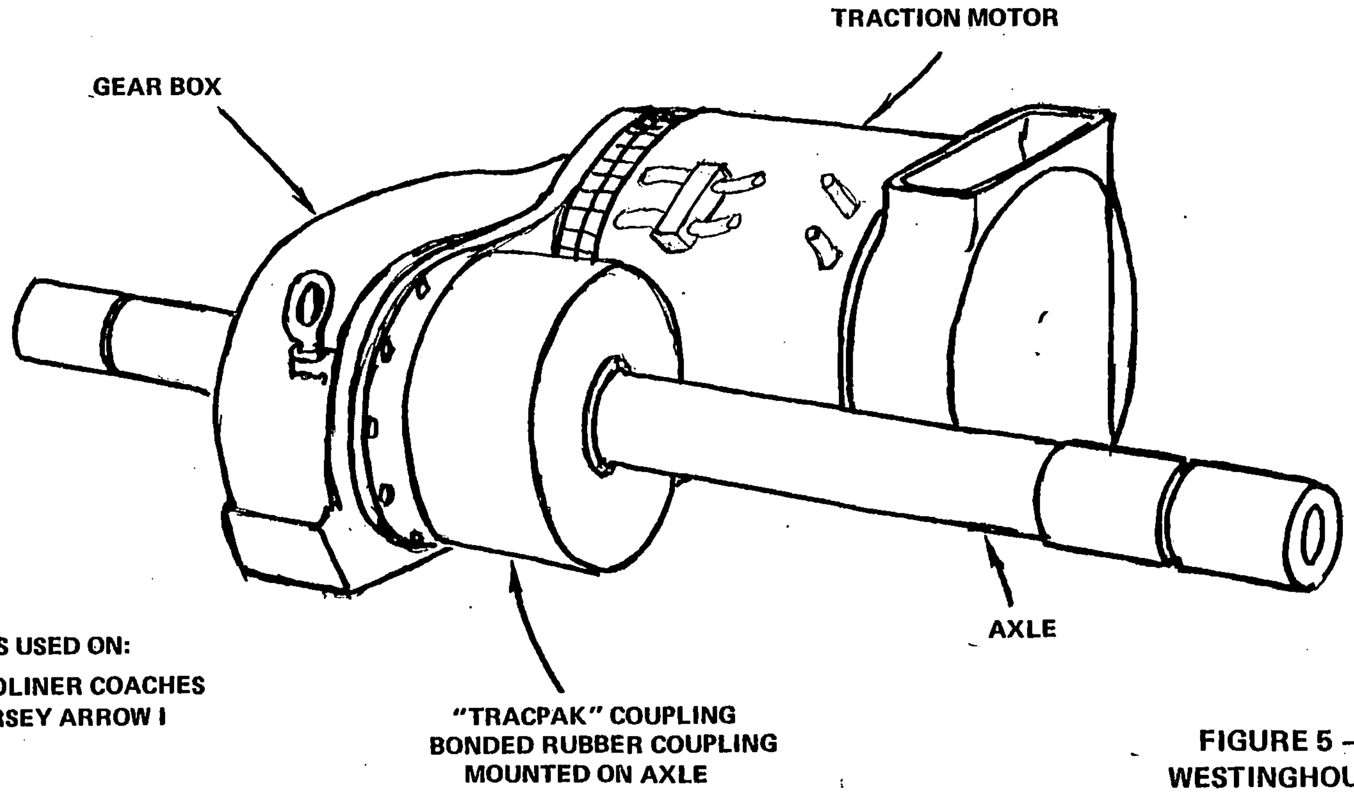
COURTESY OF GE MAINTENANCE MANUAL ON M2

are located in a line through the center of mass of the motor. The corresponding gear unit supports are located on a gear box extension surrounding the axle and on the torque reaction arm of the gear box. Additional shock mounted stabilizing rods are used to help maintain alignment between the motor and gear box.

Shock Mounted Motors and Gear Units

The Westinghouse equipped Metroliners and the Jersey Arrow I commuter cars have a shock mounted motor and gear arrangement with the trade name "Tracpak" which provides isolation from the axle with a single large rubber shaft coupling. The gear unit has a hollow output shaft or quill which surrounds the axle and is both supported from and coupled to the axle by the rubber coupling. Within the coupling, donut shaped rubber pads which surround the axle are bonded to annular flanges on the axle drive hub and to a two part external driving housing. The rubber is held in compression within the two housing halves which are secured together with bolts to prevent stress reversals which would adversely affect the life of the rubber. Figure 5-3 is a drawing of a Tracpak drive.

On the original Metroliner design and on the Jersey Arrow I cars a vertical rubber bushed link carries the gear unit on the truck frame and reacts the drive torque. The motor in turn is shock mounted to the gear unit at the driving end and is supported at the other end by a second rubber bushed link. A flexible motor shaft coupling accommodates small misalignments. On the upgraded Research and Development Metroliner the motor support was changed and the motor was rigidly attached to the gear unit with a single rubber sandwich pad provided for support and to react drive torque. This arrangement was not satisfactory and was not adopted in the Amtrak enhancement program.



AS USED ON:
METROLINER COACHES
JERSEY ARROW I

FIGURE 5 – 3
WESTINGHOUSE
"TRACPAK"

COURTESY OF WESTINGHOUSE ELECTRIC

6 - TRUCK FRAME MOUNTED MOTORS

In a continuing effort to reduce unsprung mass, the next logical step is to mount the traction motor on the truck frame and provide a flexible coupling to the axle hung gear unit. The problems encountered with this type of arrangement are generally associated with the angular deflection of the coupling and the space available within the truck frame. This is particularly acute with parallel drives where a "cardan" shaft or other special coupling is required to accommodate both angular misalignment and translational movement between the motor and gear unit input shafts. The term "cardan" shaft refers to a shaft with flexible couplings at each end which offer a constant velocity transmission at the output end coupling throughout the operating range of misalignment between the input and output shafts. Provision is also made for some longitudinal movement between the input and output shafts by means of splined connections or other devices.

An alternate approach to parallel drives is the use of right angle gear units with the motors extending under the center transom of the truck. In some cases the gear units are offset to opposite sides of the truck to permit locating each motor at the opposite end of the truck from the axle which it powers. A long cardan shaft which passes alongside the other motor is used which minimizes the angular displacement at the couplings. Figure 6-1 is a sketch of a transit car truck showing this arrangement.

The location of motors and routing of drive shafts for truck mounted right angle drives presents a serious conflict with the design of certain trucks because it requires a high placement of the center pivot through which traction forces must be transmitted between truck and carbody . Placing this thrust point above the center of mass of the truck has resulted in a tendency to develop a longitudinal oscillation between the truck and the carbody. It should be noted that the longitudinal oscillation problem is not confined to right angle drives but has also occurred on parallel drive trucks with the bolster radius rods located too high.

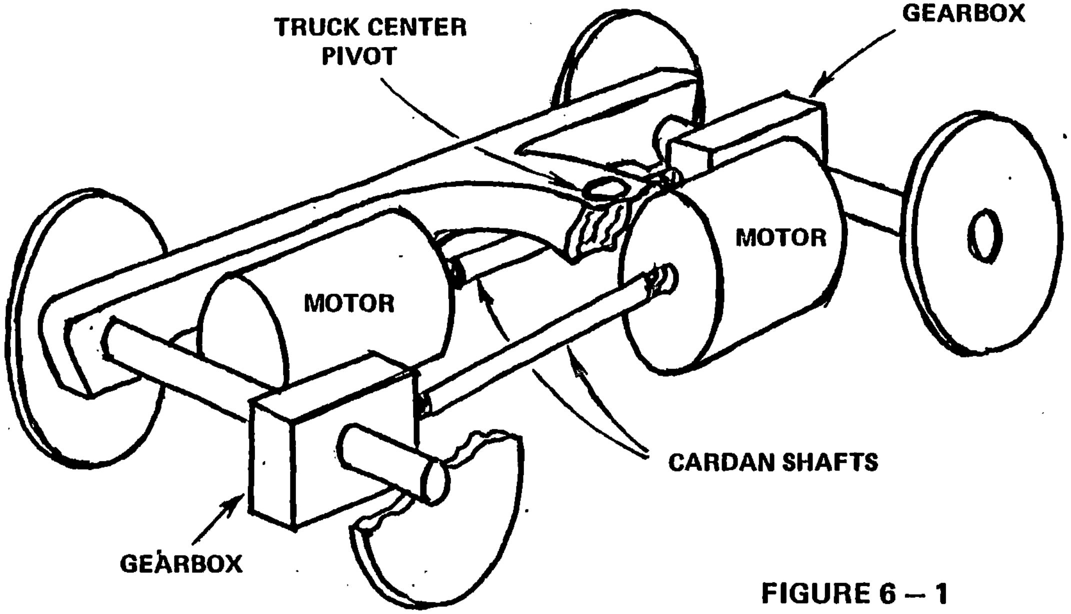


FIGURE 6 – 1

SKETCH OF TRANSIT TRUCK WITH RIGHT ANGLE DRIVE

COURTESY OF LTK&A

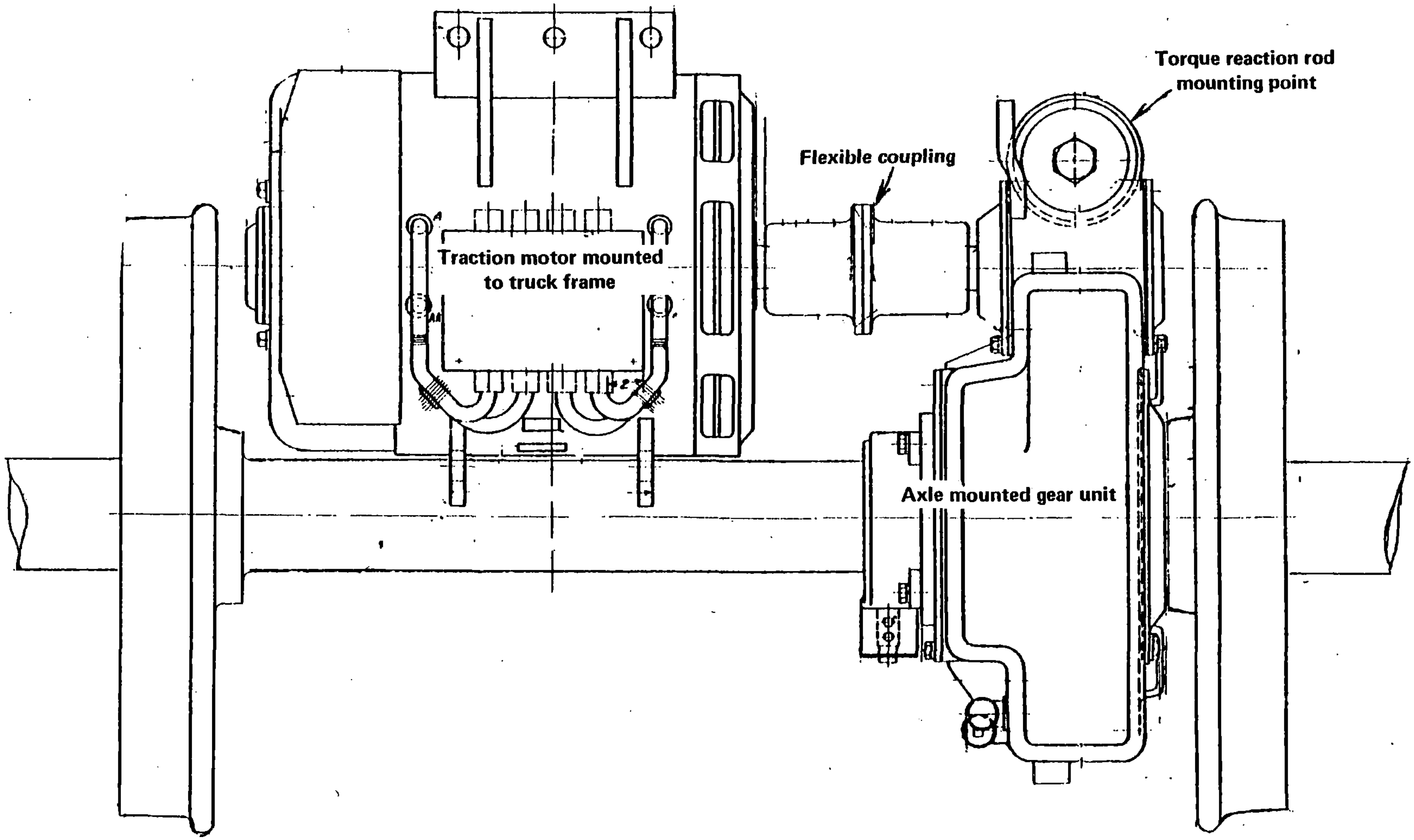
Westinghouse WN Drive and GE Metroliner

The Westinghouse "WN" drive which has been applied in quantity (over 5,000 cars) to New York City transit cars, has the traction motor mounted solidly to the center transom of the truck frame and an axle mounted double reduction gear. The gear box is attached to the center transom next to the motor with a rubber bushed link to provide support and react the drive torque. The motor and gear unit input shafts are held in approximate alignment in this way and connected with a special coupling having crown gears on both shafts which engaged an internally splined collar. This provides a coupling capable of accommodating a certain amount of vertical and angular misalignment. Figure 6-2 illustrates this coupling.

The drive arrangement for the GE equipped Metroliners is similar to the WN drive except that space limitations imposed by the larger traction motors necessitated a shorter coupling.

FIGURE 6 – 2

WN DRIVE



COURTESY OF WESTINGHOUSE WN DRIVE FOR NYCTA AND OTHERS,
REWORKED FROM CATALOG SHEETS AND MAINTENANCE DATA

British HST

The Brtish HST is a combination of fairly conventional coaches with a special lightweight diesel-electric locomotive at each end of the train and multiple unit controls. The HST employs truck frame mounted motors coupled to axle mounted gear units with a unique arrangement to accommodate relative movement. Because of the space limitations within the truck imposed by wheel plate mounted disc brakes, there is insufficient space for a cardan shaft between the motor and gear unit. The pinion shaft of the gear unit has therefore been made hollow and a cardan shaft extends from the motor, through the pinion shaft, to a drive flange on the opposite side of the gear unit. Figure 6-3 is an illustration of the HST power truck while Figure 6-4 is a detail of the drive arrangement.

Each universal joint on the cardan shaft is comprised of six rubber bushed links between flanges on the coupling shaft and the respective motor or pinion shaft flange. The rubber bushed links accommodate axial movement between motor and pinion shafts eliminating the need for wearing surfaces such as splined couplings. Axle torque is reacted through a rubber bushed link between the gear box and truck frame and through the primary suspension. This cardan shaft arrangement is said to be able to accommodate a total relative radial movement of 2 1/2 inches between the two shafts (plus and minus 1 1/4 inches).

The maximum net horsepower per axle is approximately 500 h.p. and the maximum tractive effort per axle is 4825 lbs.

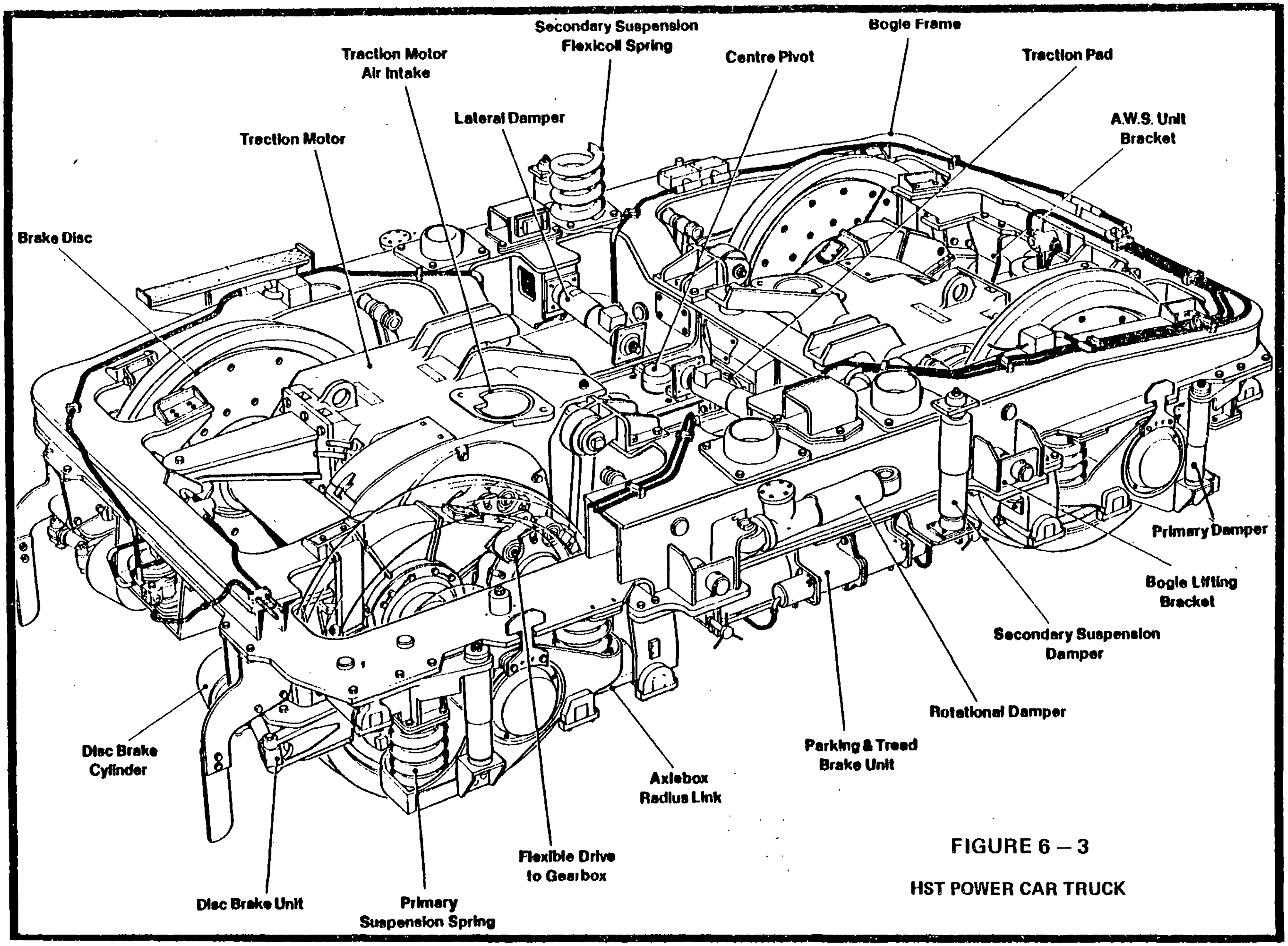


FIGURE 6 – 3

HST POWER CAR TRUCK

COURTESY OF BRE

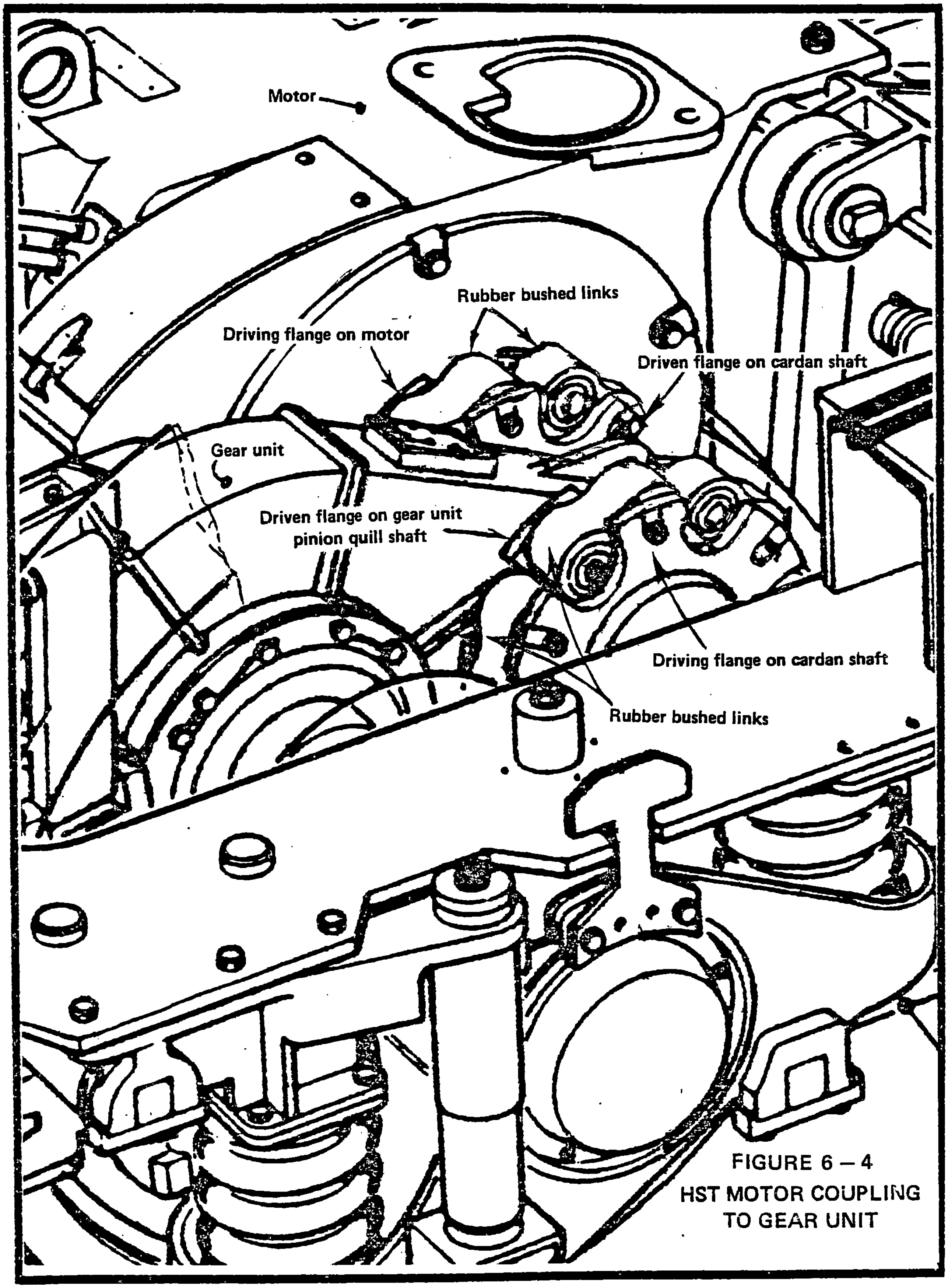


FIGURE 6 – 4
HST MOTOR COUPLING TO GEAR UNIT

COURTESY OF BRE

AEM7

The ASEA standard drive arrangement, used on the modified Rc4 demonstrator locomotive which was tested on the NEC in 1976, is being applied to the new AEM7 locomotive being built for Amtrak by EMD. It employs a truck frame mounted motor coupled to an axle mounted gear unit. In order to obtain a cardan shaft of sufficient length, the motor shaft is constructed as a quill and a fairly long cardan shaft extends through this quill coupling the gear unit to the motor at the opposite end of the motor. Figure 6-5 is a cross section drawing of the ASEA drive.

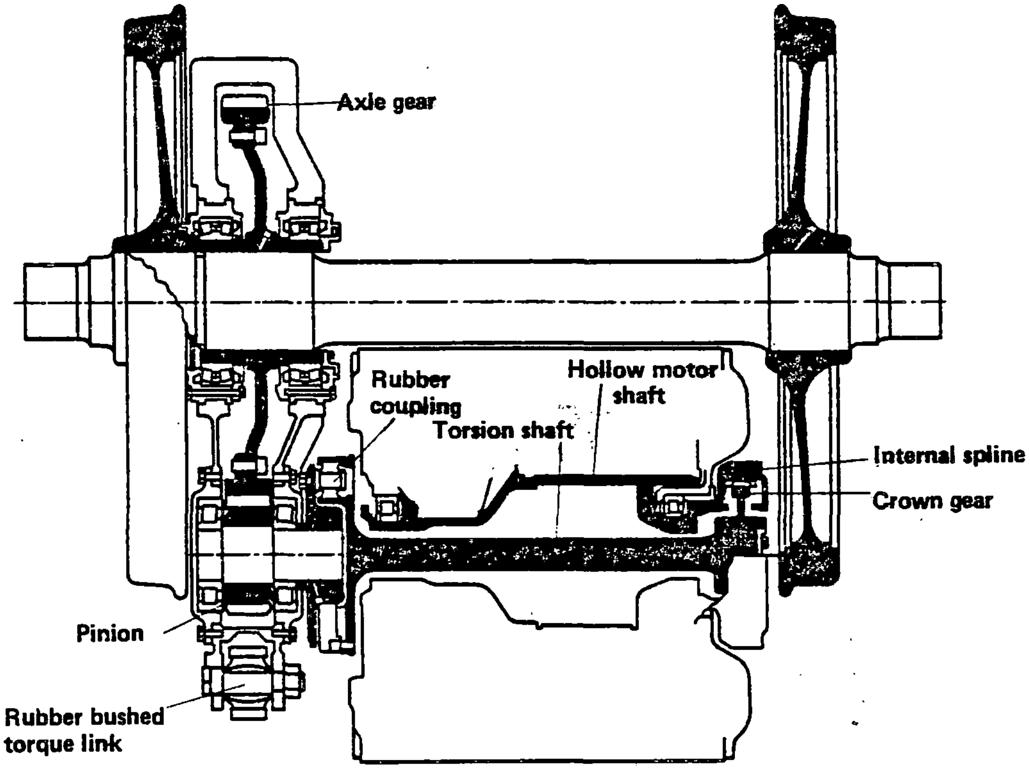
The motor end of the cardan shaft has a coupling comprised of a crown gear which engages an internal spline in the end of the motor shaft and accommodates both angular deflection and the relative lateral movement between the axle mounted gear unit and the truck frame mounted motor. The gear unit end of the cardan shaft is comprised of a series of pre-compressed rubber blocks which accommodate shaft deflection by shear deflection in the rubber. The cardan shaft itself is a torsion bar which further absorbs torsional shocks. Gear unit torque is reacted through a rubber bushed support link.

Starting tractive effort is 12,825 lbs. per axle for the AEM7 and the rated top speed is 125 mi/h. The continuous horsepower per axle is 1330 at 70 mi/h.

FIGURE 6 – 5

ASEA DRIVE FOR AMTRAK AEM 7 LOCOMOTIVE

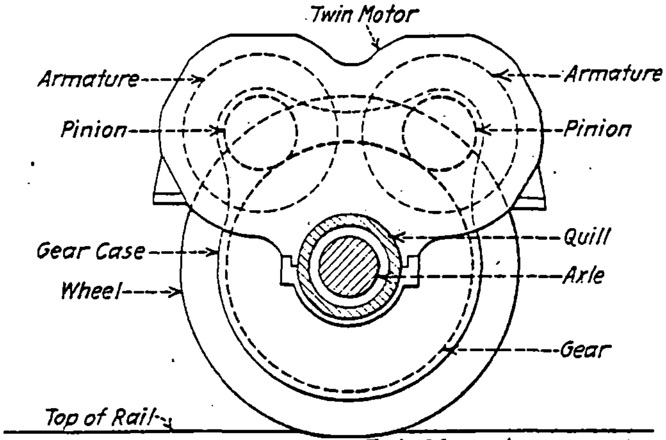
Truck Frame Mounted Motor with Internal Cardon Shaft to Axle Hung Gear Unit



COURTESY OF ASEA BROCHURE ON RAILROAD EQUIPMENT

7 - TRUCK FRAME MOUNTED MOTORS AND GEAR UNITS

The last step in reducing unsprung mass within the truck is the removal of both the gearbox and the motor from the axle and supporting them on the truck frame, using a flexible coupling arrangement to drive the axles. These arrangements are generally referred to as quill drives because the output shaft of the gear unit is a hollow shaft or "quill" through which the axle passes. A flexible coupling of some sort then connects the quill shaft to the driving wheel-axle assembly. In addition to the reduction in unsprung mass, truck frame mounted motors and gear units also offer the advantage of isolating the driving torque reaction forces from the primary suspension.



Gear-and-Quill Drive—Twin-Motor Arrangement. *

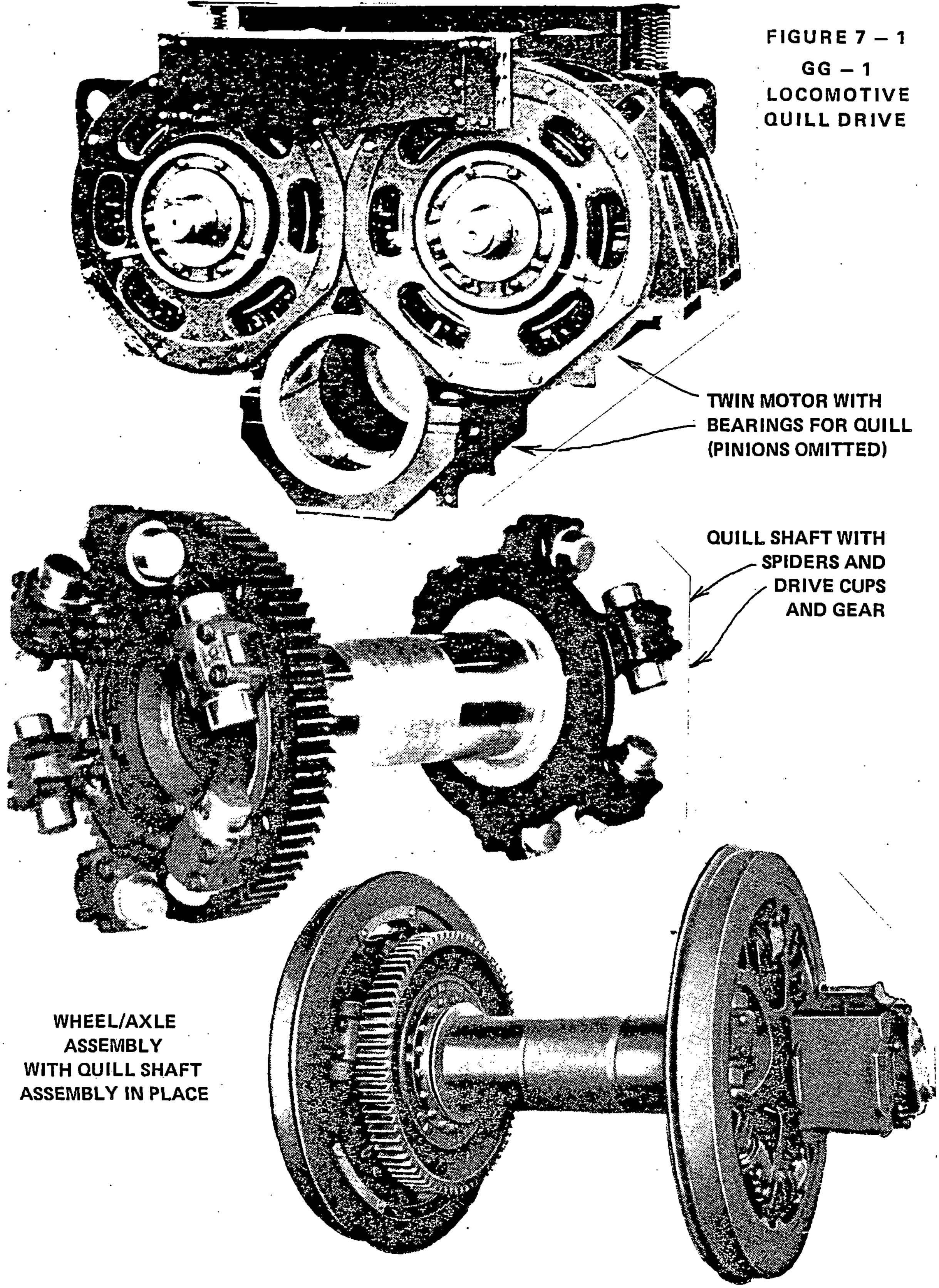
The problem with quill drives is that the flexible coupling to the axle must be able to handle the final output torque to the axle (motor torque x gear ratio). This requires a considerably larger coupling than used between frame mounted motors and axle hung gear units.

Pennsylvania Railroad GG-1

The most prominent example of the quill drive is the GG-1 locomotive which has been the principal electric locomotive in the NEC for almost 45 years. Each of the six driven axles are powered by a pair of 25 Hz commutating series-wound motors having a common stator frame. Pinions on the two rotors engage a common gear on the quill shaft which is carried in bearings on the locomotive frame. Driving flanges called "spiders" on each end of the quill shaft have projections which extend between the spokes of the driven wheels of the locomotive and transmit torque through rubber compression pads called "drive cups". Each driven axle has journal bearings at its ends which are located in frame pedestals and carry the weight of the locomotive through leaf springs with equalizer linkages. Figure 7-1 is a composite photograph of the components of the GG-1 quill drive.

*COURTESY OF SIMMONS-BOARDMAN, "RAILROAD ELECTRIFICATION AND THE ELECTRIC LOCOMOTIVE", 1923.

FIGURE 7 – 1
GG – 1
LOCOMOTIVE
QUILL DRIVE



TWIN MOTOR WITH BEARINGS FOR QUILL (PINIONS OMITTED)

QUILL SHAFT WITH SPIDERS AND DRIVE CUPS AND GEAR

WHEEL/AXLE ASSEMBLY WITH QUILL SHAFT ASSEMBLY IN PLACE

COURTESY OF LOCO, BUILDERS CYC. OF 1944 BUT ALSO APPEARS IN NUMEROUS PRR HISTORICAL DATA AND IS APPARENTLY A PRR PUBLICITY PHOTO SERIES

The GG-1 has three driving axles in each of two articulated frames. A two-axle guiding truck is provided at each end of the locomotive with lateral springing accomplished with rocker devices to provide lateral guidance and stabilization of the main frames. The body of the locomotive is pivoted on the two frames. The wheel arrangement is designated 2-C+C-2 by the AAR standard nomenclature.

The GG-1 has a nominal rating of 770 horsepower per axle with a short time maximum of 1550 horsepower per axle. Tractive effort per axle, based on the rated starting tractive effort of the locomotive, is 11,783 lbs. The driver axle load is 50,500 lbs. per axle, which is one of the lightest used on U.S. locomotives.

GG-1 Predecessors and Development

The development of the GG-1 design is an interesting case in developmental testing with prototype designs which addressed specific problems in tracking characteristics which had occurred with earlier locomotive designs.

It is significant to discuss two quill drive predecessors, the O-1 and P-5a, and a concurrent quill drive design, the R-1.

The O-1 was built in a limited quantity of eight units with electrical equipment by three different suppliers for a comparison and like the GG-1, employed a twin motor arrangement. However, the tractive effort per axle was higher at 18,750 lbs. (vs. 11,783 lbs.) as was the power per axle at 1250 continuous horsepower (vs. 770 hp) for a total continuous rating of 2500 horsepower on two axles. The driving axle load of 75,000 lbs. was 50% greater than the GG-1. The driving wheel diameter of the O-1 was 72 inches which was larger than the 57 inch driver of the GG-1, and compensated slightly for the increase in wheel to rail contact stresses caused by the higher axle load. The two driving axles of the O-1 were carried in a rigid frame with a two axle guiding truck at each end for stability (2-B-2).

The quill drive arrangement of the O-1 differed slightly from that of the GG-1 in that there was only one coupling between the axle and quill shaft. A single spider and one set of drive cups engage one driving wheel per axle, and the torque was transmitted through the axle to the other wheel.

The tractive effort and horsepower limitations of the O-1 led to the development of a similar but larger locomotive, the P-5a. The P-5a had three driving axles, rather than two, but had the same pilot truck arrangement (2-B-2) and approximately the same axle load, power, and tractive effort ratings per axle. The P-5a was built in a fleet quantity of 90 units.

Early difficulty with tracking stability of the O-1 and P-5a locomotives occurred and was corrected to an extent deemed satisfactory, however a more studied approach was then taken in the development of the GG-1. A competitive developmental project was undertaken in which General Electric, Westinghouse Electric, and the railroad's engineering department participated. Two competing locomotives, the R-1 and the GG-1, were built and tested extensively before the GG-1 was declared the "winner" and placed in production for a total of 139 units.

The R-1 locomotive was derived from the P-5a and had four driving axles in a rigid frame, with a two-axle pilot truck at each end producing a 2-D-2 wheel arrangement. The body was similar in styling appearance to the GG-1.

In the comparative tests between the R-1 and GG-1, the GG-1 showed lower lateral impact forces as measured by track instrumentation and a better tracking characteristic as exhibited by accelerometers on the locomotives. The R-1 had an axle load of 57,500 lbs. which was considerably lighter than the P-5a but heavier than the GG-1. The R-1 used the same motors as the P-5a giving 1250 horsepower per axle for a total of 5000 horsepower for the locomotive, or slightly more than the GG-1. Table 7-1 presents comparative data for these locomotives.

COMPARISON OF PENNSYLVANIA RAILROAD ELECTRIC LOCOMOTIVES

Class	GG-1	R-1	P-5a	O-1
Wheel arrangement	2-C+C-2	2-D-2	2-C-2	2-B-2
Total weight	*477,000 lbs.	402,000 lbs.	394,000 lbs.	300,000 lbs.
Weight on drivers	*303,000 lbs.	230,000 lbs.	229,000 lbs.	150,000 lbs.
Weight per driven axle	* 50,500 lbs.	57,500 lbs.	76,333 lbs.	75,000 lbs.
Horsepower-continuous	4620 hp	5000 hp	3750 hp	2500 hp
Tractive effort-starting	* 70,700 lbs.	57,500 lbs.	57,250 lbs.	37,500 lbs.
Tractive effort-continuous	* 17,300 lbs.	18,750 lbs.	16,600 lbs.	11,100 lbs.
Speed at continuous rating	* 100 mi/h	100 mi/h	90 mi/h	90 mi/h
Continuous horsepower-per axle	770 hp	1250 hp	1250 hp	1250 hp
Starting tractive-per axle	* 11,783 lbs.	14,375 lbs.	19,083 lbs.	18,750 lbs.

* Note: Variations in data on GG-1 will be noted because of gear ratio and production lot changes.

TABLE 7-1

German ET403

The German ET403 is a high performance MU train comprised of individual cars with all axles powered. The existing trainsets employ streamlined cab cars at each end and two intermediate cars.

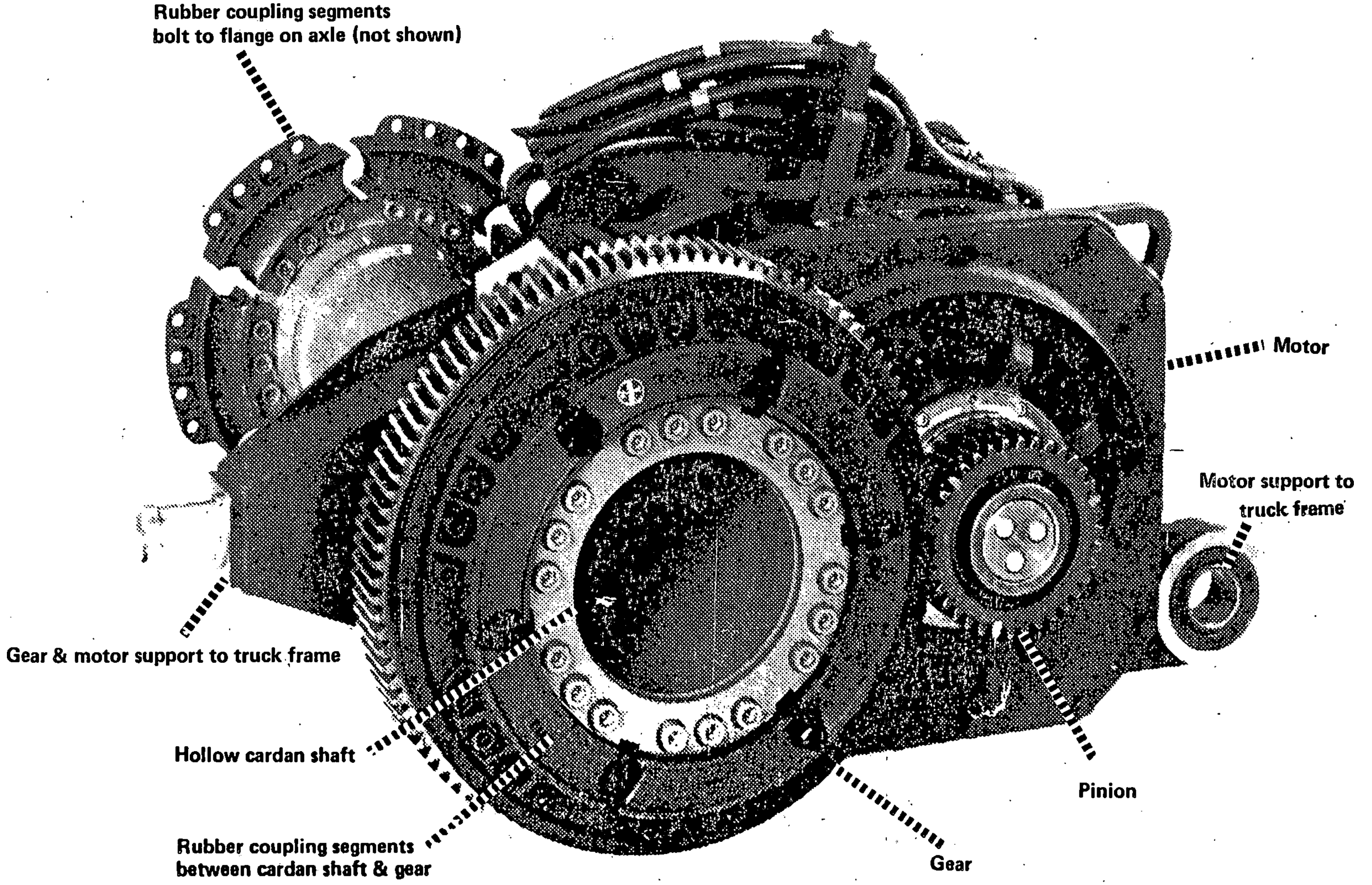
The ET403 has a form of quill drive with the motors and single reduction parallel gear units shock mounted to the truck frame. The truck arrangement of the ET403 presents a very close fit of motor and brake components. Cheek mounted brake discs are fitted to both inner and outer faces of each wheel plate. This crowded truck layout dictated a compact quill drive.

A cardan shaft, concentric with the axle, couples the gear unit quill shaft to the axle. A six-segment rubber coupling at each end of the cardan shaft accommodates the angular and lateral deflection of the cardan shaft and provides torsional cushioning. The geometry of the cardan shaft is unique in that the cardan shaft passes through the quill shaft of the gear unit with the coupling located between the gear unit and the adjacent wheel. This permits a long cardan shaft and minimizes angular deflection at the couplings. In order to accommodate the axle and cardan shaft, the quill shaft must be of a large diameter, necessitating a large diameter support bearing. Figure 7-2 is an illustration of the motor, gears, and cardan shaft components for the ET403.

Starting tractive effort per axle is 2783 lbs. The accelerating tractive effort is fairly close to this value up to 65 mi/h at which point it declines on a motor curve.

FIGURE 7–2
GERMAN ET403 TRACTION MOTOR DRIVE

Truck Frame Mounted Motor and Gears with Concentric Cardan Shaft to Drive Axle



COURTESY OF TECHNICAL LITERATURE ON THE ET403 SUPPLIED IN GERMAN WITH ENGLISH TRANSLATIONS

Alsthom Monomotor

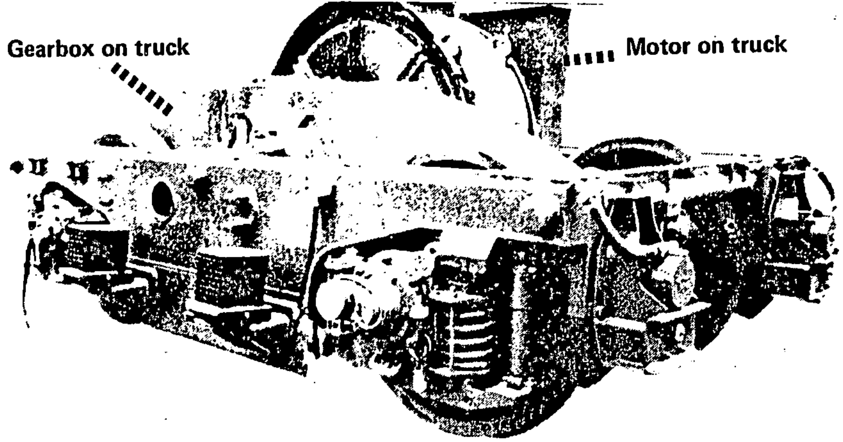
An interesting example of French locomotive construction is the type BB 22200 built for SNCF by Alsthom and designed for dual current operation on either 25 kV, 50 Hz or 1.5 kV direct current. A similar type BB 7200 was also built for operation on direct current only. The BB 22200 locomotives have a two axle monomotor truck in which a single large 2000 kW motor (2667 horsepower) and an extensive gear train are mounted to the frame of each truck and drives both axles. The gearbox output shafts are quill shafts with concentric cardan shafts coupled to each axle. The gear train has a central input pinion engaging two idler gears which in turn engage the two output quill shaft gears. Spur gears are used avoiding the need for thrust bearings and to permit a narrow gearbox. This arrangement provides for a short 2.8m (9' 2 1/4") wheelbase while placing the motor shaft well above axle height with the motor extending up into the body of the locomotive. Figure 7-3 is a composite illustration of the monomotor truck and details of the cardan shafts to the axles.

To facilitate axle removal the output shafts and gears are carried in removable sections of the gearbox. A flexible coupling is applied between the motor and gear unit to accept minor shaft misalignments.

The cardan shaft has two configurations of universal couplings. At the gearbox end, the coupling has a conventional arrangement with two radial pins extending from each of two yokes on the quill and cardan shaft. These yokes are rotated 90° apart and engage an external ring. Rubber bushings are used to accommodate the rotational movement between the pins and ring which occur when the universal coupling is deflected out of line.

The coupling at the axle connection differs in that the pins are parallel with the axle (rather than radial). The pins are attached to the yokes and rubber bushings are also used, however deflection at the coupling produces angular misalignment between the pins and the ring. The rubber bushings accommodate this angular movement by functioning as self aligning bearings and also permit lateral movement of the axle by shear displacement of the rubber. The wheel plate serves as the driven yoke, having holes in which the two driven pins are secured.

The starting tractive effort is approximately 16,300 lbs. per driving axle. Maximum rated speed of the locomotives is 112 mi/h with a normal service speed of 100 mi/h. The maximum continuous horsepower of 5333 is developed at 100 mi/h while a short time rating of 7600 horsepower is available for 15 minutes in the range of 55 to 90 mi/h. A freight version with gearing for 62 mi/h has also been produced. Sixty-eight of the 150 type BB 22200 locomotives and 35 of the 110 type BB-7200 locomotives have freight gearing.



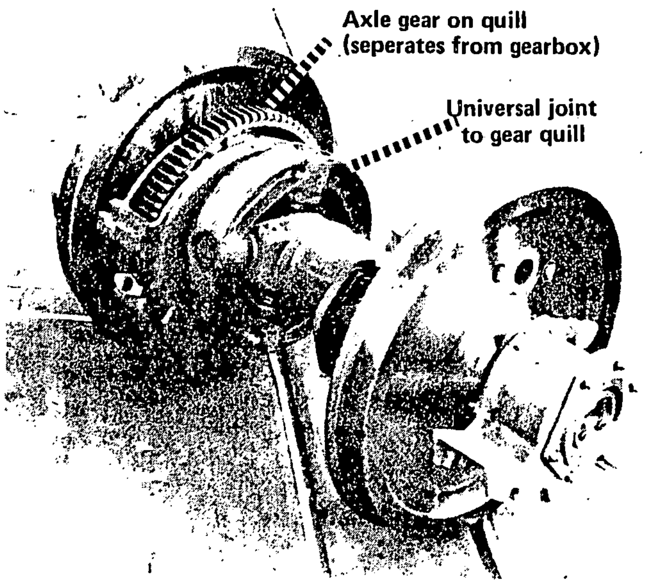
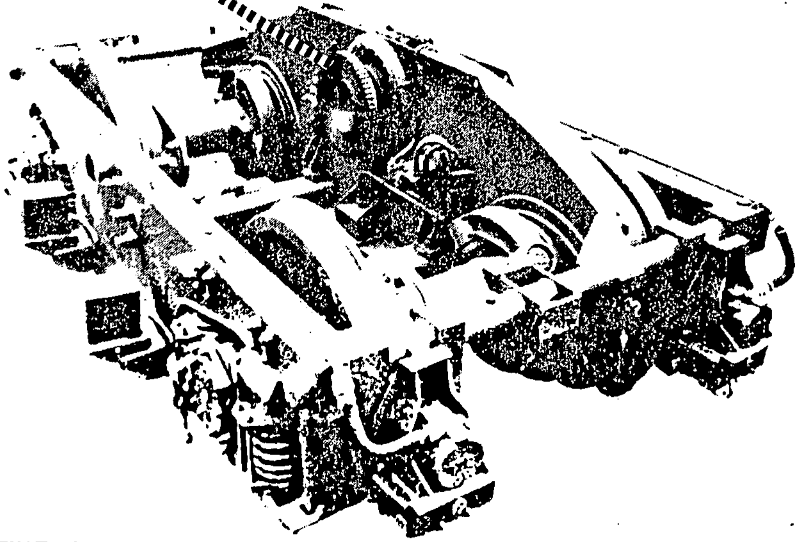
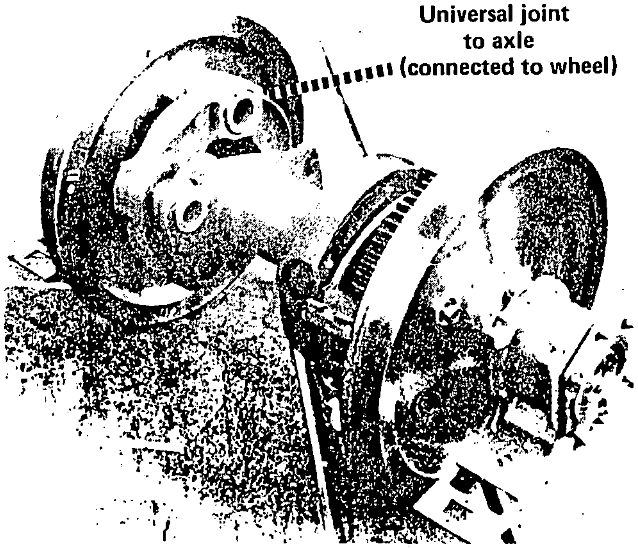


FIGURE 7–3

ALSTHOM MONOMOTOR TRUCK
FOR SNCF 22200 LOCOMOTIVES

Showing Concentric Cardan Shaft Drive to Axles





COURTESY OF FRENCH RAILWAY TECHNIQUES NO. 4 - 1978

Monomotor LRV

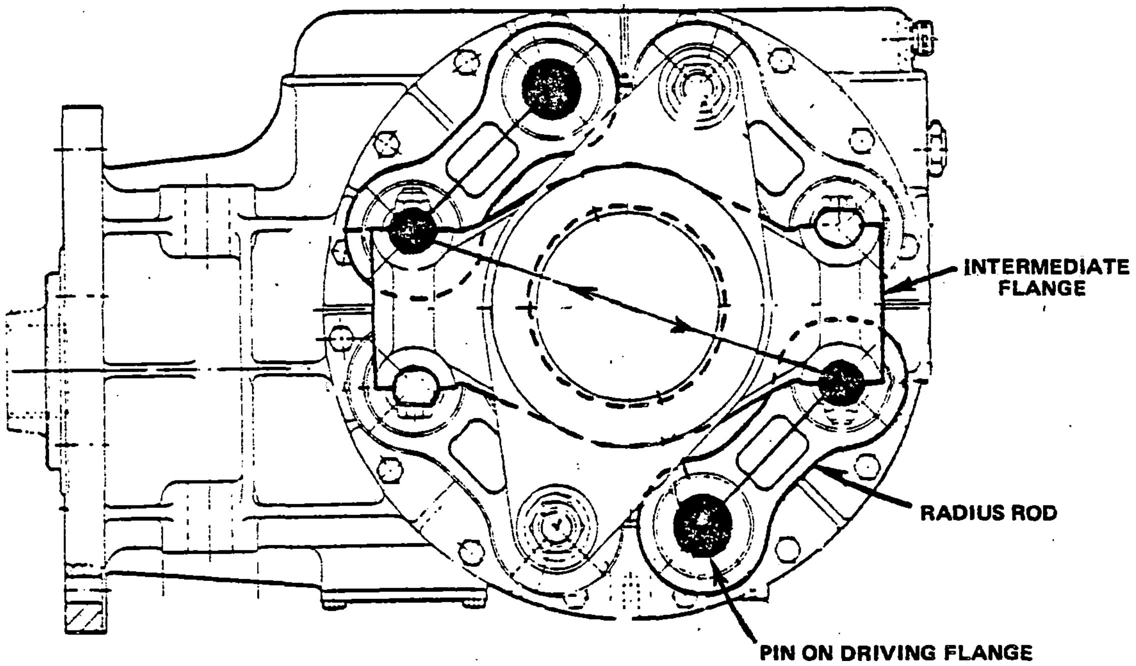
Light rail vehicles commonly have monomotor truck arrangements with truck frame mounted motors and gear units. While many of these have axle couplings which utilize rubber pads deflecting in shear to accommodate relative movement between axle and gear unit quill, some utilize couplings having a series of linkages which offer a greater degree of isolation.

The Garrett motor and gear arrangement applied to the Boeing LRV is an example of a drive employing a single longitudinal shaft motor coupled to two right angle hypoid gear units with quill drive. The motor and gear units are bolted together as a unit and shock mounted to the truck frame. A link type coupling connects each gear unit quill shaft to the respective axle accommodating the travel of the relatively stiff primary suspension and the shock isolation of the motor and gear unit mounting.

The Garrett axle coupling is comprised of two sets of linkage, operating in series, which have a common intermediate flange. Each set of linkage has two parallel radius rods which connect the driving flange to the intermediate flange (or the intermediate flange to the driven flange) and permit relative movement perpendicular to the shaft along one axis only. The two sets of linkage are positioned 90° apart to accommodate continuous radial movement (hence rotation).

Figure 7-4 is a two part illustration of the coupling which illustrates the action of the two linkages.

1ST LINKAGE
DRIVING FLANGE TO INTERMEDIATE FLANGE



2ND LINKAGE
INTERMEDIATE FLANGE TO DRIVEN FLANGE ON AXLE

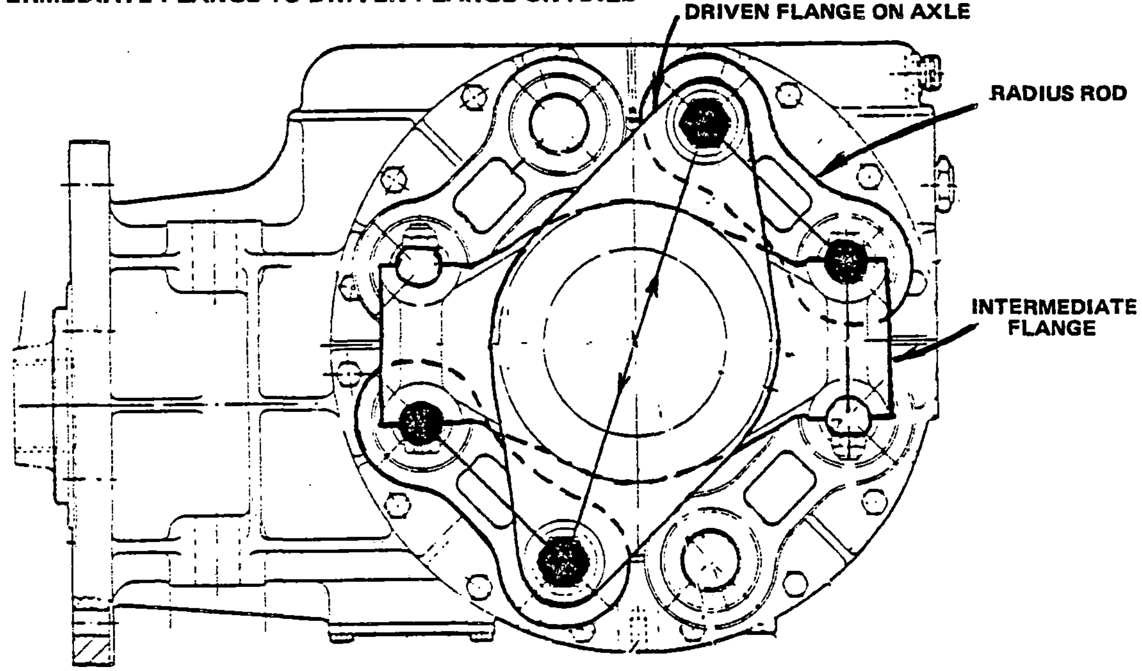


FIGURE 7 – 4
GARRETT COUPLING FOR BOEING LRV

COURTESY OF BOEING DRAWING (OF GARRETT GEAR UNIT)

8 - BODY MOUNTED MOTORS

The only remaining step in the reduction of unsprung mass is to relocate the traction motors from the truck frame to the body where they can be carried on the secondary suspension. Historically, drive arrangements with shafts and gears between body and truck have been used with gasoline and diesel engines having mechanical or torque converter drives where, because of size and maintenance requirements, the engine could not be truck mounted. Electric traction motors, in contrast, were generally mounted in the trucks because of the apparent advantages of simple and compact arrangement. More recent concern with the riding qualities of high speed electric train sets operating at speeds in excess of 150 mi/h has led to consideration of transferring the motor mass to the secondary suspension. The attendant penalty is the increased complexity and maintenance of drive components.

Three of the electric trains reviewed by IPEEP were designed for speeds of over 150 mi/h and have body mounted traction motors. These are the French TGV-PSE, the British APT, and the Italian ETR401. Their drive arrangements are reviewed along with the diesel/torque converter drive of the Budd SPV2000 and its predecessor, the RDC.

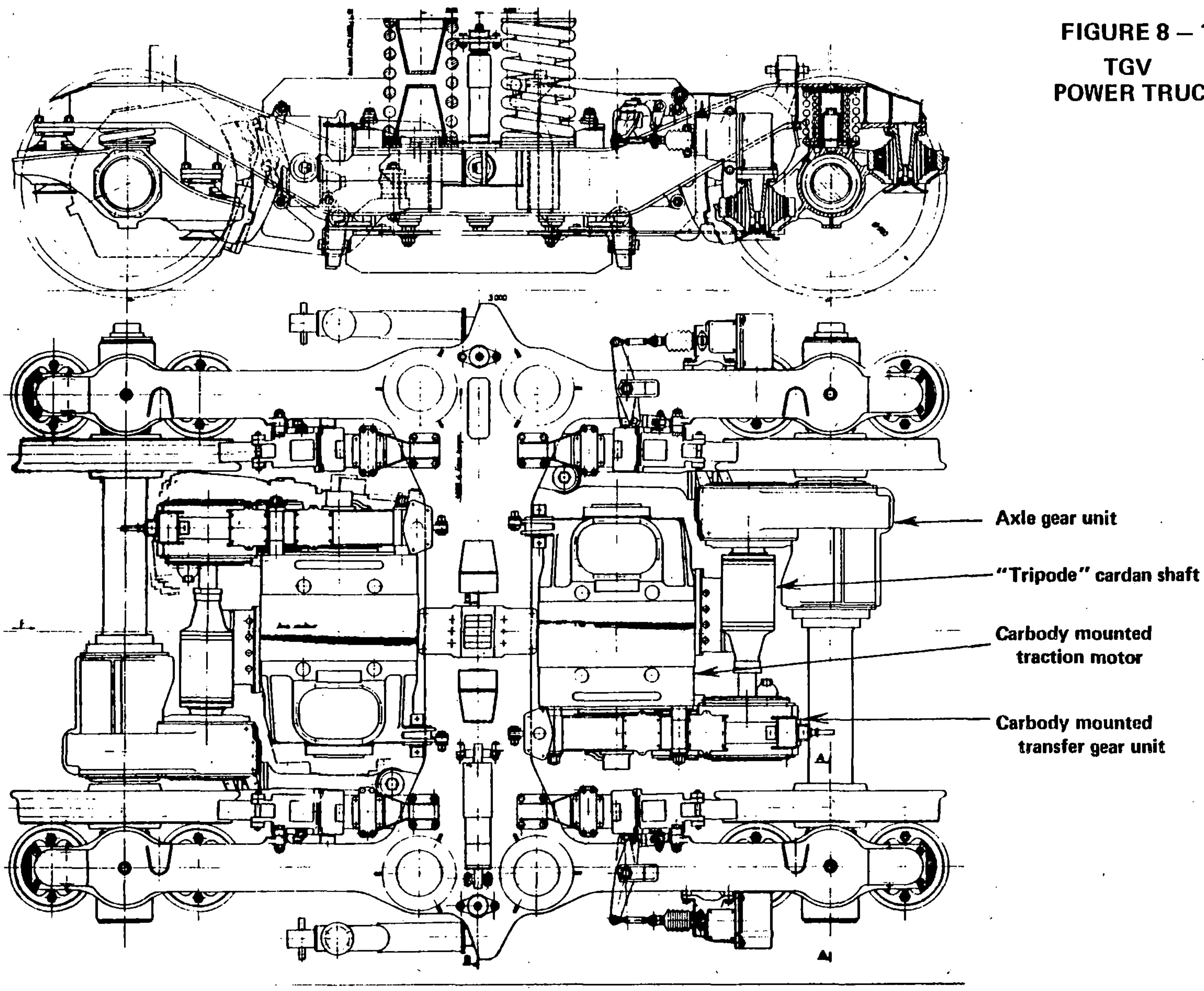
French TGV-PSE

The French TGV-PSE is comprised of an articulated set of passenger cars with a separate electric power car (locomotive) at each end. In addition to two motor trucks on each power car, one truck at each end of the articulated car set is motorized, deriving its power from the adjacent power car.

The drive for the TGV-PSE is unique in that it retains the layout of a parallel drive with the motors located within the area of the truck, however the motors are shock mounted to the carbody allowing the mass of the motors to be carried by the secondary suspension. Power is delivered through a transfer gear box attached to the motor and then through a special slip jointed cardan shaft to a second gear unit mounted on the axle. The transfer and axle gear units are on opposite sides of the truck with the cardan shaft parallel with the axle. Sufficient clearance is provided within the truck frame to accommodate relative movement between the carbody mounted motor and the truck frame. Figure 8-1 is an arrangement drawing of the TGV-PSE power truck, while Figure 8-2 is a detail of the traction motor drive components alone. By locating the motors within the truck, there is no adverse effect on the vehicle's center of gravity.

Because of the body mounted motor arrangement, the type Y230 power truck used under the power cars and the ends of the articulated car set is actually lighter than the type Y231 non-power

FIGURE 8 – 1
TGV
POWER TRUCK



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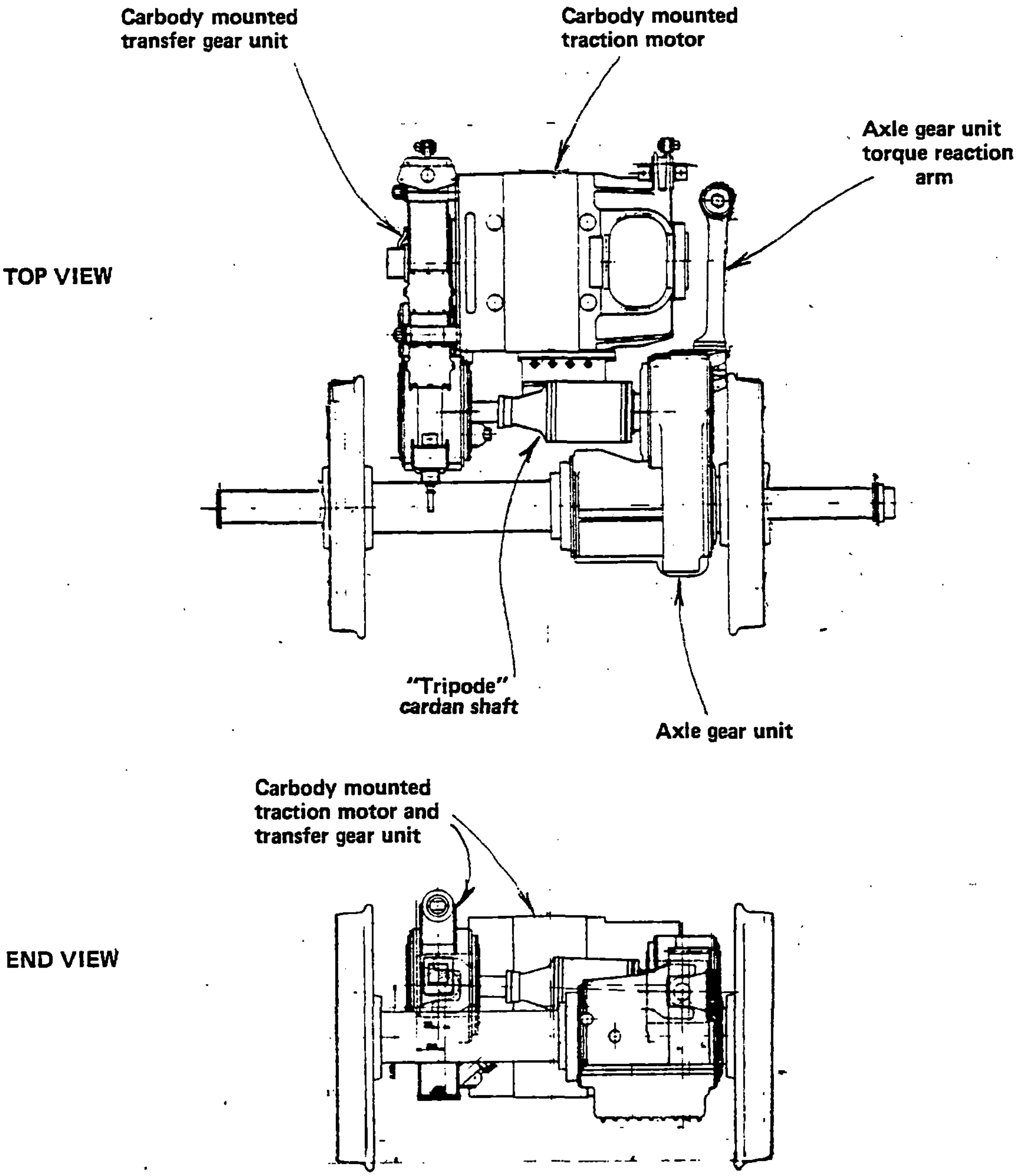


FIGURE 8 – 2
TGV CARBODY MOUNTED
TRACTION MOTOR

COURTESY OF CHEMIN DE FER NO. 326, 1977 - 5 SEPT. - OCT.

truck used at the articulated car connections. Although the power truck mass includes the axle gear unit, the array of four brake discs per non powered axle contributes slightly greater mass, accounting for the difference. The unsprung mass of a powered axle is given as 2,932 lbs. while the unsprung mass of a non-powered axle (with discs) is 3,543 lbs.

The arrangement of a transverse slip jointed cardan shaft between the body mounted motor and the axle gear unit introduces a serious problem in that the force required to telescope a conventional splined coupling is a function of the torque being transmitted because of the friction between the spline surfaces. Thus a large lateral force may be required to telescope the spline when operating at high levels of propulsion, or dynamic braking torque, while very little force will be required while coasting. This varying lateral force introduces an undesirable bias in the lateral spring and damping rates of the suspension which also affects yaw damping.

To preclude this problem a special splined coupling which the French have termed the "Tripode" was developed using roller contact surfaces. The Tripode has three large splines in the external half of the telescoping coupling which engage three rollers on pins on the inner member of the coupling. Needle bearings are used between the rollers and pins to eliminate friction bearing surfaces. This configuration reduces the telescoping friction forces to a negligible level. Conventional universal joints are used at each end of the sliding coupling.

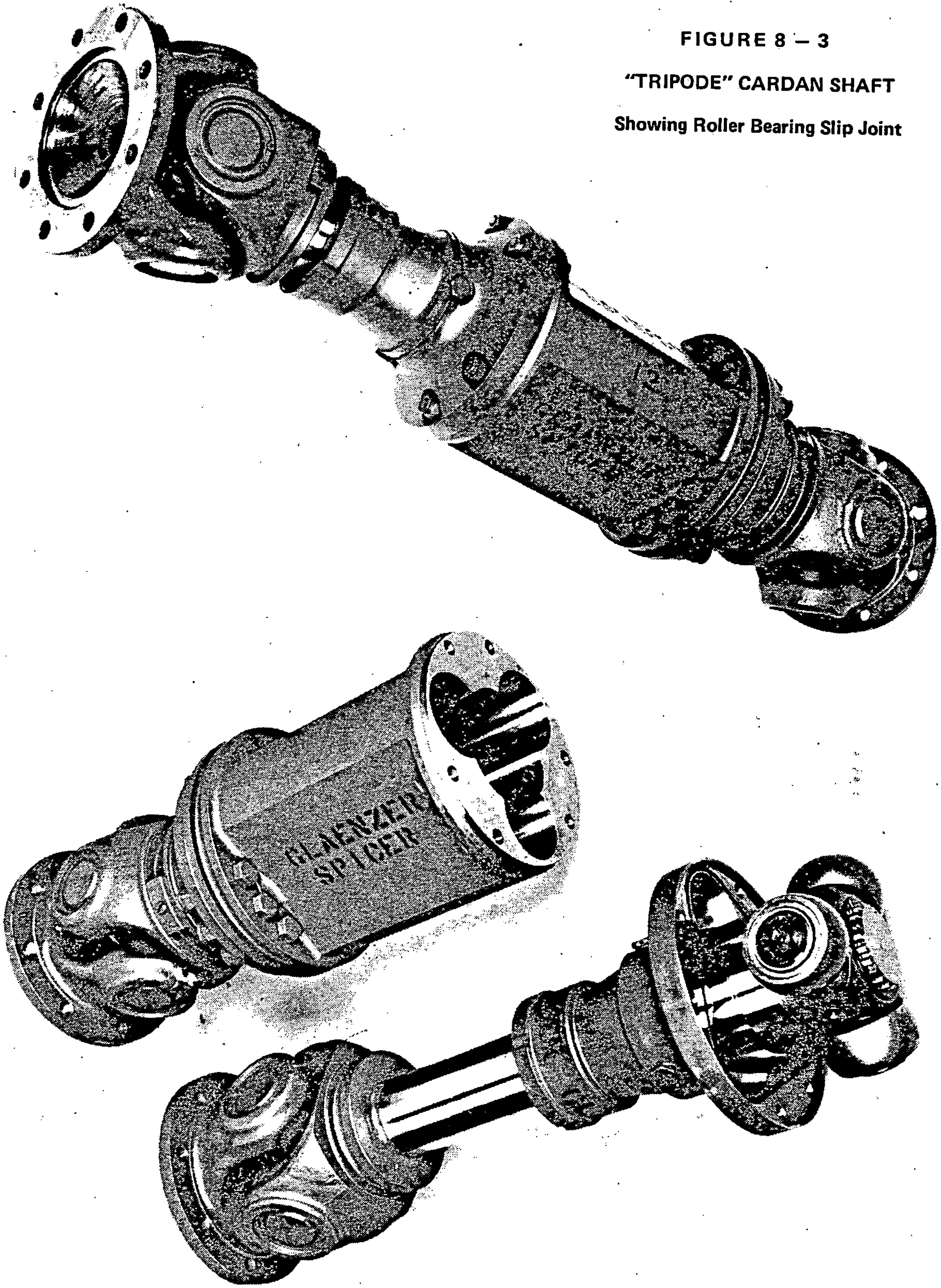
The Tripode was derived from the somewhat longer drive shaft used between rear mounted engine/transmissions and the rear axle in large busses. It has considerable experience in this service. Extensive prototype testing was performed with the Tripode on the Z7001 experimental electric car and endurance tests were performed at test facilities including those of the SNCF. Two somewhat different designs are offered by two manufacturers; Voith and Glaenzer-Spicer. Figure 8-3 is an illustration of the Glaenzer-Spicer version of the Tripode.

The tractive effort transmitted by the TGV drive is 3990 lbs. per axle when starting and the continuous tractive effort requirement for 260 km/h operation (161.6 mi/h) on level tangent track is 1087 lbs. per axle. With new wheels (worst case) and taking the axle gear ratio of 41 to 54 into consideration, this subjects the Tripode coupling to 4572 foot-pounds of torque when starting and 1246 foot-pounds of torque at 1975 revolutions per minute at the 161.6 mi/h condition.

FIGURE 8 — 3

"TRIPODE" CARDAN SHAFT

Showing Roller Bearing Slip Joint



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British APT

The British APT is a system of tilt body, articulated passenger-carrying cars and separate tilt body electric power cars (locomotives). Train consists for production versions have not yet been determined, but the prototype arrangement is made up of one or two mid-train power cars located between articulated car sets.

In the APT the traction motors are mounted within the car body of the locomotive along with the hydrokinetic brake unit. Power is transmitted from transfer gear units attached to the motors through longitudinal cardan shafts to the trucks. Right angle gear drives to the axles are shock mounted to the truck frame and coupled to the axles through concentric cardan shafts to further reduce the unsprung mass. This arrangement places the mass of the traction motors and hydrokinetic brake units on the secondary suspension and the gear units on the primary suspension. Figure 8-4 shows the arrangement of the drive train.

The physical arrangement of the motors and hydrokinetic brakes in the car body places the motors for each axle approximately above the opposite axle of the same truck. The motors, gears, and shafts at each truck are offset to opposite sides of the locomotive providing adequate clearance between the shafts as they pass each other to accommodate truck movement.

Placement of the motors and hydrokinetic brake units above the floor tends to raise the center of gravity which would be undesirable with the high curving speeds expected of tilting body trains. To overcome this weight distribution, the transformer and smoothing reactors are placed below the locomotive floor between the trucks, with the lighter control components and air reservoirs within the body.

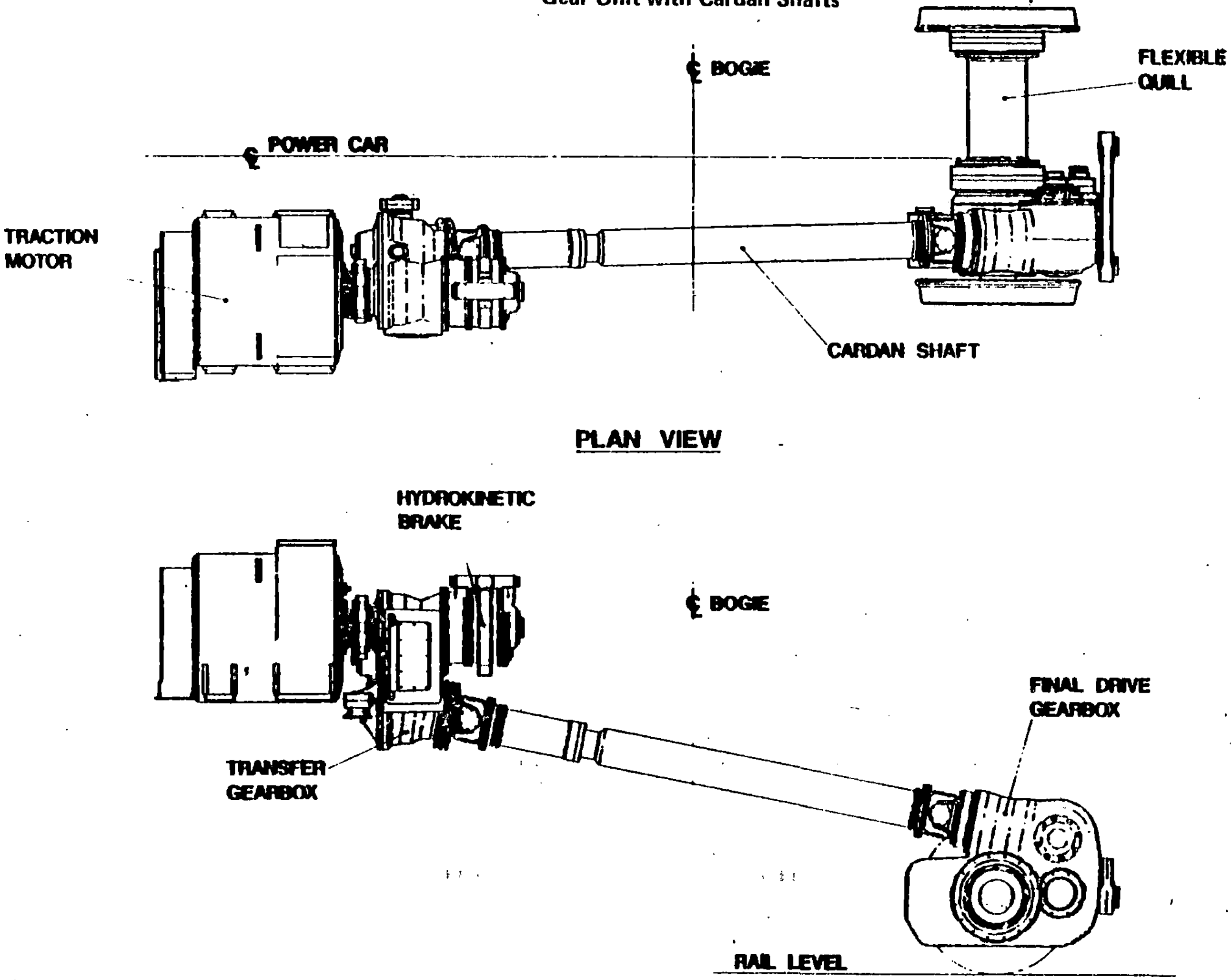
The APT locomotive truck presents some unusual problems in providing adequate space for traction motor drives and the tilting body suspension system. The tilt mechanism, while fairly simple in principle, requires a considerable amount of space as it is comprised of a tilting truck bolster suspended from swing hangers between two transverse frames in the truck. The length of the drive shafts from the body to the truck mounted gear units is sufficient to preclude any effects on geometry from carbody tilting.

In addition to the tilt linkage there is a complex yaw damper arrangement having a carbody mounted longitudinal rocker shaft which is connected to the truck frame at both ends through hydraulic dampers. The yaw dampers provide unrestrained lateral truck movement while offering resistance to truck rotation. The location of the rocker shaft axis close to the tilting axis of the locomotive minimizes the influence of body tilt angle on the

FIGURE 8 – 4

APT TRACTION MOTOR DRIVE

Body Mounted Motor and Truck Frame Mounted Gear Unit with Cardan Shafts



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dampers in comparison with that which would obtain with the use of more conventional longitudinal dampers between the truck and the body at the sides of the locomotive. A separate damper is used to control lateral movement. Figure 8-4 is an isometric drawing of the APT power truck.

Another feature of the APT locomotive suspension which complicates the space problem is the use of a body mounted traction bracket extending down into the truck between the central transoms and one axle. This lever provides a low connection link between truck and car body to minimize weight transfer between axles due to traction forces. The central location minimizes the effect of the body tilt angle on the alignment of the traction link. On one truck of the locomotive there is an additional set of linkages extending up through the locomotive car body to the pantograph base to negate the effect of body tilting on the pantograph by maintaining the contact shoe in a plane parallel with the cross level of the rail.

Maximum tractive effort of the APT is 5,750 lbs. per axle. This is maintained fairly constant until 70 mi/h at which point the tractive effort declines along the motor curve.

Italian ETR401

The Italian ETR401 is a tilting body multiple unit electric car set having streamlined end cab cars and designed for operation on 3 kV direct current. The ETR401 cars have a body mounted traction motor arrangement powering only one axle per truck. A right angle drive is mounted on the inboard axle of each truck with a longitudinal cardan shaft extending to the motor. This arrangement leaves adequate space within the truck to accommodate two brake discs per axle and the complex bolster and swing hanger arrangement required by the tilting body suspension. At the same time truck weight is kept to a minimum by supporting the traction motor on the secondary suspension. The gearbox is mounted directly in the center of the axle and flanked by two brake discs. Driving torque is reacted through a link to the support member for the brake calipers. Figure 8-5 is the truck arrangement drawing for the ETR401.

Because the ETR401 is designed for sustained high speed, it does not require the traction potential of having all axles driven and therefore can benefit from the reduction in drive components and the inherent reduction in mass afforded by fewer components of greater unit capacities. The use of 3 kV direct current power transmission in Italy further reduces vehicle weight by eliminating the need for an on-board transformer, and frees underfloor equipment space which can be used for body mounting of the traction motors. This arrangement would be much more difficult on an A.C. powered vehicle.

Maximum tractive effort per axle is 3,050 lbs. which is maintainted to approximately 65 mi/h at which point it begins to decline following the motor characteristics.

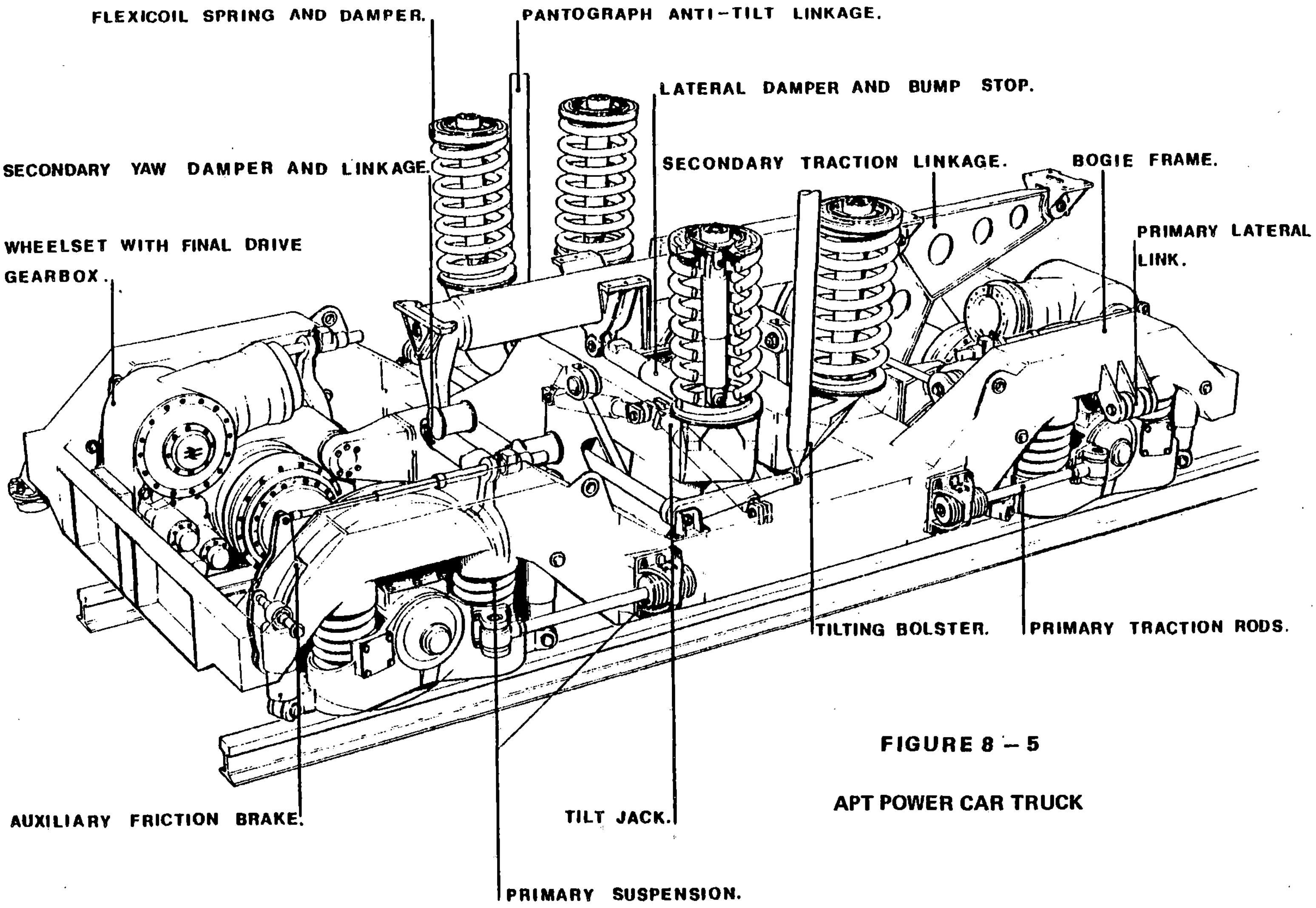

FIGURE 8 – 5

APT POWER CAR TRUCK

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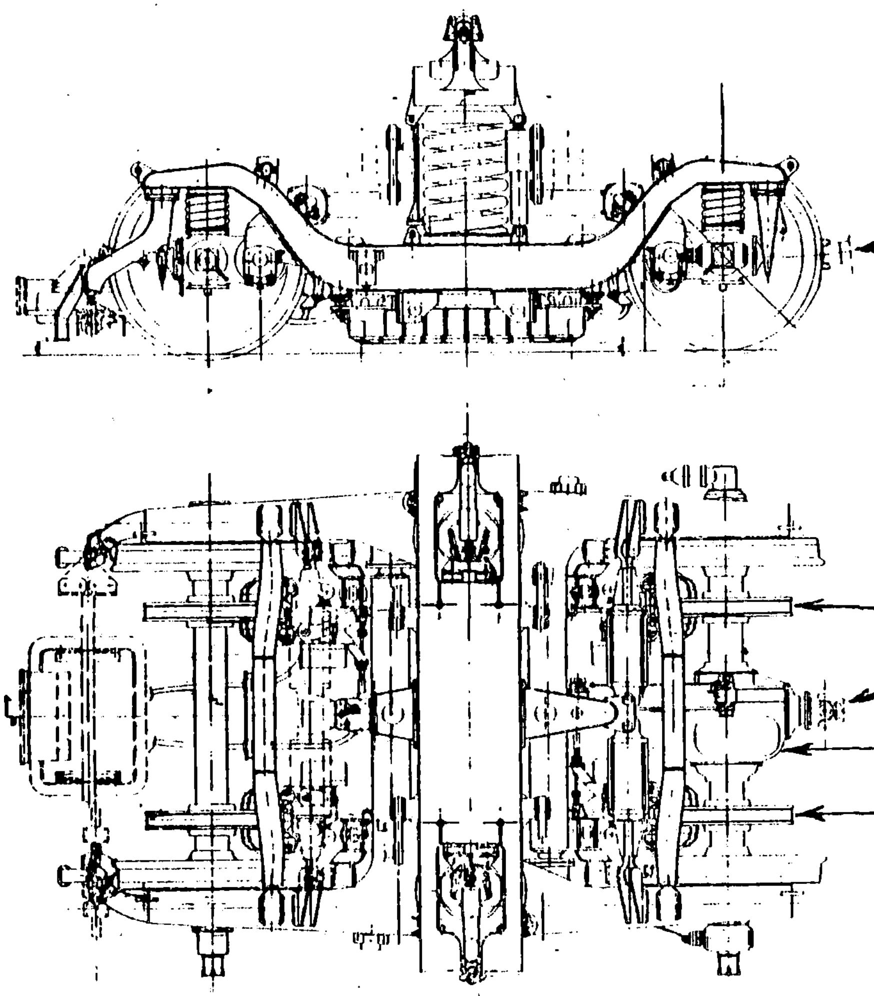
SPV2000, RDC and Others

The Budd SPV2000, utilizes diesel engines and torque converters to drive all axles. This concept was derived from the highly successful Budd RDC of the early 1950's which had a diesel engine and torque converter coupled to the inboard axle of each truck in a manner very similar to the Italian ETR401. The basic drive concept was shared by other internal combustion engine vehicles having mechanical or torque converter transmissions, and has been expanded to drive all axles in the new SPV2000 by adding a second right angle gear unit to the outboard axle of each truck. A transfer gear stage on the inboard axle gear unit permits the input shaft to pass above the axle with no change in the offset between the pinion and ring gears of the hypoid right angle drive.

With the original RDC, horsepower per driven axle was limited to about 260 h.p with a starting tractive effort of slightly over 4000 lbs. per axle. The SPV2000 has approximately 180 to 200 HP per axle, depending on engine option, and a maximum starting tractive effort of 3,250 lbs. per axle.

A similar four wheel drive using one body mounted traction motor per truck has been offered by General Motors Overseas Operations on their model GA-8, 800 horsepower diesel electric locomotive which is suitable for a range of narrow gauges. Power per axle is limited to somewhat less than 200 HP while tractive effort per axle may be as high as 8,275 lbs., depending on gear ratio.

FIGURE 8 – 6
ETR401 TRUCK



Carden shaft to carbody mounted traction motor

Brake disc

Cardan shaft to carbody mounted traction motor

Axle mounted right angle gear unit

Brake disc

COURTESY OF FIAT TRUCK DRAWING, SUPPLIED BY FIAT

9 - MAINTENANCE CONSIDERATIONS

An important consideration in the design of any equipment for U.S. railroads is the generally heavy usage and relatively long interval between maintenance events to which U.S. railroads are accustomed. With the exception of daily or trip inspection of safety related items, such as brakes, the only maintenance scheduled is the monthly inspection and test program required by the FRA for locomotives and self propelled cars. Because the daily or trip inspections are generally very brief and not comprehensive, non-safety related items often continue in service and are not picked up until the monthly inspection. The brakes must remain operative, however.

The monthly inspection events are, therefore, the only scheduled maintenance events required on U.S. equipment. In the course of monthly inspections various brake and electrical tests required at 3, 6, 12 and 24 month intervals are also performed. More frequent schedules of maintenance may be performed by the railroad, however, this is the exception rather than the rule, and any work done at more frequent intervals is performed as required on a failure rather than a preventive basis. It is estimated that most locomotives and multiple unit cars are shopped on the average of twice per month, once for monthly inspection and once for running repair of a significant failure.

The foreign maintenance standards observed in the course of IPEEP program have been generally higher than any found in the U.S. This level of maintenance permits successful operation of complex equipment with inherently high maintenance requirements which would probably not obtain if the same equipment were subject to U.S. service.

It is therefore important that maintainability be considered very carefully in specifying new equipment. This is particularly true in areas such as traction motor drives in which the trade-offs in design involve the use of more complexity to offset the effects of excessive unsprung mass. Several key conditions affecting the maintainability of traction motor drives are listed here.

- Components should be accessible for inspection to determine wear limits or the need for corrective maintenance without disassembly.

- Routine maintenance requirements should be minimal, avoiding wear surfaces, lubrication points, and seals. Rubber bushings and shock couplings generally require no maintenance throughout their service life and therefore are preferrable.

- Parts subject to deterioration should be designed for replacement with a minimum of disassembly.

- Employ a maintenance philosophy of developing life expectancy statistics in a test program and then replace components on a mileage basis before failure occurs.
- Drive train components will probably be replaced as units with overhauled and matched components and assemblies.

The maintenance requirements for each of the drives reviewed in this paper are closely related to other design features of the respective train such as truck designs and suspension designs and train configuration, and to railroad maintenance facilities. It would be unrealistic to quantify the various traction motor drive designs out of this context, however an evaluation of proposed traction motor drives should be made as a part of planning for any new high speed passenger equipment for the U.S.

PART 2. REVIEW OF MODERN SLIP DETECTION AND CONTROL SYSTEMS FOR ELECTRIC LOCOMOTIVES AND MULTIPLE-UNIT CARS

Richard A. Uher

1.0 EXECUTIVE SUMMARY

The purpose of this working paper is to review the state of the art of adhesion improvement in traction and to present synopses of those systems which hold high potential for a future high speed passenger train on the Northeast Corridor.

Modern wheel slip detection and correction systems tested in this country and used abroad can improve utilization of adhesion. They cannot, however, improve adhesion conditions which are caused by rail surface conditions, dynamic wheel weight relief, wheel/axle adhesion limit differences due to preceding wheel cleaning action and dynamic effects and certain traction drive effects. They can correct adhesion loss by weight transfer.

Modern slip detection is accomplished by detecting wheel speed differences, abnormal wheel acceleration and torsional oscillations in the wheel/axle set which have been found to increase rapidly as the creep speed approaches the adhesion maximum. Slip correction is accomplished by reducing tractive effort on an individual axle basis if creep is caught in time or by larger reductions of tractive effort either on an individual axle, truck or vehicle basis when creep has progressed too far or under conditions of multiple axle slip.

A set of requirements for the design of any slip control system is proposed based on this review.

- Slip detection should be fast and accurate.
- Solid state traction control, with separate motor torque reduction is preferred over other types.
- Mechanical characteristics of the traction drive should encourage natural reestablishment of adhesion by "slip-stick".
- Slip control should operate fast enough to reduce wheel wear but slow enough to maintain high tractive effort.

Three modern slip control systems were reviewed.

- Sentry Adhesion System (General Electric Co.)
- Creep Control System (ASEA)
- AC Drive (Automatic Slip Control)

Since the performance of these systems was not tested on the same locomotive, no conclusion regarding which one is better can be drawn.

2.0 INTRODUCTION

Improved utilization of available adhesion is an advantage for passenger and freight locomotives and self-propelled cars with high accelerating rates (3.0-3.5 MPHPS). There is less of an advantage realized with self-propelled cars with lower accelerating rates (1-2 MPHPS), typical of those running on the Northeast Corridor and its branch lines.

A freight locomotive's load of freight cars is determined by its adhesion capability on the ruling grade. A passenger locomotive can provide better acceleration to its consist if it has high adhesion; and, if the profile over which it runs has many speed restrictions and passenger stops, the schedule time can be improved.

The purpose of this working paper is to review the state-of-the-art of adhesion improvement in traction and to present synopses of those systems which hold high potential for a future high speed passenger train on the Northeast Corridor.

In order to fulfill the objective of the paper, it was necessary to complete a review of the known factors which influence adhesion in order to determine which can or cannot be controlled by a wheel slip control system. Thus, Section 3.1 covers the basic definitions used in the subject of adhesion and section 3.2 contains a review of the wheel/rail interface which pertain to adhesion and its improvement. With this introduction to the basic phenomena, Section 3.3 reviews the factors which influence adhesion including rail surface conditions, which is by far the primary influence, imposed wheel creep, wheel weight relief caused by both static and dynamic forces, wheel/axle adhesion limit differences due to wheel cleaning action and dynamic effects, tread brake action cleaning and traction drive effects.

Section 4.1 discusses modern methodology for slip detection. In particular, wheel speed difference, wheel acceleration and detection of torsional oscillations in the wheel/axle set in the approach to the adhesion limit is discussed. Section 4.2 considers modern methods used in the traction equipment for slip correction. Finally, Section 4.3 develops a set of requirements for modern slip control systems.

In Section 5.0, three slip control systems are reveiwed.

- Sentry Adhesion System (General Electric)
- Creep Control System (ASEA)
- AC Drive (Automatic Slip Control).

Section 5.4 presents the problems which must be solved in making a comparison among these systems.

3.0 BASIC ADHESION PRINCIPLES

In order to understand the fundamentals of slip detection and correction, it is necessary to discuss some of the principle phenomena connected with adhesion. The reader is referred to Reference 1 for a more detailed coverage of these principles. Much of the summary discussion here is a condensation of that reference.

During the last two decades, research into the phenomena constituting adhesion has borne some fruit. The study of slipping and sliding of wheels after exceeding the adhesion limit has been related to the tractive-effort/ speed curve of the motive power. It has been found that adhesion, or the lack of it, should be treated as a stochastic process and statistical methods should be applied in order to interpret measured results.

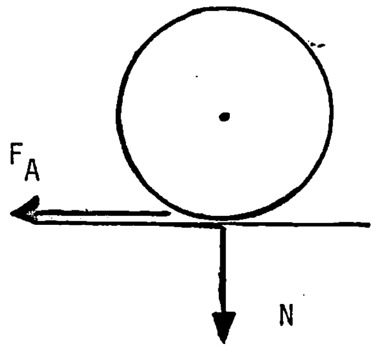
3.1 DEFINITION OF ADHESION

There is a limit to the maximum tractive or braking effort which can be applied via the steel wheel. This limitation is referred to as the adhesion limit.

Figure 3.1 illustrates the definitions which pertain to adhesion. The adhesion coefficient, which can be related stochastically to the adhesion limit, depends on many factors

- Creep phenomena at the wheel/rail interface
- Rail and wheel surface conditions
- Speed of Wheel and Vehicle
- Vehicle/Rail Dynamics
- Characteristics of Traction System.

Each of these phenomena which determine the adhesion coefficient and the adhesion limit involve complex interactions. In fact, the complexity is so extreme that railroads still depend on testing and experience to determine



$F_A = \mu N$

The quantity, μ, is called the coefficient of adhesion.

N = Normal force of wheel on rail

F_A = Tangential force applied via tractive or braking system

The adhesion limit, μ_M, is defined by the expression

$$\gamma = \text{Prob}\ (\mu \leq \mu_M)$$

where γ is some high percentage (usaully taken as 90%).

This above expression is interpreted as follows:

With the same conditions of environment, speed track and motive power, the probability that the adhesion coefficient will be less than the adhesion limit is γ.

FIGURE 3.1 BASIC DEFINITIONS OF ADHESION what adhesion limit to use.

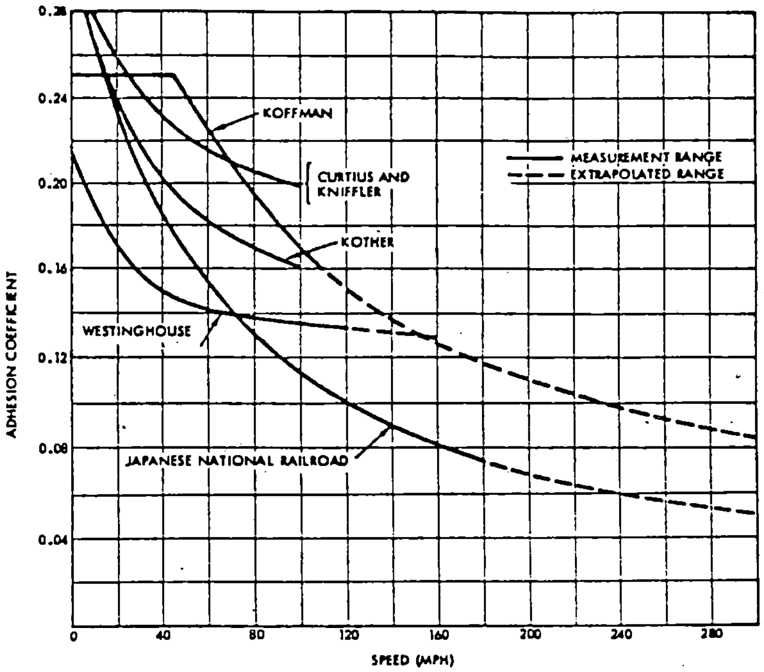
Figure 3.2 shows the adhesion limits obtained from different measurements on different wet and dry rails. It is not clear what probability levels were chosen for these curves.

3.2 CREEP PHENOMENA AT WHEEL/RAIL INTERFACE

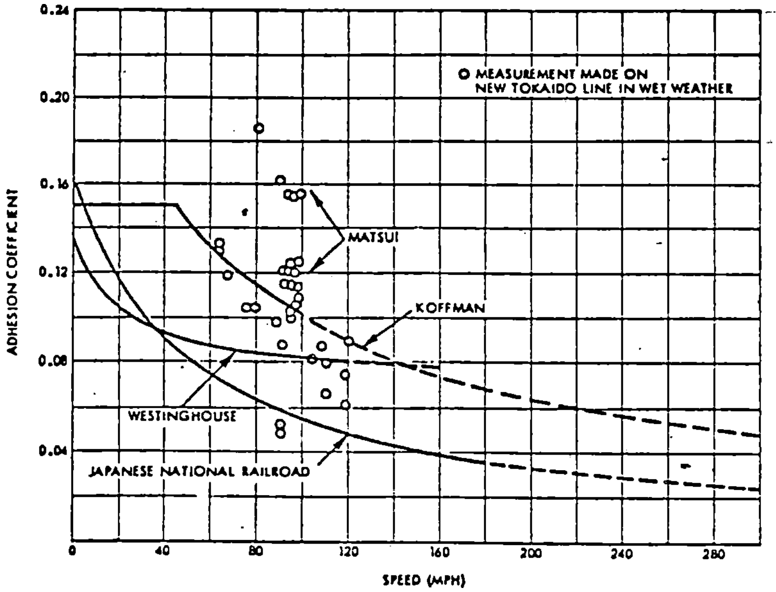
The contact between two objects always occurs at a contact surface whose shape, area and stress distribution depends on the mutual force between the bodies, their materials and their shape. For motive power in railroad application, the contact surface between wheel and rail has an elliptical shape whose length in the direction of motion increases with increasing conicity and wheel diameter. The contact area is not proportional to the force applied. The mean pressure increases with this force (which means that the contact area increases slower than the applied force) and decreases with increasing wheel diameter.

When torques are applied to a rolling wheel either because of the action of rolling train resistance or through the tractive and braking system, an area of compression and tension develops on and immediately below rail and wheel surface. This effect is illustrated in Figure 3.3. The larger the applied tangential force between wheel and rail, the further the zero line of stress is displaced from a line drawn perpendicular to the rail and through the center of the wheel.

Because of the stress/strain relationships developed upon transmittal of a tangential force between wheel and rail and because the surface contact is areal rather than lineal, the relative circumferential speed of the wheel at the rail is different from the wheel's forward speed. As a consequence, in order to transmit tractive or braking effort, it is necessary

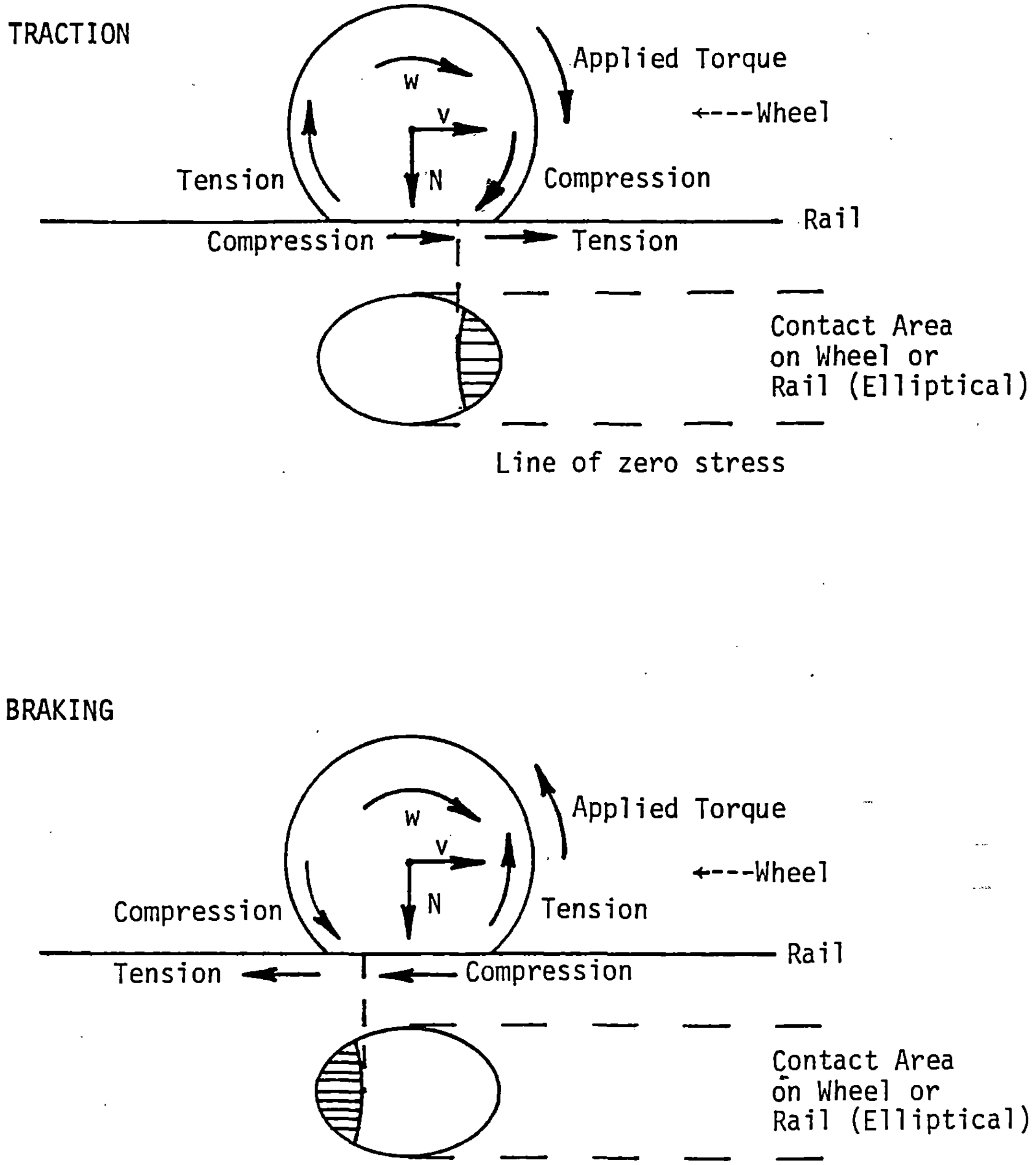


DRY WALL



WET RAIL

FIGURE 3.2 VALUES OF ADHESION LIMIT AS A FUNCTION OF SPEED AS A RESULT OF MEASUREMENTS ON WET AND DRY RAIL



w = Angular speed of wheel
v = Linear speed of wheel
N = Normal force

FIGURE 3.3 DISTRIBUTION OF STRESS IN THE CONTACT AREA to have some creep speed (difference between wheel circumferential and forward speeds). The relation between the amount of tangential force transmittable and the required creep speed can be illustrated by plotting the adhesion coefficient at some forward speed (V_0) as a function of creep speed as is shown in Figure 3.4. Note that the adhesion coefficient drops to zero unless their is some creep.

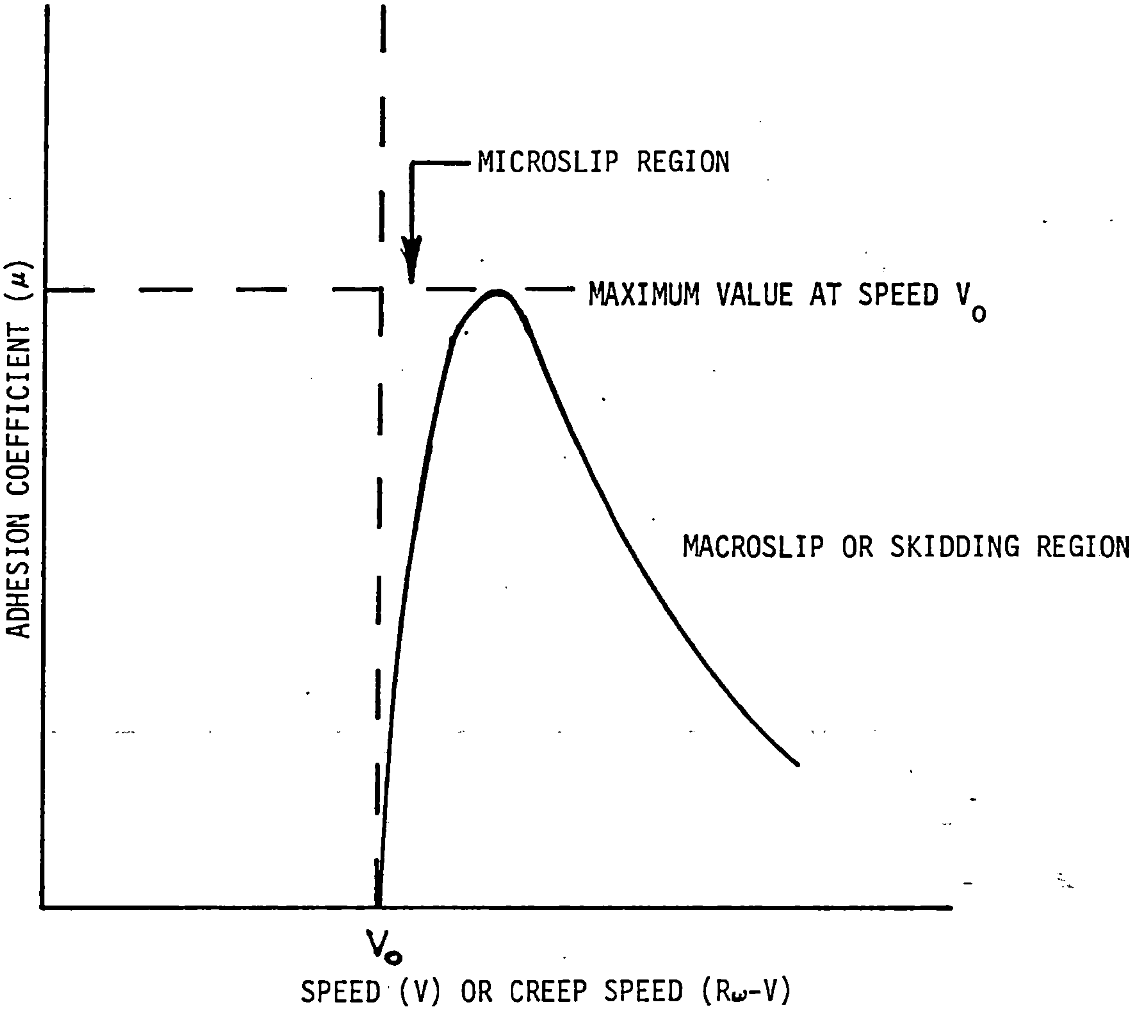
The ideal place to operate is the microslip region shown in Figure 3.4 and as near to maximum adhesion value as possible with existing rail conditions. The macroslip or skidding region operation is not desirable because of instabilities and the high wheel and rail wear rates encountered at these levels of wheel creep. Thus it is the job of any traction/wheel slip control system to operate near maximum adhesion as much as possible.

3.3 FACTORS WHICH INFLUENCE ADHESION

3.3.1 Rail Surface Conditions

The effects of rail surface conditions on adhesion have been investigated over many decades in many different kinds of tests both in the field and in the laboratory. The principal knowledge gained over the years may be simply stated as follows:

- Absolutely clean, dry rails will cause an adhesion coefficient at low speed in the range from 0.6-0.7. This condition can be simulated in the laboratory but can never be realized in practice on the road.[2]
- Moisture propagated oil films are a major cause of wheel slip. Tests[3] conducted in the U.S. have shown that ninety percent of all wheel slips occur on curved track, at road crossings, switch points, frogs and crossovers where oil deposits were present outside the rail wear band. Traffic and heat destroy the oil film while light rain or dew causes it to develop as soon as the water comes into contact with the oil deposit. Long and heavy rain can wash away the deposits completely and restore adhesion.



R = Wheel radius
ω = Wheel angular speed

FIGURE 3.4 ADHESION COEFFICIENT AS A FUNCTION OF CREEP SPEED

- Heavy oil films (5 x 10^{-6} g/cm^2) tend to reduce the adhesion coefficeint at low speeds to a value of 0.16. Figure 3.5 shows the adhesion coefficient's dependence on lighter film thicknesses and humidity. These graphs result from laboratory tests.[1]

- At low speed, adhesion on very wet, clean rail is similar to that on dry, clean rail. However, on wet rail there is a greater slipping effect even though maximum values remain about the same. (In other words, referring to Figure 3.4, the slip speed at maximum will be larger at peak adhesion on wet rail than on dry rail.)

- Rust films exhibit both improvement and degradation of adhesion. A thin, dry (yellowish) rust film is observed to improve adhesion while thick, moist (brownish) rust films reduce it.

- Industrial pollutants such as coal dust and cement generally have an adverse effect on adhesion if the film is thick enough to interrupt rail contact. The effect becomes worse as the humidity increases.

- Falling leaves in the autumn substantially reduce adhesion. They are made into a viscous paste which is spread over large distances by the action of wheels and moisture. Values as low as .05 have been encountered.[1]

- Quantities of very fine particles of iron, oron oxide, iron carbide and silicon dioxide when spread on oil films (up to 40 x 10^{-5} g/cm^2) will improve adhesion. If oil films are too thick, particles will have no effect. The presence of water reduces the adhesion improvement of these particles on the oil film.

It is clear from our past knowledge of the effect of rail surface condition on adhesion, that many different rail surface conditions which can be met in a typical run can cause an extreme variation from point to point along any given track or from time to time along the same track. Thus, both the creep speed from zero to peak adhesion values and the peak adhesion value will vary from point to point and from time to time. Test results have indeed verified this.

There are obvious ways to improve adhesion by fixing rail surface conditions. Sanding which has been used for several decades and rail cleaning by various devices (including application of heat, water etc.) are among the more popular.

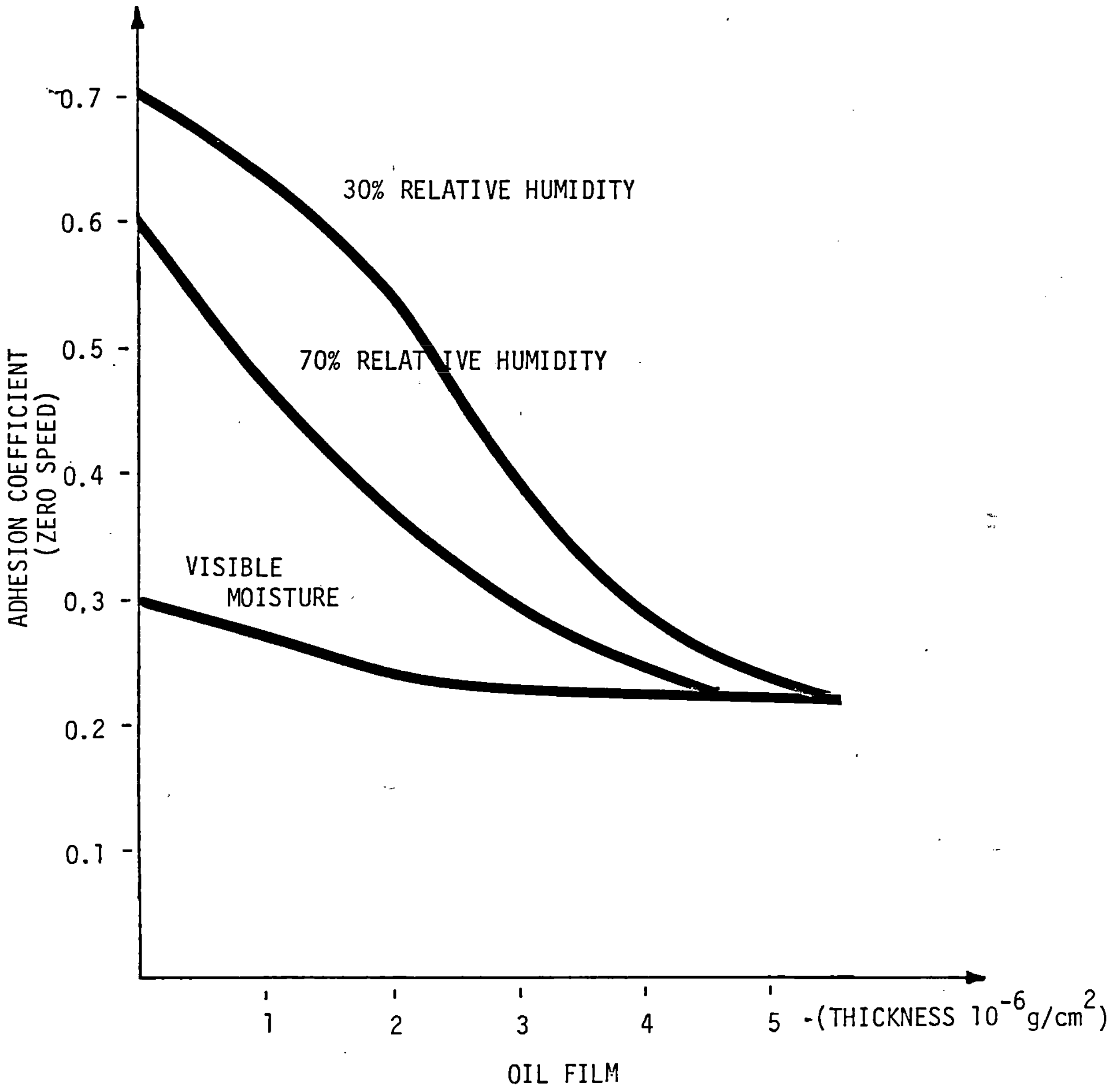


FIGURE 3.5 VARIATION OF ADHESION COEFFICIENT WITH SURFACE FILM AND RELATIVE HUMIDITY

3.3.2 Imposed Wheel Creep

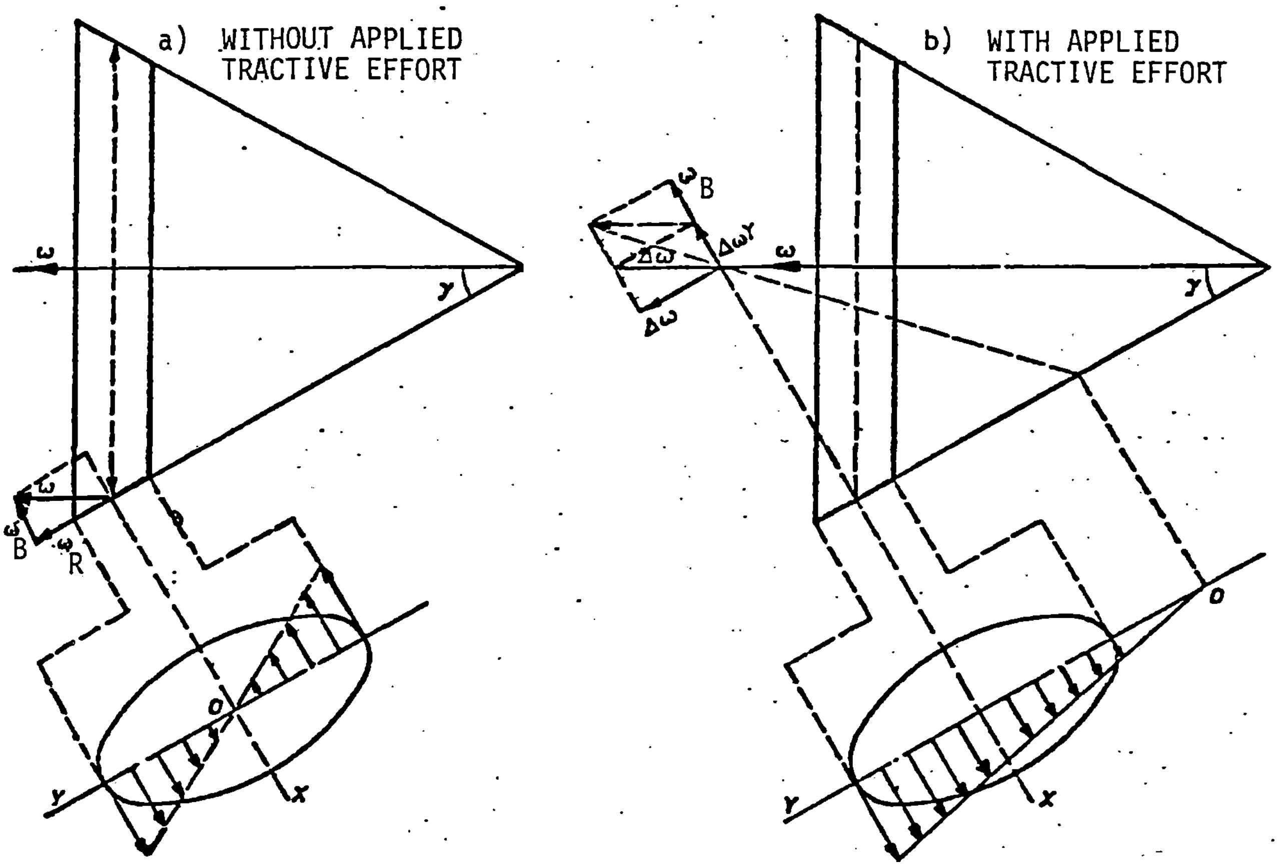
In the discussions concerning the relation between the adhesion coefficient and wheel creep speed (Figure 3.4), it was mentioned that the amount of tractive (braking) effort which could be transmitted between wheel and rail depended on wheel creep speed. However, wheel creep is a vector quantity which has both magnitude and direction and should be more properly called wheel creep velocity. There are several wheel creep effects which must be added vectorially to determine the global wheel creep velocity. Thus, the maximum tractive effort in the direction of forward motion of the train will be reduced because:

- It will decrease with increasing angle between wheel creep velocity and the forward direction,
- Wheel creep velocity is in general different for the two wheels of the same wheel set.

This decrease in adhesion is caused by several types of creep effects.

Wheel Conicity

Figure 3.6 demonstrates the effect of wheel conicity on wheel creep velocity. Because the rotational axis of the wheel is not parallel to its rolling surface, there is an imposed creep. In the absence of tractive effort, the center of rotation is nearly coincident with the center of the contact area (Figure 3.6a). This rotational creep modifies the forward creep caused by tractive effort application in such a way that the creep velocity is rotated at a slight angle to the forward direction of the wheel and the center of rotation is displaced as shown in Figure 3.6b. This effect reduces the net tractive effort which can be applied in the forward direction over the case of cylindrical wheels.



DEFINITION OF SYMBOLS:

O - Point of zero relative velocity between wheel and rail

γ - Coning angle

ω - Rotational speed of wheel

ω_R - Component of rotational velocity on wheel tread surface

ω_B - Component of rotational velocity perpendicular to wheel tread surface

$\Delta\omega$ - Creep speed due to application of tractive effort

FIGURE 3.6 IMPOSED SLIPPING BECAUSE OF WHEEL CONICITY (REFERENCE 1)

Wheel Diameter Differences and Lateral Forces

Lateral forces are developed between the wheelset and the track because of variation in gauge and alignment. These forces act in a direction perpendicular to the direction of motion and any creep velocity which develops as a consequence of them will not affect the tractive effort. However, if wheels on the same wheelset have different diameters, the associated transverse motion will induce different creep velocity components in the forward direction. These will have the tendency to reduce the overall adhesion coefficient.

Curving and Hunting

Any factor which affects the striking angle of the wheelset to the track in the forward direction will decrease the creep velocity component in that direction. Negotiation of curves and truck hunting are two such effects.

3.3.3 Wheel Weight Relief

The term weight relief refers to a driving wheel which has less vertical load imposed on it by the rail under driving (braking) conditions than under non-driving (non-braking), static conditions. Weight relief can adversely affect the amount of tractive effort which can be applied by the traction vehicle. There are two major causes of weight relief:

- Weight transfer, which is a relatively constant weight relief on certain wheelsets caused by application of tractive effort.
- Dynamic weight relief, which varies with time and occurs on all wheels. It is caused by the interaction of the vehicle with the track.

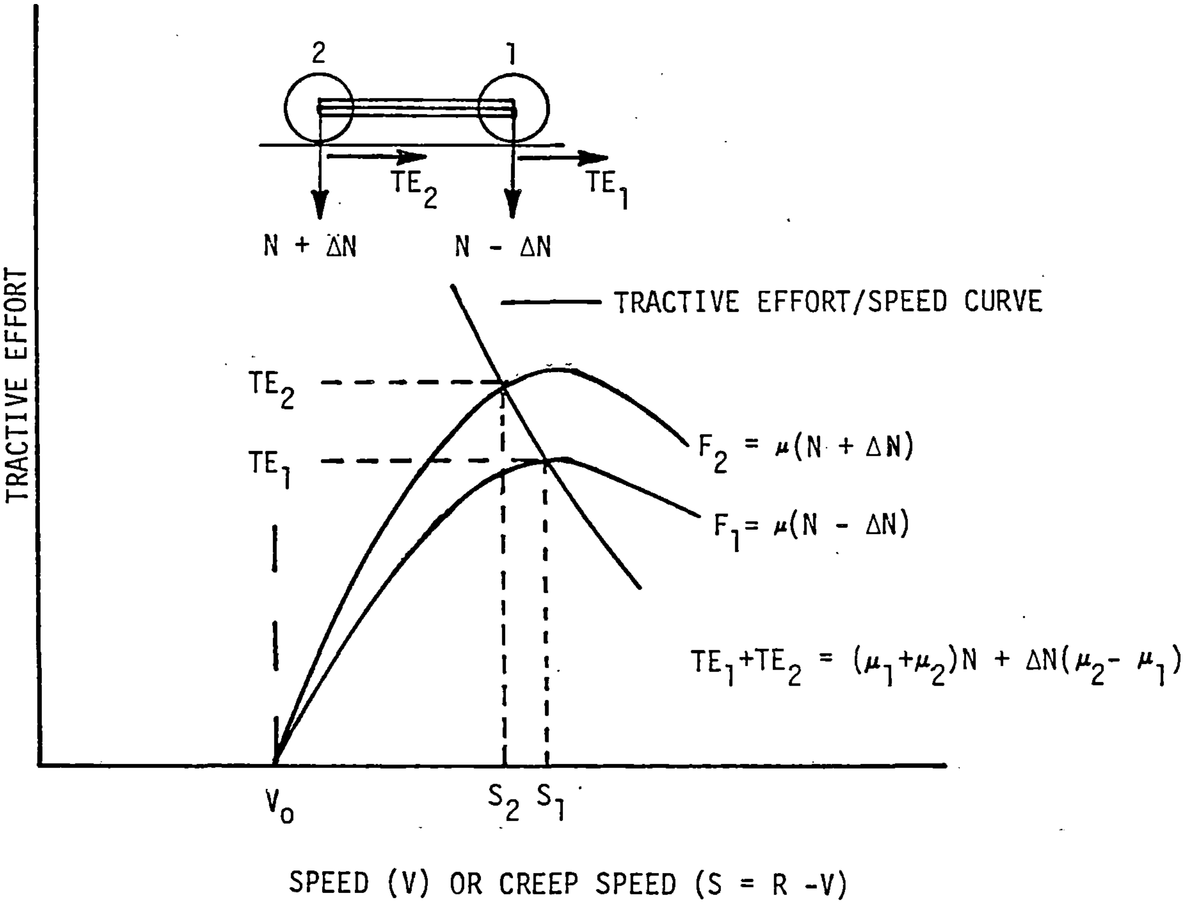
Weight Transfer

Weight transfer is the redistribution of wheel/rail loading as tractive effort is applied on the vehicle. Some of the wheelsets will feel a weight increase while others will feel weight relief. Weight transfer is a specific characteristic of the driving vehicle and depends on several factors, among them

- height of coupler above track (locomotives)
- above track height of the longitudinal coupling between driving truck and body
- truck wheelbase
- distance between truck center
- characteristics of traction motor suspension, gear units and coupling.

If each wheelset is driven with a separate traction motor, the maximum tractive effort should be limited so as not to exceed the value of allowable adhesion on the wheelset with the greatest weight relief. If both motors on a two axle drive are operated from the same control, there is some weight relief compensation as illustrated in Figure 3.7. This compensation arises because the tractive effort/speed curve has a negative gradient as a function of speed. Because of the weight relief on axle 1 and the nature of the adhesion/creep speed curve, the creep speed will be slightly higher which reduces the tractive effort put out by that axle, which in turn reduces the weight relief.

If the wheelsets on the same truck are mechanically connected such as in the case of a monomotor truck, the speed of these wheelsets including their creep speed will remain the same (provided, of course, the wheel diameters are the same). Thus with the assumption of similar adhesion coefficients for both wheelsets, the total tractive effort developed would not be influenced by weight relief. This is illustrated in Figure 3.8. Weight transfer is still a factor between trucks on the same vehicle.



V_o = Forward speed

R = Wheel radius

= Wheel angular speed

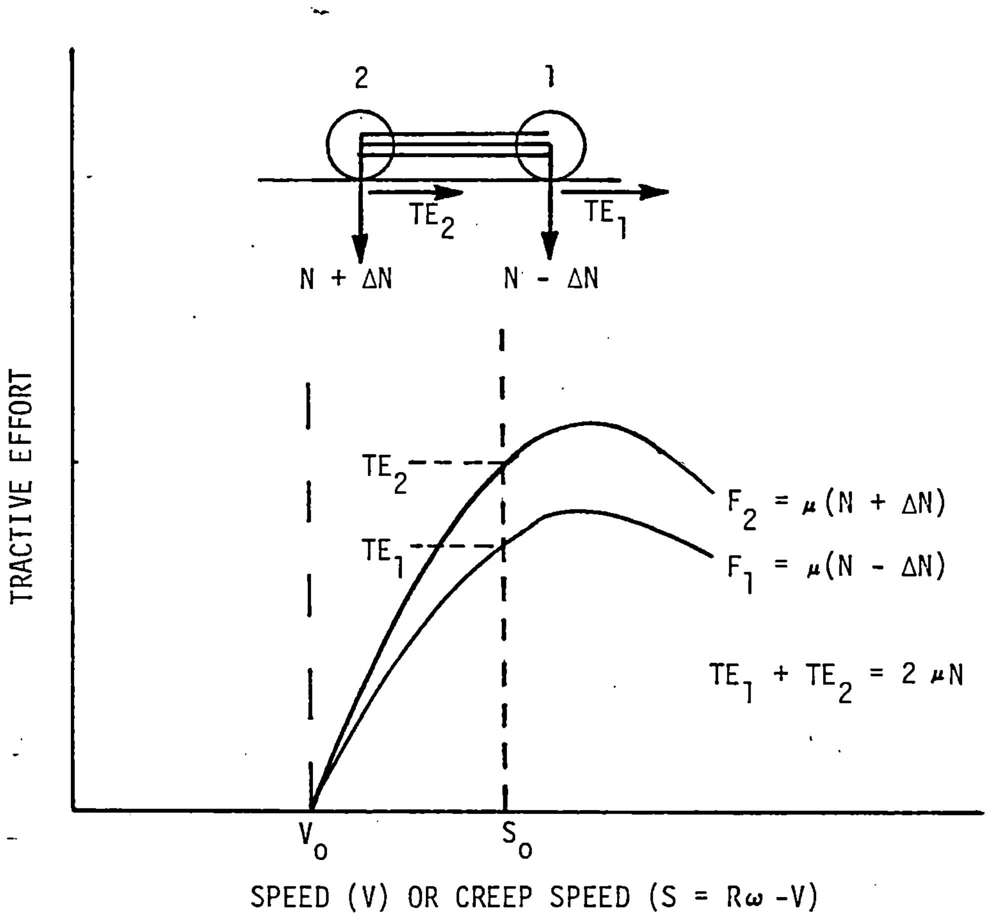
N = Normal force (non-driving)

ΔN = Weight relief on Axle 1

μ_1 = Adhesion coefficient at creep speed S_1

μ_2 = Adhesion coefficient at creep speed S_2

FIGURE 3.7 WEIGHT RELIEF COMPENSATION ON AXLES ON SAME TRUCK WITH INDIVIDUAL MOTORS OPERATING FROM SAME CONTROL



V_o = Forward speed
R = Wheel radius
= Wheel angular speed
N = Normal force (non-driving)
N = Weight relief on Axle 1
$_o$ = Adhesion coefficient at creep speed S_o

FIGURE 3.8 WEIGHT RELIEF COMPENSATION ON AXLES ON SAME TRUCK WHICH ARE MECHANICALLY COUPLED

Dynamic Weight Relief

The driving wheelsets are part of a vehicle which is a locomotive or a self-propelled car. Thus the wheel/rail interaction which involves the vehicle suspension system and track irregularities has an influence on weight relief which varies rapidly with time. This weight relief is instantaneously different for each wheel on the vehicle and can be both positive and negative. However, its average value will be zero, since it is a dynamic effect.

Variations in cross level and vertical alignment are the principal track inputs which result in this weight relief variation. Because of wheel conicity, gauge variation and lateral alignment also produce some weight relief effects; but, these are very small.

The effect of dynamic weight relief on adhesion is a very complex problem and depends on several factors:

- Mechanical parameters of the car including sprung and unsprung masses, moments of inertia and spring and damping constants
- Train forward speed
- Class of track (power spectral density)

Since dynamic weight relief increases with vehicle speed, the effect on adhesion is also expected to increase.

3.3.4 Wheelset Adhesion Limit Differences

There are two effects which can cause the wheelsets of the same driving vehicle to experience different adhesion coefficients.

The first effect is the cleaning caused by the leading wheelset. The first axle normally encounters the poorest rail surface conditions. Its passing over the rail provides a coarse cleaning for the following wheelset.

Of course, each succeeding wheelset provides some cleaning for the following wheelset, so that each successive wheelset should normally see a higher adhesion coefficient.

There is a second effect which can somewhat neutralize the successive cleaning. Although the first axle provides cleaning on the average, the following axles, because of their lateral motions, may not follow the same path. This causes variation in adhesion coefficients from axle to axle which in general is different from the rule described above, namely, that each successive axle see a higher adhesion coefficient.

3.3.5 Braking Action

Tread braking has always been considered superior to non-tread braking in terms of adhesion performance. The effect of the tread brake is to clean both wheel and rail of film which reduces the adhesion coefficient. The mechanism of cleaning is generally recognized as vaporization by heat of the film material.

There is controversy, however, between use of cast iron, tread brake shoes and composite material shoes.[1] Cast iron shoes are alleged to leave behind particles of iron, iron oxide and iron carbide which tend to improve adhesion both by deposits on the wheel as well as the rail. In contrast, composite material shoes are alleged to leave behind films which have low adhesion properties.

This issue is very controversial. There has been no conclusive proof in the United States that this does occur in practice.

3.3.6 Propulsion System Considerations

The propulsion system, which consists of the traction control and drive subsystems, has an important influence on the adhesion capability of the motive power when operating near the adhesion limit of any of the driving wheelsets. The principal influences include the mechanical characteristics of the drive, type of traction control, type of traction motor and the traction control/motor circuit configuration.

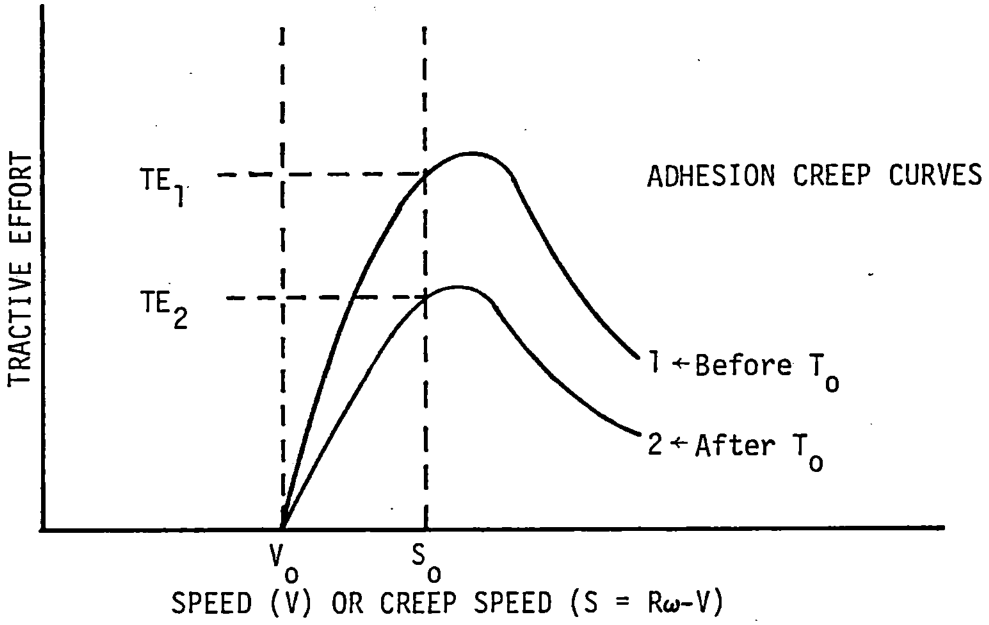
Traction Drive Mechanical Characteristics

Mechanical characteristics which influence adhesion at the adhesion limit include:

- Moments of inertia of motor armature, gears and wheel/axle.
- Damping and elastic characterics of all drive coupling in the rotational direction.

The role of the mechanical characteristics can be described with the help of Figure 3.9. At time, T_0, rail conditions are encountered such that the adhesion/creep curve changes (from 1 to 2). As a consequence, the magnitude of the tractive effort which can propel the vehicle becomes TE_2 which is less than TE_1, the tractive effort being output by the traction drive. The difference (TE_1-TE_2) will accelerate the wheel, however, because of the elasticity in the traction drive, the abrupt change in torques will cause an oscillation to develop in the wheelset as well. The frequency and amplitude of this oscillation are dependent on the mechanical characteristics of the drive. The total effect on the wheelset will be a rapidly increasing slip speed with a superimposed oscillation in slip speed. During the negative cycle of this oscillation, it is possible that adhesion can be reestablished. The phenomena is known as "slip stick".[1]

The greater the elasticity in the drive unit, the higher is the probability that adhesion will be established by encountering better rail



$TE_1 - TE_2$ will accelerate wheel

V_o = Forward speed
R = Wheel radius
ω = Wheel angular speed
T_o = Time when adhesion creep curve changes from 1 to 2
S_o = Creep speed at T_o
TE_1 = Tractive effort before T_o
TE_2 = Tractive effort at T_o

FIGURE 3.9 ILLUSTRATION OF MOMENTARY LOSS OF ADHESION conditions further along the track. High damping in the drive, which tends to reduce the oscillation magnitude, has an adverse effect on reestablishing adhesion.

Type of Traction Control

Smooth traction control such as that afforded with solid state devices is best for maintaining adhesion near its limit. Any abrupt changes in motor current can cause adhesion loss.

An example of this is seen in Hitachi's experience on subway cars.[4] Chopper control improves adhesion by 10% over cam-control resistor switching. The latter control steps the current while the former provides a smooth change.

A second source of current variation in traction motors comes from voltage oscillations which arise because of solid state switching. The resulting current ripple is usually reduced using smoothing reactors.

In locomotives using single phase AC traction motors, there is a pulsating torque which aggrevates a loss of adhesion problem. Modern electric locomotives which are now produced for United States operation do not have this problem.

Tractive Effort/Speed Characteristics

In any propulsion system, the relation between tractive effort and speed under creep conditions at the adhesion limit determines whether or not adhesion can be reestablished once it is lost. This relation is determined by the type of traction motor, the motor control method and the control/motor circuit configuration.

Since the relation between slip and the adhesion limit for three phase AC induction motor drives has been discussed in a previous working paper[5], only propulsion systems using DC motors are considered here.

The steepness of the tractive effort/speed curve for a slipping axle at the adhesion limit is important in determining whether or not adhesion will be reestablished. This is illustrated in Figure 3.10. In Figure 3.10a, the tractive effort/speed curve is steep enough so that adhesion loss establishes a new operating point on the tractive effort speed curve (so that the wheel set accelerates from creep speed S_0 to S_1 and then stops) and tractive effort at S_1 will be transmitted to the rail. In Figure 3.10b, no new operating point is established and the wheelset creep will increase indefinitely. In both cases, slip-stick movement may reestablish adhesion, but it is more likely to do so in Figure 3.10a. Thus, it may be concluded that it is more likely to reestablish adhesion after loss if the tractive effort/speed curve is steep.

There are several things which determine the steepness of the tractive effort/speed curve as well as other effects which influence reestablishment of adhesion. Among them are:

- Type of Motor (Series, separately excited)
- Motor circuit (Two series/two parallel, four parallel)
- Number of motor circuits per independent control (One, two or four)
- Control Method (Constant current, constant voltage, field control)

The following statements can be made concerning these considerations:

- When using field control, the separately excited DC motor will have a steeper torque/speed characteristic than the series motor.
- Motor configuration of two series/two parallel are inferior to four parallel when operating from similar control.
- It is preferred to have each motor operating from a separate control.

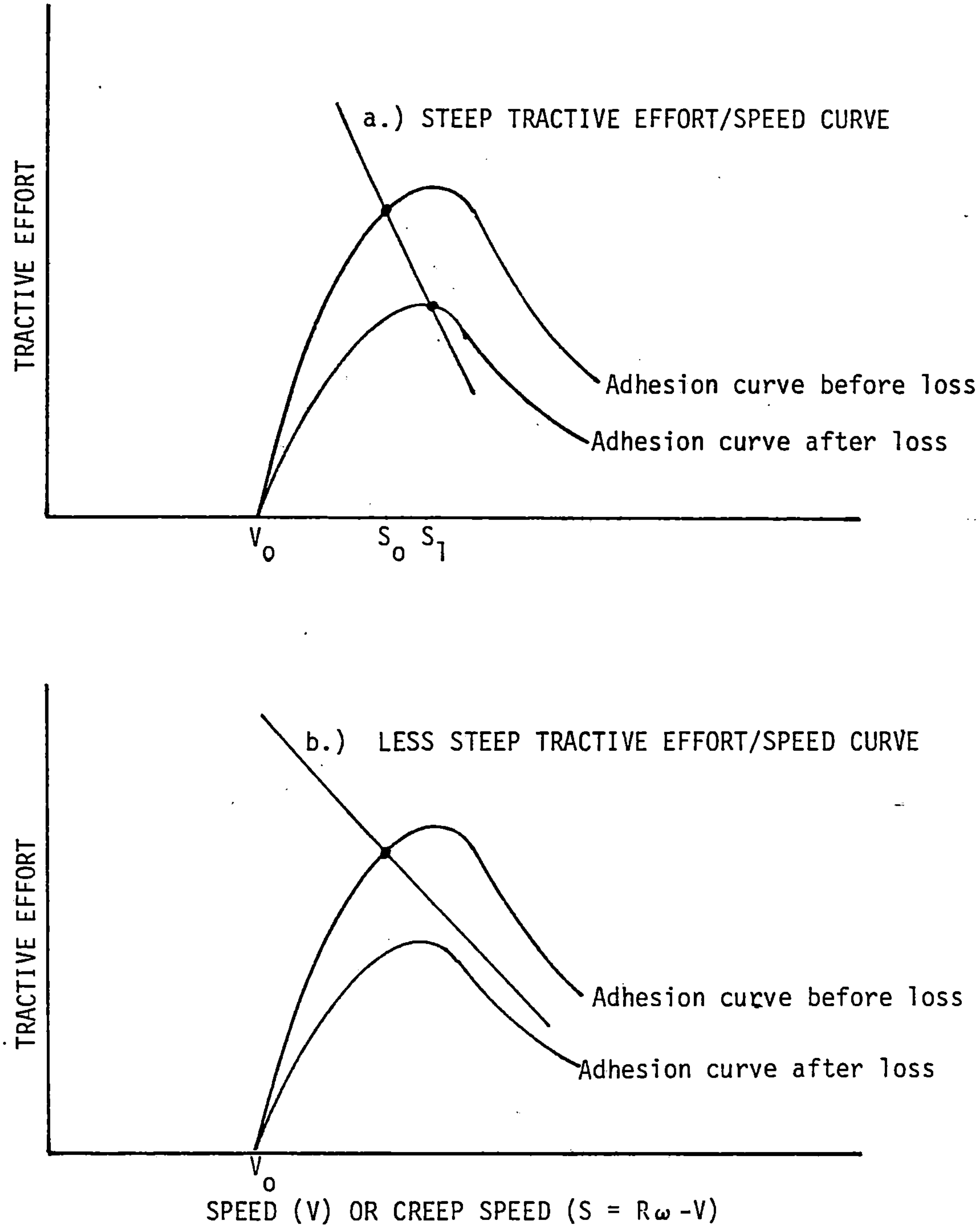


FIGURE 3.10 EFFECT OF STEEPNESS OF TRACTIVE EFFORT/SPEED CURVE ON REESTABLISHMENT OF ADHESION

4.0 SLIP DETECTION AND CORRECTION METHODOLOGY

There are several advantages to detecting and correcting wheel slip as early as possible.

- High average tractive effort can be transmitted to the rail allowing light weight motive power for passenger equipment and higher loads for freight locomotives.
- Because less creep is realized per unit tractive effort delivered, less wheel wear will occur.
- Avoidance of rail burns caused by slipping driving wheels.
- Avoidance of "juddering"[6] which are torsional vibrations in the wheelset which can cause problems in the traction drive equipment.

The first step in achieving these advantages is a good method for detecting wheel slip such that the increase in creep speed can be as small as possible. Once slip is detected, it should be corrected as fast as possible either by changing rail conditions (sanding) or by reducing tractive effort.

4.1 SLIP DETECTION

4.1.1 Conventional Methods

Two modern conventional methods for slip detection which have been utilized for the past decade are:

- wheel speed difference
- wheel acceleration

Wheel Speed Difference

The wheel speed difference method of slip detection depends on a knowledge of the speed of the driving axles as compared to a reference axle. The obvious problem is the reference axle. In practice, such an axle (which would give an indication of true rolling speed) is generally not available. The next best thing is to choose as the reference axle an average of all of the driving axles and observe the speed difference between that average and each of the wheels.

There are several problems with the wheel speed difference method of detection which limits its usefulness.

- Synchronous slip, that is, the condition when all axles on the vehicle are slipping at relatively the same creep speed, cannot be detected.
- Because of wheel size differences and tolerance in electronic detection circuitry, the time delay between when slip begins and when it is detected can be great. If thresholds are set too small, correction may proceed before slip occurs and tractive effort capability can be reduced on this basis alone.

In any speed difference detection scheme, speed difference thresholds are generally different at higher speeds than lower speeds. In fact, speed difference thresholds are generally set on a percentage basis.

Wheel Acceleration

The wheel acceleration method of slip detection depends on a wheel or wheels accelerating much more rapidly than the highest acceleration rate it would see in normal service. Since wheel acceleration can change instantaneously, the problem of time delay experienced in the wheel speed difference method is not present. However, taking corrective action too quickly may prevent the natural "slip-stick" action associated with the traction drive to be fully effective. Wheel diameter differences are not a problem here since they just have a proportional effect on the acceleration. This system can accommodate synchronous slip as well as single axle slip. One disadvantage of this method of detection is that a wheelset can accelerate under the threshold if rail conditions are slightly below favorable.

Wheel Speed Difference and Acceleration Detection

Most modern motive power units use a combination of wheel speed difference and wheel acceleration detection schemes in order to compliment each others. In addition, the requirement for locked axle and overspeed protection can also be combined in the same detection unit.

There are several methods for measuring the speed and acceleration of the wheel sets, however, it seems that modern equipment relies on digital tachometers which are mounted on the motor armature shaft using gear teeth as counting points. The accuracy of these devices depends on the rotational speed of the motor armature relative to the wheel and the number of magnetically distinguishable teeth on the gear counter. The digital signals are converted to voltage or current levels usually on an electronic card.

4.1.2 New Methodology

ASEA[7] has developed a new method for slip detection which has been applied to their Rc4 locomotive as well as the AEM7 locomotives which are now being manufactured by Electromotive Division (EMD) of General Motors for AMTRAK.

The detection scheme makes use of the phenomena of "juddering". As previously stated, "juddering" is a torsional vibration in the wheelset by which the two wheels oscillate in opposite directions using the axle as a torsional spring. This oscillation has a characteristic natural frequency which depends on the wheel/axle mechanical properties. The amplitude of this oscillation increases rapidly near the adhesion limit. Thus, this phenomenon affords a mechanism for detecting, within certain tolerance levels, the approach to the adhesion limit.

Because the gear unit connection is not mounted in the middle of the axle, these oscillations are transmitted via the gear unit to the reaction rod to the truck frame. In the ASEA system, these oscillations are detected using a PRESSDUCTOR® force transducer which is a magneto-elastic transducer yielding an output signal which is a linear function of the force acting on it. This unit was developed and is manufactured by ASEA.

The signals transmitted from the Pressductor® are filtered using a tuned bandpass filter to allow those with the correct oscillation frequency to be monitored. The amplitude of the filtered signal is monitored and a slip is said to occur if some threshold value is exceeded.

4.2 SLIP CORRECTION

Slip correction will occur once the tractive effort output by the motor to the offending axle is below the amount which can be transmitted from wheel to rail at the creep speed. This can be illustrated by referring to Figure 4.1.

The tractive effort output to the rail at creep speed, S_0, is shown on the adhesion/creep speed curve labeled 1 in the figure. A loss of adhesion results in a new adhesion/creep speed curve labeled 2. By the time wheelslip is detected, the accelerating wheelset's creep speed has reached S_F. To arrest the acceleration of the wheelset, the tractive effort must be reduced to the level shown on curve 2. However, reduction of tractive effort (T_A) is applied to keep the wheelset from accelerating. To correct slip, the tractive effort must be reduced below the arresting level so that the wheelset will begin deceleration until finally it can reach the stable region. In most slip correction systems, tractive effort is reduced to zero and held there until the creep speed achieves its original value.

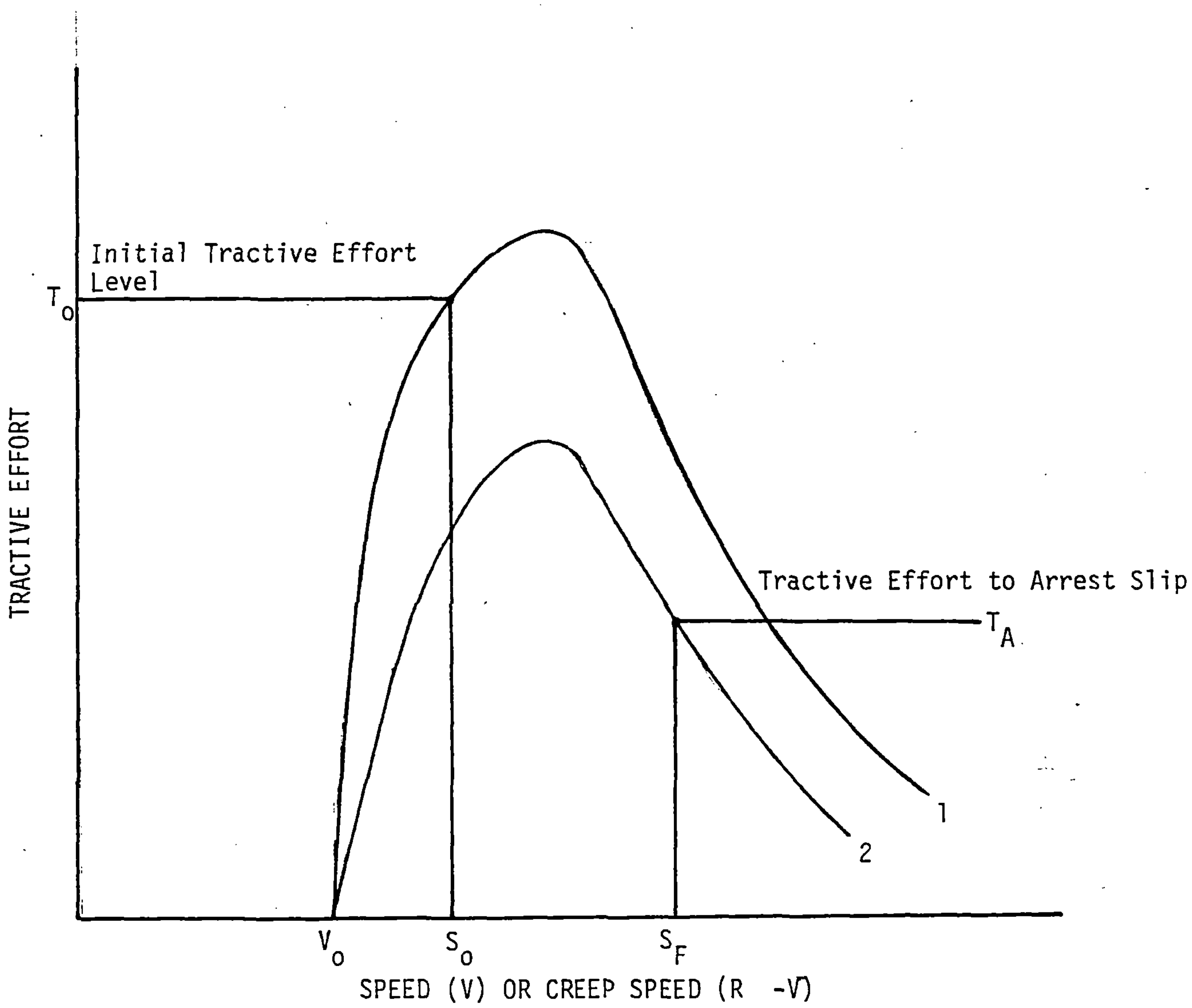


FIGURE 4.1 ILLUSTRATION OF SLIP CORRECTION BY TRACTIVE EFFORT REDUCTION

Although this method causes maximum deceleration of the wheelset, it also causes loss of tractive effort on the axle in question. This tends to reduce the tractive effort capability of the motive power.

Tractive effort on DC traction motors can be reduced by reducing the armature current or changing the field current. Generally, slip correction in DC series motors is accomplished by reducing both field and armature current, while in separately excited machines, field current is manipulated. Newer methods of slip correction involve pulsing current through the fields of a series DC motor in order to reduce the current momentarily to zero.

If two or more series motors operate from the same control, it is sometimes necessary to reduce traction output on all motors to correct slip. This, as explained previously, limits the traction capability of the unit.

A second method of slip correction involves changing the amplitude of the adhesion/creep speed curve so that adhesion may be reestablished once slip is detected. Methods of accomplishing this task include sanding and application of heat or chemicals to the rail.[8] Sand has little effect at high speeds as a consequence of wind action and can become a serious contaminant in ballast and equipment for passenger service. However, it is effective at lower speed operation. The previous statement is also true of chemicals which are applied from moving locomotives. There is also an environmental objection to this latter method. Plasma torches have been tested in the past, however, results show that high power levels are required for significant adhesion improvements.[9]

Chemicals are effective in removing oil-water films from the surface of the rail if they are applied from the wayside to known places of consistently bad adhesion such as frogs, switch points and curves.

In considering high speed passenger service, slip correction will be limited to tractive effort reduction in some form, although application of sand (if used sparingly and correctly) may also be helpful.

4.3 REQUIREMENTS FOR SLIP DETECTION AND CORRECTION

From the two previous sections, it is clear that the basic objective of slip detection and correction for high speed passenger service is to provide the highest possible tractive effort under all conditions of adhesion at all speeds with minimum wheel wear and lowest capital cost. Although this objective will be approached as modern traction control systems and wheel slip detection and correction systems are applied, there will still be room for improvement.

The ideal slip detection and correction system would instantly compute the adhesion/creep speed curve on which it were operating, determine the point of operation to achieve maximum tractive effort and set the tractive effort limit to that point. Since this has not yet been achieved, it is possible to state some requirements which slip detection and correction systems should approach.

1. Slip detection should be fast. Whether wheel speed differences, wheel acceleration or "juddering" are used, the method should detect a slip before the wheel creep speed exceeds the point of maximum adhesion in most cases.
2. Slip detection should be accurate. Any scheme should give minimum false slip indication to the slip correction system.
3. Solid state traction control with some capability to reduce tractive effort separately on each motor is preferred. Motors should be operated in parallel.
4. Mechanical and electrical characteristics of the propulsion drive should be such to encourage "slip-stick".
5. The slip correction and detection system should operate rapidly to reduce wheel wear but slowly to maintain high tractive effort. These conflicting objectives must be traded off.

6. For high speed passenger service, to have all axles of a train powered is generally preferred adhesion-wise over locomotive hauled trains. This is a result of operating at much lower adhesion levels thus requiring less operation of any slip detection and correction system.

5.0 MODERN SLIP DETECTION AND CORRECTION SYSTEMS

There are several versions of modern slip detection and correction systems in operation on both diesel-electric and electric locomotives and electric self-propelled cars. The principal features of the requirements which must be met and how they are met can be pointed out by discussing two particular systems, one manufactured and developed by the General Electric Co. and the other by ASEA. Both companies use quite different approaches for maintaining adhesion and both approaches are technically advanced.

"Automatic" slip correction afforded by three phase AC drive locomotives as manufactured by Brown Boveri Inc. is also discussed. In this case, a certain level of high adhesion maintenance is already built into the equipment and it would be a passive rather than active slip control system.

5.1 SENTRY ADHESION SYSTEM (GENERAL ELECTRIC COMPANY)

A block diagram of an individual axle wheel slip control system for a modern electric locomotive developed and manufactured by the General Electric Co.[10] is shown in Figure 5.1.

Speed signals from all axles are fed into a speed difference detector which produces outputs of wheel speed differences and rate threshold detectors which differentiate the speed signals into acceleration signals. All slip corrections can be accomplished on an individual axle basis. An overspeed indicator is used in the unlikely event of all axles slipping without triggering the threshold or wheel speed difference detectors.

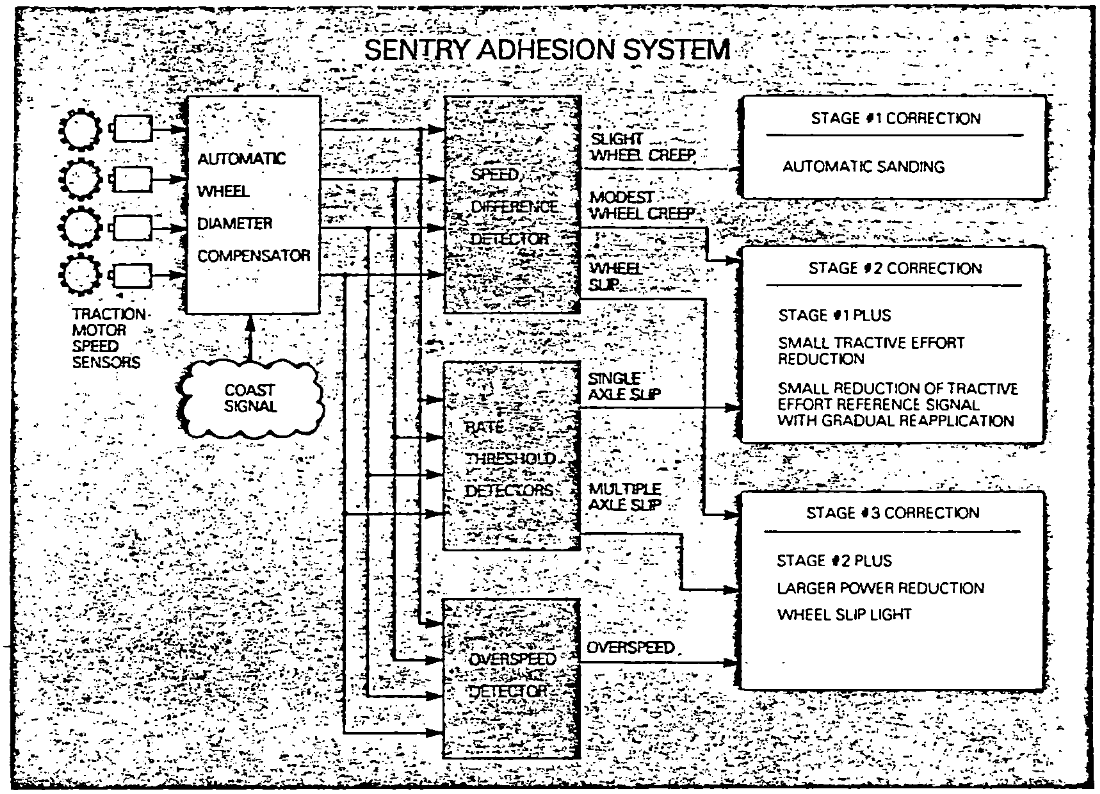


FIGURE 5.1 (Courtesy Hal Henderson - General Electric Co.)

The automatic wheel diameter compensator automatically calibrates the speed signal during coast operation to account for wheel diameter differences and to improve creep speed measurement accuracy. The inductive speed sensors operate via a special gear mounted on the motor shaft. These motor mounted sensors are six times more accurate than the axle mounted alternator on earlier General Electric locomotives and MU-cars.

This adhesion system has been tested satisfactorily at levels from 23-26% adhesion under adverse conditions of wet rail, severe grades and reverse curves. The principal improvements over present day systems are attributed to:

- More accurate speed signals,
- Automatic wheel diameter compensation and,
- Individual axle control.

5.2 CREEP CONTROL SYSTEM (ASEA)

As mentioned previously, the ASEA wheel slip detection and correction system depends on individual axle slip detection which utilizes a new method of detection by observing the amplitude of the torsional vibrations in the wheelset at its characteristic natural frequency. This is further backed-up by wheel overspeed detection.

A block diagram of the creep control system for the Rc4 locomotive[11] is shown in Figure 5.2. This locomotive, which was tested on U.S. track as the prototype for the AEM7 now being manufactured by EMD has a propulsion system which is phase control with separately-excited DC motors. The circuit diagram is shown in Figure 5.3. There are separate propulsion controls from each truck.

Block diagram of the control equipment in a Rc4 locomotive.

1 Current reference
2 Speed reference
3 Speed regulator
4 Selector for maximum speed feedback
5 Transmission link
6 Current limiting unit
7 Selector for maximum armature current
8 Armature current regulator
9 Load sharing control
10 Trigger pulse unit for bridges 1 and 2
11 Field current regulator
12 Selector for maximum field current
13 Load sharing limitation
14 Temperature control of convertor cooling oil
15 Armature voltage regulator
16 PRESSDUCTOR transducer in reaction rod
17 Filter
18 Individual creep regulator
19 Total tractive effort regulator for two motors
20 Selector unit
21 Creep protection containing dynamic slip protection, overspeeding protection and load sharing blocking
22 Motor module 1
23 Motor module 2

a Reduced ventilation
b Catenary voltage
c Field weakening

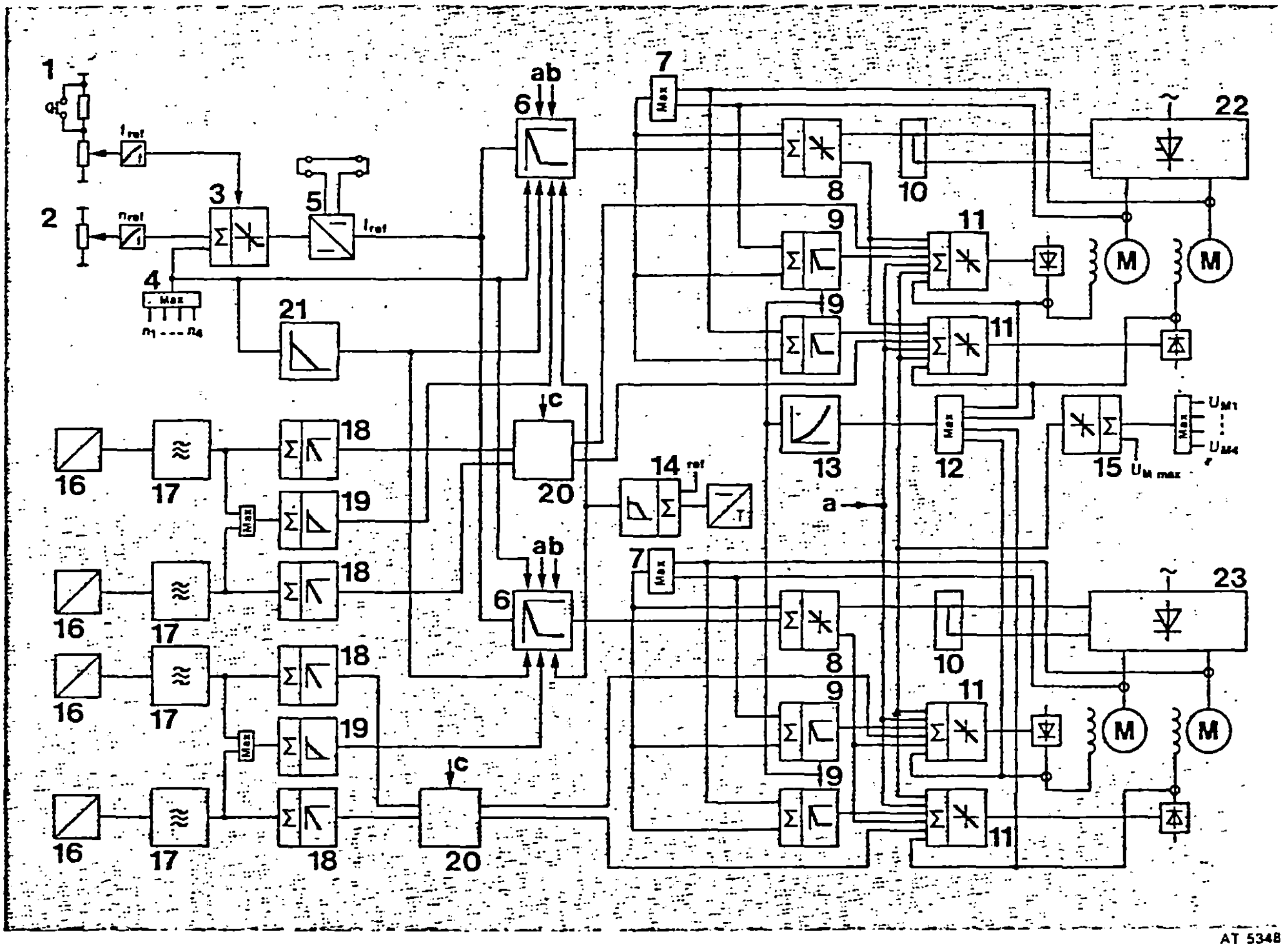


FIGURE 5.2 (REFERENCE 11)

Simplified diagram of the main circuits in a class Rc4 locomotive.

1 Pantograph
2 Main circuit-breaker
3 Lightning (surge) arrester
4 Main transformer with reactor
5 Non-uniform thyristor bridge
6 Harmonic filter
7 Motor isolator (disconnector)
8 Separately excited traction motor
9 Field convertor
10 Train heating supply
11 Auxiliary machinery supply
12 Earthing transformer
13 Earthing brushes

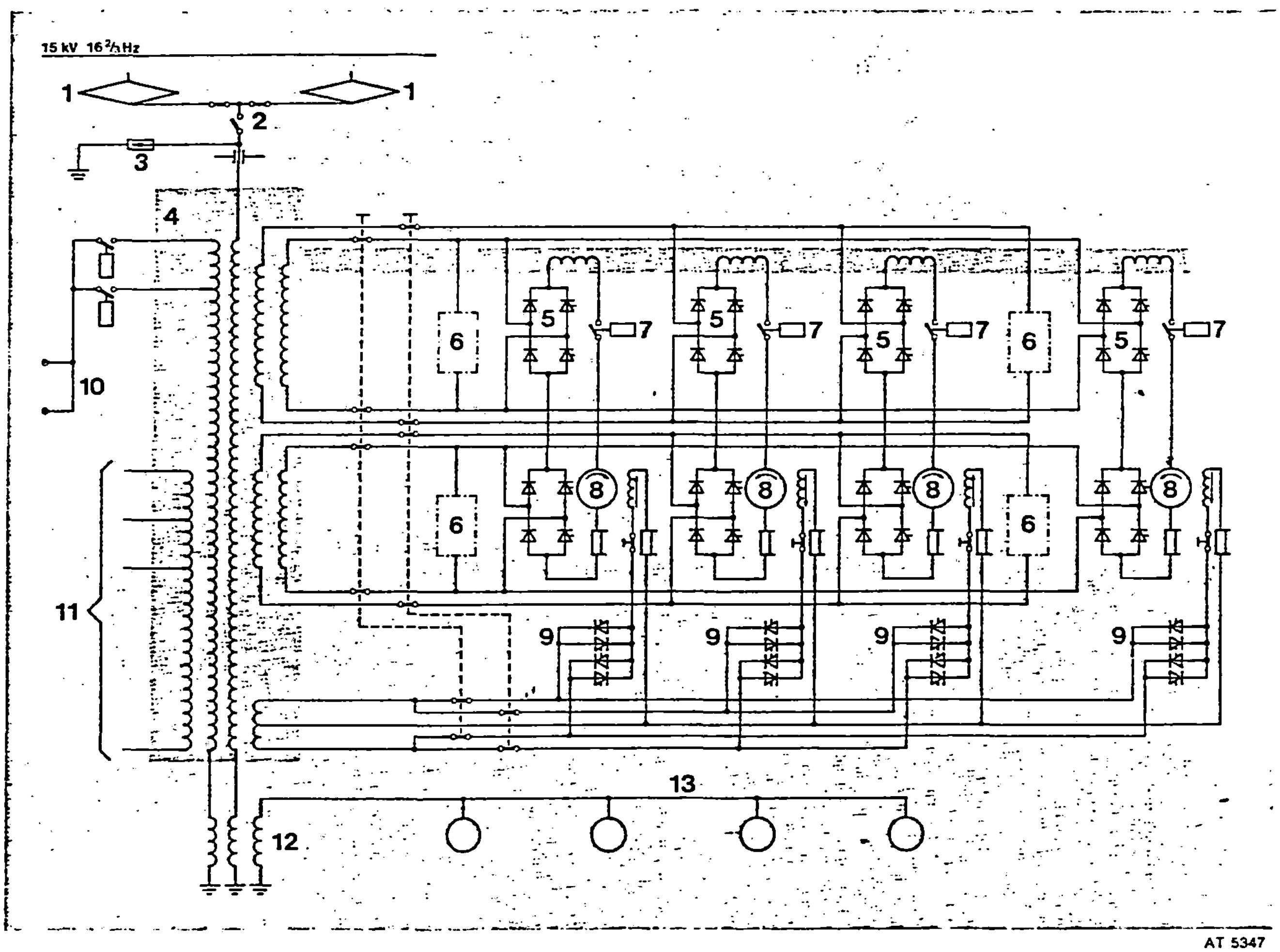


FIGURE 5.3 (REFERENCE 11)

With reference to the block diagram, torsional oscillation amplitude signals produced in the wheel/axle set are detected in the Pressductor® transducer (16) which is in the reaction rod. These signals are filtered and rectified (17) so that only the amplitude of the oscillations at the natural torsional oscillation frequency of the wheel/axle set at 45 Hz are passed to the individual axle creep regulators (18). The regulators are activated when the amplitude exceeds a preset value. A selector unit (20) is used to select which mode of correction is to be applied and this depends on whether the motor is in full or weak field condition.

- If the motor is in weak field, the field strength is increased which causes a rapid drop in armature current and torque, which tends to correct the creep.
- If the motor is in full field, the field on the other traction motor on the same truck is weakened. This causes the armature current in that motor to rise and as a result the armature current controller (8) attempts to lower the current on both motors tending to correct the creep on the offending motor.

*A description of this device appears in Reference 12.

The individual axle creep control also has a stronger slip correction capability in the event both axles on the truck are slipping and as a backup unit. This unit (19) receives the maximum of the two creep signals and sets the current limit.

Overspeed protection is also provided as a backup to the creep control system.

It is ASEA's claim that, "Measurements have demonstrated that the system leads to considerably higher average tractive efforts"[11]. In another article[7], "Adhesion tests in Norway have demonstrated that a class Rc2 thyristor locomotive can, in all types of weather, dispatch a train based on 27% adhesion. When the creep control system is in use, this figure can be increased to almost 30 percent".

5.3 SLIP CONTROL AND THE THREE PHASE AC DRIVE

One advantage usually quoted for three phase AC drives is the ability to use available adhesion because of the naturally steep torque/speed curve characteristic of the asynchronous motor running at fixed frequency. The tractive effort developed by an axle driven by an asynchronous motor controlled by an inverter at a given frequency is proportional to the motor slip speed which is the difference between the electrical and mechanical speeds of the motor. (The electrical speed in RPM is 2 π x applied frequency). As the adhesion limit is reached, the wheel creep speed increase naturally increases the motor mechanical speed. Since this reduces the motor slip speed; and consequently the torque, the wheel slip condition is corrected automatically. As a consequence, the applied tractive effort remains close to the transmittable tractive effort.

When several asynchronous motor driven axles are operated in parallel from the same inverter, the wheels cannot individually slip because of the strong electrical coupling. This case is similar to the case of mechanical coupling between wheels. This will not give as high tractive effort as if they were individually controlled.

Provisions must be made to correct slip when all wheels driven from the same inverter are slipping. However, the speed of these wheels, even under poor rail circumstances is always limited to the electrical speed of the motor. Thus by limiting frequency, overspeed detection is not required.

5.4 COMPARISON OF SLIP DETECTION AND CORRECTION SYSTEMS

It is improper to compare a slip detection and correction system on its own merits. As was discussed in the previous sections, slip detection can be accomplished in several different ways while slip correction depends on the overall propulsion system.

The problem with such comparisons, even under experimental conditions, is that adhesion, which in some measure is an indicator of how well the slip control system works, depends on many more variables which are uncontrolled among the traction vehicles on which the adhesion is being measured. That the adhesion coefficient is a stoicastic variable means that many tests must be made under the same conditions before any conclusions are drawn. Even in this case, the slip detection and correction system must be mounted on vehicles with identical mechanical characteristics, run on the same stretch of track and under the same rail surface conditions.

Whether a passsive system, which is obtained for free using an AC drive, is better than an active system used on modern locomotives with DC motors, is still open to question. AC drives which operate near the adhesion limit are subject to "juddering" which plays havoc with equipment and raises maintenance cost.

The slip detection and correction system is part of the locomotive. Thus, in the end, it is the locomotives which are being compared. Lightweight locomotives which can produce large tractive efforts under all rail conditions are generally preferred to heavy ones which produce the same tractive effort if the costs are relatively the same.

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PART 3. ON-BOARD HIGH VOLTAGE SWITCHGEAR FOR M.U. CARS AND LOCOMOTIVES

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1. SUMMARY

The new electrification system for the NEC will distribute the single phase railroad loads across the three phase commercial power generation systems of the utility companies between Boston and Washington, introducing the need for phase breaks which is not a feature of the older single phase electrification from New York to Washington. The phase breaks will occur at approximately 5 to 7 mile intervals and will require the ability of all vehicles to turn-off all propulsion and auxiliary loads before traversing each phase break and then turn on all loads following the phase break.

Although existing European systems have phase breaks, the new system for the NEC represents a far more severe duty cycle requirement for the on-board switching functions due to the increased frequency of the phase breaks (about six times as many). Relatively short feed distances are necessitated by the NEC electrification to avoid losses while handling the high power levels required to accelerate heavy trains at the high rates called for by NEC schedules. This will result in approximately 40 phase breaks between Boston and Washington.

During construction of the new electrification, it will be necessary for all vehicles to have transformer characteristics and primary connections to permit operation on both frequencies and voltages. With the New York to New Haven segment of the NEC presently being converted to 12.5 kV, 60 Hz, this will involve three combinations of frequency and voltage requiring one transformer connection for 11 kV, 25 Hz or 12.5 kV, 60 Hz, and a second connection for 25 kV, 60 Hz.

Catenary voltage detection and protective control will be required to permit connecting the transformer for the proper voltage range and prevent application of excessive voltage to the transformer when connected for the lower voltage range.

The basis for the decision to employ on-board primary breakers in the NEC includes two considerations other than fault protection. The first is that the alternative approach of interrupting the auxiliary load with the pantograph while passing from the contact wire across an insulator would draw an arc causing severe pitting of the end of the wire and arc-tracking of the insulator. This would result in higher maintenance of the catenary elements. Failure to remove propulsion power would greatly aggrevate the situation. The second concern is that voltage changes will occur on various routes on which the trains may operate (even after corridor conversion is complete) requiring that vehicles be able to change transformer primary connections "on the fly". On-board catenary voltage measurement and assurance of correct connection is considered mandatory prior to energizing the transformer in order to avoid damaging errors. This necessitates disconnecting the transformer from the pantograph circuit until catenary voltage has been measured.

Both manual and automatic negotiation of voltage changes and phase breaks have been considered and the decision to use an automatic system is based on several factors including the frequent occurrence of breaks every 5 to 7 miles corresponding to average intervals of 4 minutes at maximum NEC speeds. This is felt to be an undersirable distraction for a human operator which would invite error.

Because of the relatively limited application of railroad electrification, the development of hardware for high voltage railroad equipment must rely heavily on adapting the developments made for utility power transmission. Adaptation of commercially available devices also offers an advantage of lower cost of devices produced for the highly competitive power equipment market. The design parameters which are most restrictive in adapting commercial apparatus are the vibration level associated with train movement and the severe space limitations imposed by vehicles - particularly m.u. cars. Dirt, snow, and vandalism also present much more severe conditions on a vehicle than with a fixed installation.

The general approach taken in Europe and specified for the NEC is to provide each vehicle with a primary circuit breaker to deenergize the transformer and auxiliary systems. This breaker is also used for onboard fault protection and represents another change from existing NEC practice in which substation breaker operation is relied on entirely. Two different types of circuit breaker have emerged for this application; the airblast breaker and the vacuum interrupter.

The change from railroad use of single phase power sources to connection with the commercial three phase power systems began at an earlier time in Europe. Because the airblast breaker was the most advanced compact commercially available design at that time, it was selected for onboard application. Packaging of these devices has been altered for railroad application to form roof-hatch assemblies with control components extending into the carbody.

Since that time the vacuum interrupter has been developed for commercial switchgear and has received railroad application in Japan, South Africa, and the U.S.

Because of the frequent phase breaks, the primary circuit breaker will be subjected to the relatively severe duty cycle of approximately 3000 operating cycles per month and as a result, will require a scheduled maintenance program. A comparison of actual service experience on the NEC will probably be required to determine the relative merit of the two generic types of breakers.

2. INTRODUCTION

NEC Electrification Conversion

The program for replacing the present single phase 11 kV, 25 Hz electrification system in the NEC with a 25 kV, 60 Hz system operating directly on the commercial three phase 60 Hz network involves significant changes in the manner of power distribution and the addition of vehicle-borne equipment not presently required. The distribution of the single phase loads across the three phase commercial network may place adjacent catenary substations on different phases and require that vehicles be able to turn off electrical loads before crossing insulated breaks in the catenary. This function will require the addition of high voltage switch gear and control equipment. In some locations a voltage change will also be involved and will require the additional on-board function of transformer primary tap changing "on the fly".

The objective of this paper is to discuss the high voltage switch gear and protective components which must be added or replaced in the course of the re-electrification program. Four specific elements of high voltage equipment will be covered in addition to the general subjects of insulation and mounting of equipment. These four elements are: (1) lightning arresters, (2) circuit breakers, (3) high voltage potential and current measurement devices, and (4) bus connections. Several of the high speed train systems reviewed in the IPEEP Program have voltage bus couplers and primary switch gear which may suit the requirements of the NEC. The upgraded Metroliners are equipped with high voltage circuit breakers and tap changers for dual voltage operation and the new Amtrak AEM7 locomotives will be similarly equipped. While the parameters for the electrification have been developed, the design of controls for the voltage change/phase break negotiation system has not been fully determined at this point.

Before proceeding with the details of high voltage components it would be beneficial to review the history of the present and proposed electrification systems and the basic principles involved in negotiation of voltage changes and phase breaks.

History

The previous selection of 25 Hz instead of the national standard generation frequency of 60 Hz may seem illogical, however when the history of railroad electrification is reviewed, the decision appears quite reasonable.

A frequency of 25 Hz was used in the early 1900's for long distance transmission because of lower transmission losses than with 60 Hz. It was employed in the eastern power distribution from the Niagara Falls hydroelectric plant, which at the time was one of the principal sources of power.

While 25 Hz was a common transmission frequency the principle reason for selecting the lower frequency for railroad use was that series type traction motors commutate poorly on a.c. - the difficulty being directly related to the frequency. Commutation at 25 Hz is much better than at 60 Hz. With an a.c. transmission system, the alternatives to series a.c. traction motors were d.c. motors with on-board conversion equipment, or a.c. induction motors. Within the technology limitations of the time, there was no practical method of producing the variable frequency supply required for speed regulation of induction motors thus making this arrangement unsuitable for <u>most</u> railroad applications. Prior to the development of suitable mecury vapor rectifiers, the use of d.c. traction motors required an a.c. motor driven generator set.

The alternative to a.c. transmission was direct current electrification using either a 600 V third rail system, as employed within New York's Penn Station, or 2.4 to 3 kV overhead systems as applied on the Butte Anaconda and Pacific in 1913 and the Milwaukee Road in the early 1900's. These were rejected by the Pennsylvania Railroad as being impractical from the standpoint of transmission and substation costs for the distances involved. Higher d.c. voltages (greater than 3 kV) required to provide transmission efficiencies comparable with a.c. transmission could not be handled within the technology limitations of the period. (Recent power technological developments may make high voltage d.c. transmission feasible in the near future.)

Weighing the available options, the Pennsylvania Railroad selected a straight a.c. system with series a.c. motors and the relatively low frequency of 25 Hz for its Philadelphia suburban electrifications, beginning in 1915, and for the intercity extensions which linked the eastern cities by 1935. While experimental work with mercury arc rectifiers was conducted prior to World War I on a New Haven Railroad m.u. car, the type of mercury arc rectifier available proved to be unsuitable. With Westinghouse's successful application of the sealed ignitron mercury arc rectifier to a Pennsylvania Railroad m.u. car in 1949 and to a locomotive in 1951 (class E2c and E3b locomotives), the requirement for low frequency power changed. More recent developments with solid state power switching make it possible to take single phase a.c. at any transmission frequency and convert it as required to drive virtually any type of a.c. or d.c. traction motor, obviating the earlier constraints on catenary power.

The new design for the NEC electrification therefore uses conventional 60 Hz power obtainable from the East Coast's commercial power grid. Approximately doubling the voltage to 25 kV from the original 11 kV level will reduce current by a factor of one half permitting the greater power capacity required for high performance and increased train density.

The new electrification system also involves a significant change in the manner of power distribution which may require the addition of on-board primary switch gear and affect the philosophy of fault interruption. These changes are perhaps more significant than the changes in voltage and frequency.

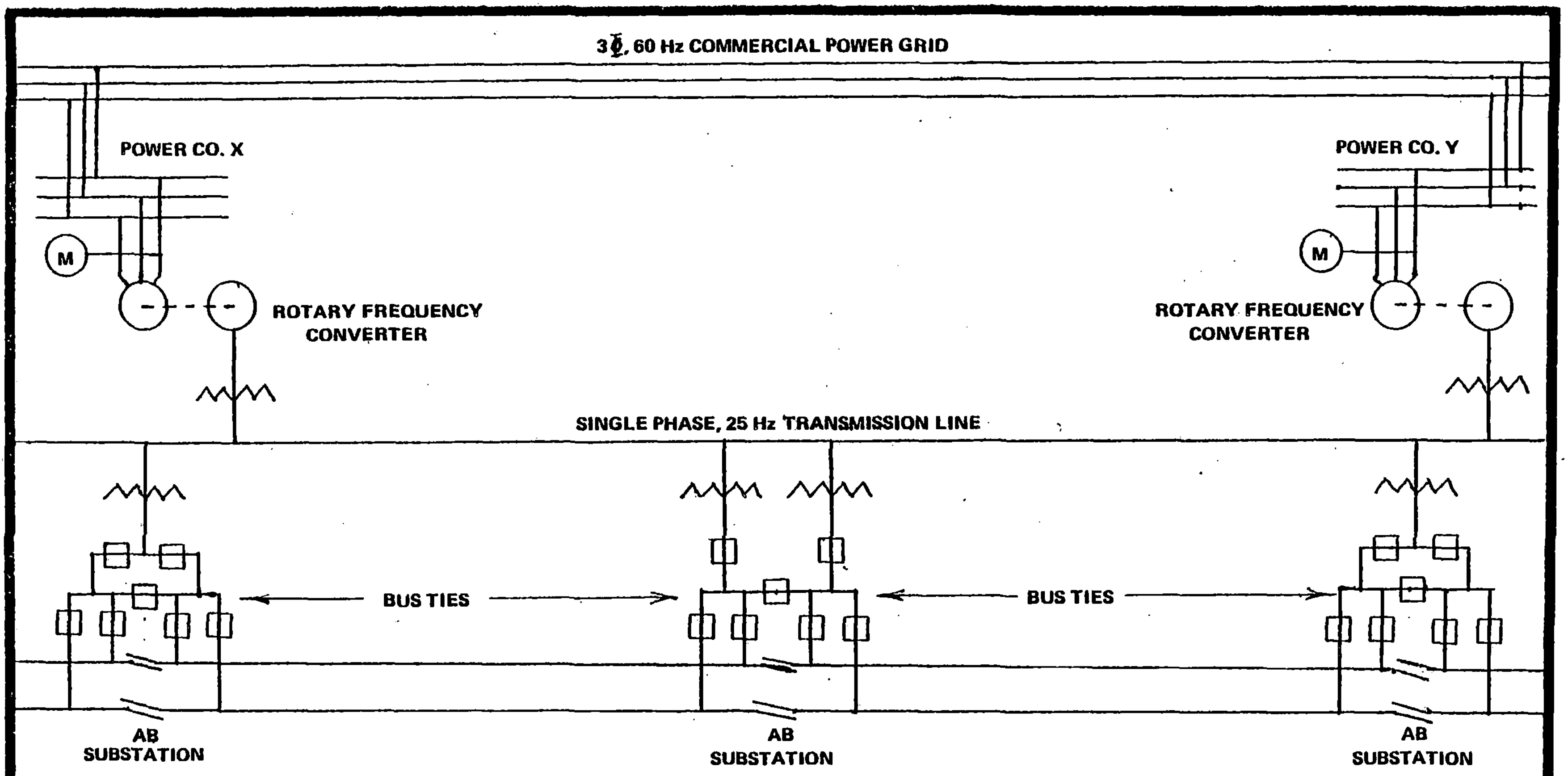
Original Electrification

The original 25 Hz system from New York to Washington and Harrisburg is supplied at six locations (originally seven) from generators and frequency converters. One of these six supplies handles the New York area directly while the other five feed a complete single phase, 25 Hz, 132 kV distribution system which parallels the railroad. From this transmission line, local substations feed the catenary at 11 kV. In addition to local distribution of 25 Hz power to the substations, the transmission line permits the transfer of power to relieve the load on any generating station. Control is exercized from a central load dispatcher in Philadelphia who coordinates the operations of the power dispatchers in New York, Philadelphia, Baltimore, and Harrisburg, and the four utility companies involved. Power can be purchased at the most economical rates in large blocks from the four power companies with the load distributed to minimize or avoid peak demand power rates. The original electrification system is schematically represented in Figure 2-1. A tabulation of the four utility companies and the feed points to the 25 Hz, 132 kV distribution system is given in Table 2-1.

The catenary is sectionalized for fault isolation with each section extending between two substations. Power is then supplied to each section from the substations at both ends forming a "double-end" feed arrangement. The 25 Hz single phase distribution system therefore permits continuous operation of trains without interruption in the primary power supply.

New Electrification

In contrast, the new 60 Hz system will be distributed across the entire three-phase grid of many utility companies without benefit of the private transmission line previously employed for load equalization. The eastern utility power grid will serve this function instead, with power being purchased locally by the railroad at each substation. Power costs will be governed by the peak demand load at each substation. Because the power delivered to each substation will be small relative to the large quantity presently purchased at the frequency converters of the 25 Hz system, the railroad will no longer continue to receive the benefit of bulk power purchases. The catenary will be electrically sectionalized and adjacent sections may be connected to different phases of the grid to assure proper load balance, necessitating phase breaks between sections.



- Supply to substations from dedicated transmission line.
- Bus tie breakers normally closed.
- Air section breaks "AB".
- *Metering points (M) at feeders*

FIGURE 2 - 1

EXISTING 11 kV, 25 Hz SYSTEM

TABLE 2-1

PRESENT UTILITY COMPANY SUPPLY OF 25 Hz POWER TO RAILROAD

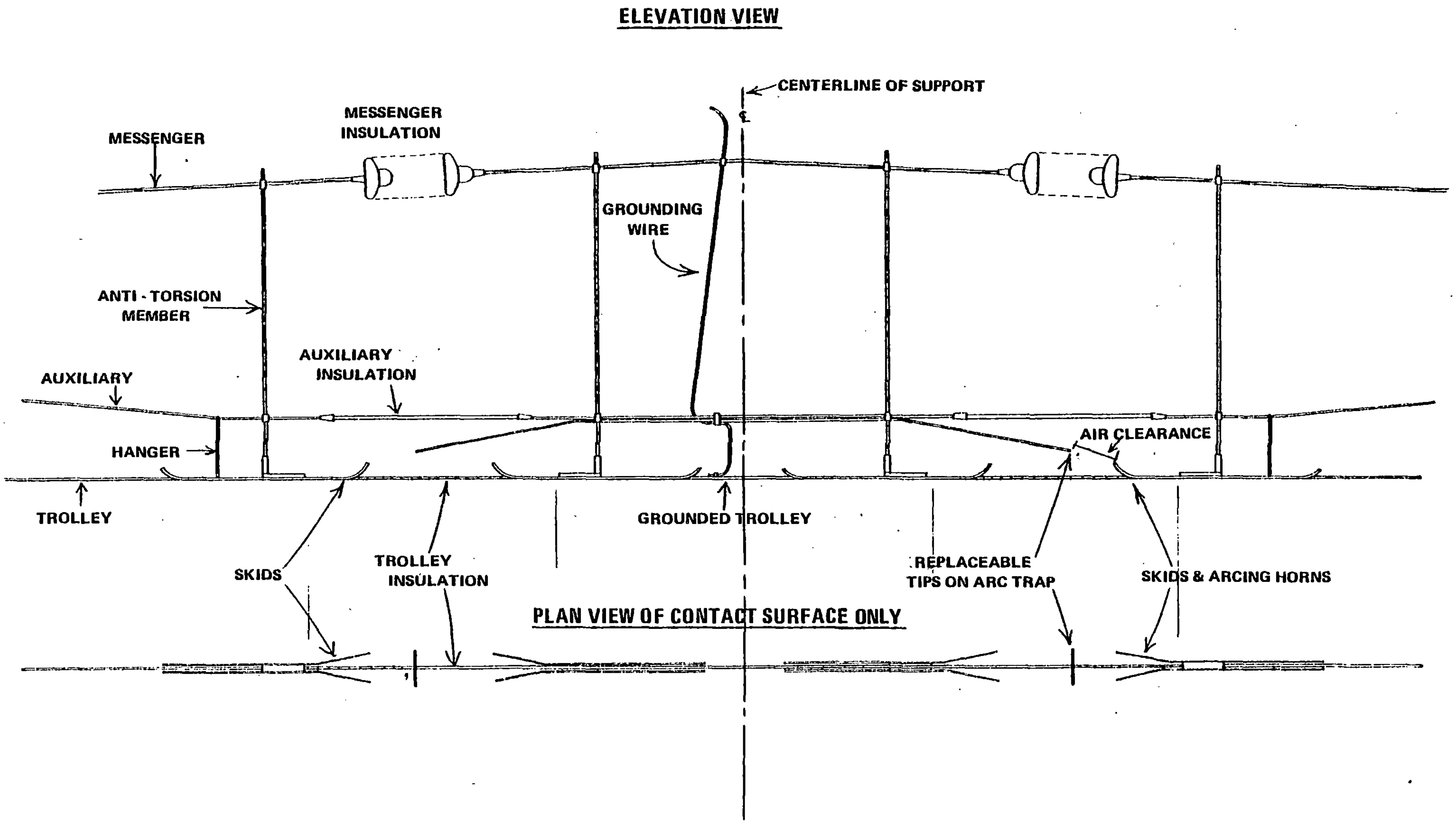
Power Company	Feeder Point to 25 Hz 132 kV Distribution Line	Notes
Consolidated Edison	None	Direct feed at 12 kv to catenary in New York area.
Philadelphia Electric (single bill and rate for combined power to 3 locations)	Metuchen, N.J.	Supply through lines owned by Public Service of N.J.
	Richmond, Pa.	Generating stations at Richmond and Somerset, Pa. supply common step-up transformers at Richmond.
	(Arsenal Bridge, Pa.)	Disconnected in Dec. 1971.
	Lamokin, Pa.	
Pennsylvania Power & Light	Safe Harbor, Pa.	25 Hz distribution line connects Safe Harbor step-up transformers to railroad transmission line at Perryville owned by PP&L and Balto. G & E.
Baltimore Gas & Electric	Benning, Md.	

The phase break presents a unique situation not required in the relatively simple electrical break used in the original electrification for fault isolation or maintenance. With the older section breaks, the ends of adjoining catenary sections extend beside each other for a short distance with each contact wire having a slight vertical ramp to permit the pantograph to pass from one to the other. The momentary contact path between the two wires through the pantograph is of no concern as both wires are energized in phase. With the new system, a difference in phase may be present across the electrical breaks, and it is vital that a pantograph must not bridge the gap causing a phase to phase short. The proposed new phase breaks utilize two insulated spacers on which the pantograph travels with a short length of wire between. This middle section of wire is grounded so that if an arc is drawn by a pantograph it will discharge to ground in an easily recognized ground fault. This arrangement is illustrated in Figure 2-2.

The new 60 Hz system will be supplied at approximately 40 points between Boston and Washington. Each substation will feed two electrically isolated sections of catenary extending an average of 5 to 6 miles in either direction from the substation. Normally open tie breakers will be provided at intermediate switching stations at the extreme ends of the catenary sections to permit feeding power through in the event of a substation failure. Most of the substations will have single 30 MVA single-phase transformers connected across one phase of each supplying utility company which feeds the three-phase power network. In several heavy traffic locations two transformers will be provided with one feeding in each direction. The supply to each segment of catenary will therefore be of a "single-end" feed. The reason for maintaining a phase break at the substation (rather than using a "center" feed), is to permit energizing its two catenary sections from the adjacent substations through the tie breakers in the event of a substation failure. Because the two adjacent substations may be on different phases, it is necessary to provide for a phase break. The new electrification system is schematically represented in Figure 2-3.

One deviation from the objective of a total 25 kV power supply is the 12.5 kV, 60 Hz re-electrification program on the former New Haven Railroad between New York and New Haven which is currently nearing completion. This 12.5 kV electrification was planned by the states of New York and Connecticut before the inception of the NECIP program and may remain a permanent feature. Additional deviations from the 25 kV plan are the numerous suburban branch lines and freight lines which are expected to remain at either 11 kV, 25 Hz or 12.5 kV, 60 Hz for the foreseeable future. These conditions along with the interim progression of re-electrification along the NEC impose requirements for dual voltage and dual frequency capabilities for virtually all vehicles.

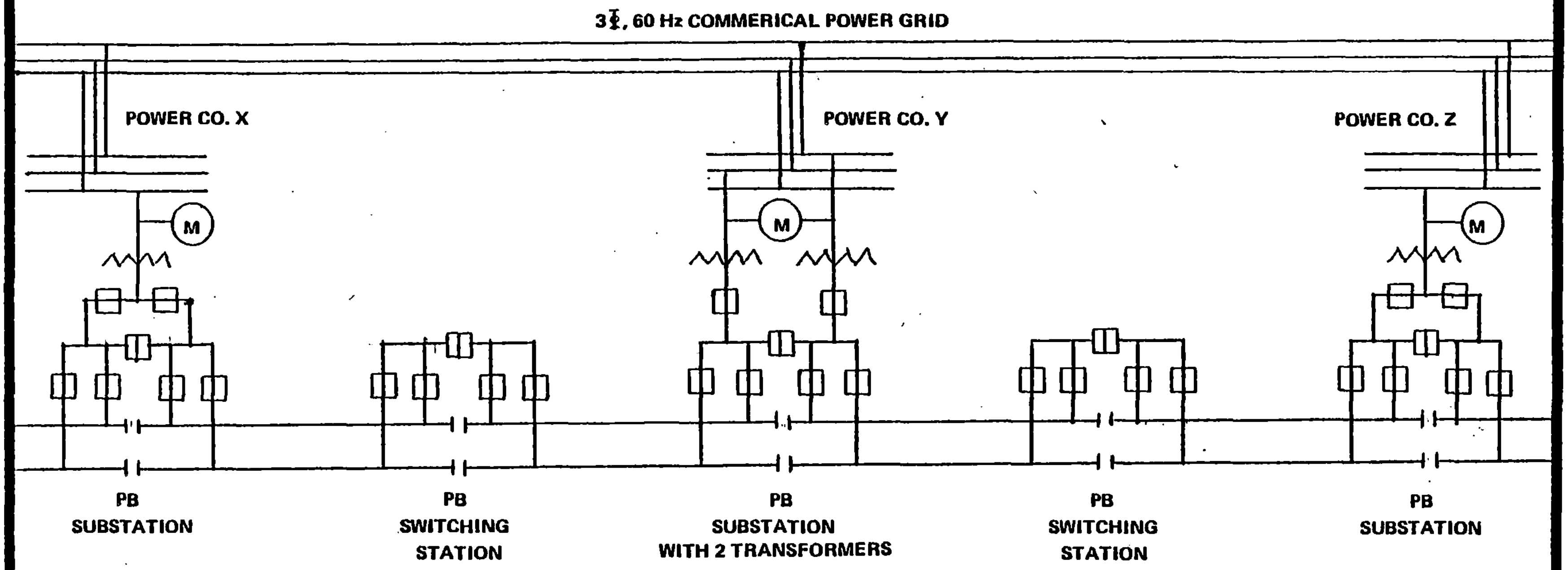
To provide this dual voltage capability, the primary circuits of vehicle transmormers must be arranged so that they can be connected with the proper turns ratio to provide the


ELEVATION VIEW

PLAN VIEW OF CONTACT SURFACE ONLY

PHASE BREAK

FIGURE 2 - 2



- Power supplied by three phase, high voltage transmission lines of numerous individual power companies along NEC.
- Substations spaced at 10 to 12 mile intervals.
- Switching stations required midway between substations.
- Phase breaks "PB" required at all substations and switching stations.
- Bus tie breakers at phase breaks kept normally open.
- Metering points Ⓜ at each substation.

FIGURE 2 - 3

SCHEMATIC REPRESENTATION OF PROPOSED 25 kV, 60 Hz NEC ELECTRIFICATION SYSTEM desired secondary voltages. Because of the simple two to one ratio of 25 kV and 12.5 kV when operating on 60 Hz, the transformers may be equipped with two primary windings of equal size which are then connected in series for 25 kV and in parallel for 12.5 kV. Because of frequency related characteristics of the transformers, equivalent secondary voltages are produced on 11 kV, 25 Hz, or on 12.5 kV, 60 Hz, and there is no switching required for the frequency change. Actual transformer switching is accomplished by an internally mounted tap changer.

Voltage Change/Phase Break Negotiation

The new electrification arrangement will result in approximately 80 electrical breaks in the catenary between Boston and Washington at which a change in phase or voltage may occur. Operation through these section breaks will make use of an automatic control system and an on-board circuit breaker to deenergize the vehicle prior to passing between sections. Upon approaching a section break the following sequence of events must be performed by the automatic voltage change/phase break negotiation system.

- receive wayside signal
- remove traction power in a jerk limited manner
- open high voltage switch

At this point the locomotive or car is ready to cross the catenary break without the danger of having the transformer incorrectly connected for a voltage change and without drawing a damaging arc at the pantograph. Upon entering the second catenary section the following sequence of events will be required of the vehicle-borne system.

- measure voltage on catenary
- assure correct transformer primary connection
- operate tap changer if required
- close high voltage switch
- reapply traction power in a jerk limited manner

Construction of the section breaks will include a short length of grounded contact wire between two insulators. This will prevent development of a short between phases or between different voltages in the event an equipment failure causes an arc to be drawn by a pantograph when leaving one section.

Although the propulsion load would be removed prior to opening the high voltage circuit breaker, and reapplied after reclosing the breaker, the supply to the auxiliary systems would be turned off and on by the breaker. The effect on various auxiliary loads will depend on the ability of rotary or solid state head-end power converters to sustain these loads.

The on-board components required for a voltage change/phase break negotiation system are the high voltage circuit breaker and the potential transformer for catenary voltage measurement.

3. LIGHTNING ARRESTERS

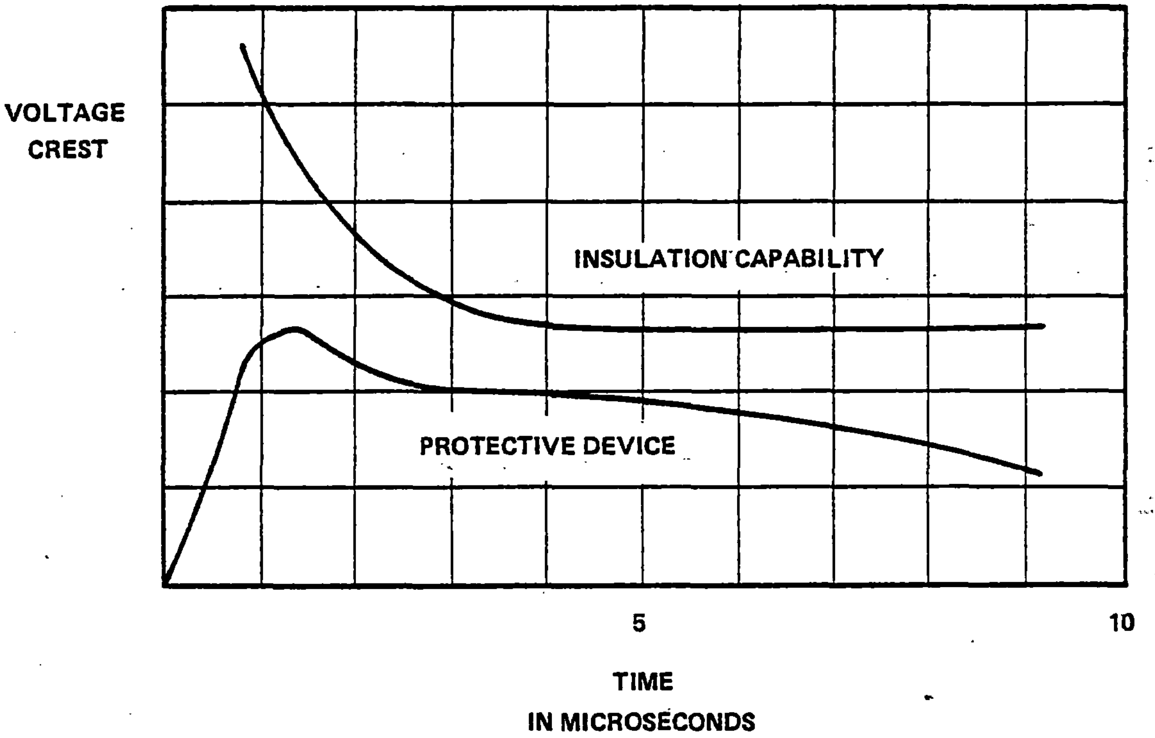
Background

The direct stroke theory of lightning behavior, which maintains that direct hits upon transmission lines rather than induced transient effects are the cause of major flashovers, became an accepted principle in the 1930's. Protective measures based on this theory have resulted in the application of grounded shield conductors running above power transmission lines. Both the existing and proposed electrification system designs incorporate this shielding. In addition, a lightning arrester is provided on each vehicle and substation to protect transformers against overvoltage.

The principle of equipment protection is to parallel the apparatus to be protected with a bypass circuit which will break down at a rate of rise or a maximum level of voltage which is less than the insulation capability of the protected apparatus. Figure 3-1 represents these characteristics. The current resulting from an overvoltage or transient will flow through the arrester and the voltage drop across the protected apparatus will be below its insulation characteristics. Because of the short duration of transients the energy to be dissipated from the transient is usually very small, however once a break down in the insulation level has occurred the power circuit voltage will continue to flow. This sustained flow will involve considerable energy. The problem in arrester design therefore, is to provide both the breakdown characteristic required to intercept a transient and the ability to extinguish the succeeding power circuit arc.

Early electric locomotives on the Pennsylvania Railroad, such as the P5a, and the MP54 multiple unit cars in the E1 through E4 propulsion configurations, utilized a simple impulse gap arrester in which a projection on the pantograph frame was located a specific distance from a solidly grounded surface. The drawback to the air gap arrangement is that when set at a distance where the power arc will be extinguished following a flashover, the breakdown voltage of the gap under the short time rise of lightning or other surge may exceed the insulation characteristics of the transformer it is intended to protect, thus permitting serious damage to occur.

The development of a compact "valve type" lightning arrester suitable for railroad application represented a significant improvement. All of the equipment currently operating on the NEC has such an arrester. In the valve type arrester an impulse gap is placed in series with a non-linear resistance element which exhibits the characteristic of having a negligible resistance at the high voltage of a surge and an increasing resistance under the lower voltage current of the power circuit. Because of this non-linear performance, the valve element permits the impulse gap to be set very close offering good protection against over voltage. Once a flashover has occurred, the valve



INSULATION PROTECTION

FIGURE 3 - 1

element reduces the sustaining arc current from the power circuit to a level which is readily extinguished by the air gap.

Two examples of the valve element are General Electric's "Thyrite" and Westinghouse Electric's "Autovalve". The Thyrite element is a semi-conductive ceramic material of proprietary composition molded in discs which are stacked within the insulating body of the arrester. The valve operation of the Thyrite may be illustrated by the example of an 11 kV arrester passing an 8000 A current when a surge of 80 kV is applied, exhibiting a resistance of 10 ohms. When the voltage then falls to 16 kV the current drops off to 27 A, exhibiting a resistance of 593 ohms and enabling the air gap to easily extinguish the arc.

The Westinghouse Autovalve element, while also molded in discs, differs in construction by having the discs separated to form very small air gaps, either by surface irregularities or thin mica spacers. The combination of discharge across the thin air gaps and the material properties of the Autovalve discs provides a similar non-linear resistance.

Dual Voltage Protection

The only protection change required for the upgraded Metroliners by the change in voltage and frequency is to replace the 15 kV arrester with a 30 kV arrester as governed by the parameters for the 25 kV electrification. This same change is presently planned for other commuter cars and locomotives which will be operating on the NEC.

There has been some discussion with regard to the adequacy of protection afforded by a 30 kV arrester when the transformer is connected for nominal 12 kV operation, since the possible voltage gradients between windings under the impulse conditions of a lightning strike or transient might be double the level permitted with the 25 kV connection. In the case of the Amtrak E60 locomotives, two 15 kV arresters are connected in series with a switching arrangement to permit 15 kV protection on the 12.5 kV connection. Sufficient space was available on the E60 locomotive, but severe space limitations in the area between the roof of existing m.u. cars and the construction limit outline force a simpler installation.

The justification for the single arrester approach is that there is little change in the basic impulse insulation level of the transformer regardless of the connection (11 to 12.5 or 25 kV) since the impulse or rate of voltage rise gradients from the windings and tap changer terminals to ground are considered to be the limiting factors. Adequate protection can probably be provided by a "station-class" arrester, (the highest commercial grade and the most sophisticated type of arrester having the most rapid response) which should exhibit a basic impulse level below that of the transformer when in low voltage connection.

While the transformer itself may receive adequate protection from the single voltage arrester when connected for the lower primary voltage, the transients induced in the secondary windings will be twice the level they would be at the higher voltage connection. This situation subjects semiconductor devices in the secondary circuits to a higher risk of damage than would otherwise obtain.

4. CIRCUIT BREAKERS

Background

The evolution of high voltage circuit breakers has progressed from oil filled, to airblast and inert gas filled breakers (such as sulfur hexafluoride), and more recently to vacuum breakers. Vehicle application of oil or gas filled breakers has not been considered because of the bulk involved leaving only the airblast and vacuum breakers as candidates. Both of these types are currently available in a form suitable for rail application from several manufacturers.

Service experience seems to be largely dependent on geographic region. The airblast breaker was applied to vehicles in Europe prior to the development of vacuum interrupter technology and has become the standard. Both vacuum and airblast breakers have been in use for a number of years in Japan.

Vehicle borne primary circuit breakers were introduced only recently in the U.S. General Electric used vacuum interrupters on the E60 locomotives, the Silverliner IV commuter cars for the Reading division of SEPTA, and the upgraded Metroliners. EMD utilized airblast breakers and other electrical equipment by ASEA on the GM6C and GM10B experimental locomotives which entered revenue service in 1976. The two short term locomotive demonstration programs by ASEA and Alsthom for Amtrak in 1976 also employed airblast breakers. The new EMD/ASEA type AEM7 locomotives being built for Amtrak will have airblast breakers. The 50 kV electrification projects in the U.S. and South Africa (both by GE and licencees) use vacuum interrupters.

Fault Interruption

With the existing 11 kV, 25 Hz system there are no provisions for on-board circuit interruption other than lowering of the pantograph. Under fault conditions when wire height is low, (tunnels) there is generally insufficient head room to break the resulting arc by this method. A simple solution to this problem was adopted by the use of rate-of-rise overload detection at the substations to open the substation breaker before lowering the pantograph on the vehicle.

In this procedure, a deliberate ground fault is applied to the catenary by connecting the pantograph to ground with a pneumatic ground switch. The resulting current surge is recognized by the substation protective devices and the wayside breaker is opened. The level of fault current which obtains is limited by catenary impedance.

The substation breaker will reset automatically in 15 to 30 seconds. If the fault has not been cleared and the breaker trips a second time, it will remain tripped until reset by supervisory control.

The circuit to control the pneumatic grounder is based on a protective relay called the Pantograph Lowering Relay (PLR) or, in the case of the GG-1 locomotive, the Pantograph Relay (PR).

An overload or primary fault on a locomotive or m.u. car is first detected by the PLR which is connected to current transformers in the primary circuit. Activating the PLR first causes the pneumatic ground contact to strike the pantograph frame imposing a dead ground on the catenary. The resulting ground current is also measured by the PLR which maintains the grounder against the pantograph and delays lowering the pantograph until the primary and ground current drops to zero, indicating the substation breaker has opened.

A mechanical latch which holds the moving contacts in their normal operating position is released when the PLR has moved to the fault position. After the primary and ground current drops to zero (substation breaker open), the PLR contacts travel past the normal position to the tripped position, releasing the pneumatic grounder and lowering the pantograph. Manual reset of the PLR to the normal operating position is required.

The pantograph relay (PR) employed on the GG-1 locomotive is a somewhat more complex current measuring relay in that it has two stages of overload protection. In the first stage or "partial trip," the relay opens the motor and auxiliary circuit contactors on the secondary side of the transformer. If the cause of the excessive primary current is removed by this action, then the relay will remained tripped but will not activate the pneumatic grounder nor lower the pantograph. If a partial trip does not remove the overload or if the overload is in the form of a violent surge such as a transformer primary fault, then the relay progresses to the "complete trip" position activating the previously discussed grounder and pantograph lowering sequence.

In the event of a dead short with the 25 Hz system, substation transformer internal impedance would limit the fault current to a maximum of 30 kA if the short were applied directly across the transformer terminals. The single phase distribution network and rotary converters which supply this network attenuate the "jolt" of such a surge on the utilities. However, with the new 60 Hz system such a "jolt" will be taken directly by the supplying utilities. Statistically there are 2 or 3 substation outages per day caused by locomotives or m.u. cars on the entire present system.

With the new electrification system, the switching time for fault interruption will be increased substantially from the present system. The existing 25 Hz system employs both an impulse breaker set to trip at 5000 A on 1/2 cycle (0.02s) and a back-up breaker which trips in 3 to 5 cycles (0.12 to 0.20s). With the new 60 Hz system there will be no impulse system and the breakers will open in 3 to 5 cycles (0.05 to 0.08s).

A fault with the new 60 Hz system could result in a current approaching 20 kA based on one 30 MVA rated transformer producing a momentary low voltage fault of 500 MVA when shorted directly across its windings. Considering catenary connecting wiring impedance, fault currents resulting from a vehicle failure may be limited to 17.2 kA at a point adjacent to a substation or less, depending on the distance from the substation. While the new system will make use of impedance measuring relays to provide substation fault protection, it will be the function of the vehicle circuit breaker to clear most on-board faults.

The circuit protection principle which has been applied to newer electrification systems is to supply each vehicle with a primary circuit breaker. In many cases these breakers have the full rated capacity of the substation however this is not possible in all cases.

On the German Federal Railways, where the maximum catenary current is 700 A with a 15 kV system, the fault level can be expected to be less than 200 MVA. The airblast breaker applied to the ET403 train (an IPEEP candidate vehicle) is rated at 200 MVA, indicating that the cars have protection equalling the full rated capacity of the system.

The French TGV lines, in contrast, have substations with 60 MVA capacity and an autotransformer system for extended distribution at 50 kV permitting substation spacings as great as 58 miles. Data on fault levels has not been made available, however, it is safe to assume a level greater than the 500 MVA capability of a 30 MVA transformers proposed for the NEC. In this case the 300 MVA Brown Boveri type DBTF airblast breakers on the TGV have less than the full fault capacity of the system.

The circuit breakers applied to vehicles operating in the NEC will generally not be able to handle the fault current level of the catenary. The ASEA airblast breakers used on the modified Rc4 demonstrator, the two EMD demonstrators, and the new EMD AEM7 locomotives for Amtrak are rated at 250 MVA. The vacuum interrupter applied to the upgraded Metroliner is rated at 4000 A (100 MVA).

The consequence of a fault in excess of the on-board breaker capacity will result in a sustained arc within the breaker until the wayside breaker opens. The operating characteristics of the substation breaker will determine the duration of such a fault and the quantity of energy released.

The Joslyn vacuum interrupter module of the type applied to the upgraded Metroliner has been tested at a sustained internal arc of 20 kA for 10 cycles (0.17 seconds) without degradation of the vacuum. Accelerated contact errosion can be expected in such circumstances however the interrupter remains "undamaged". (No comparable test data is available on the behavior of an airblast breaker.)

The most serious consequence of a fault in excess of the on-board breaker capacity is not the damage to the breaker but the energy released on the vehicle-usually in the transformer. For safety reasons it is important to interrupt the fault as quickly as possible regardless of where the interrupting is performed.

During informal meetings with the NEC electrification designers, serious objection was expressed to the continued use of the pneumatic grounder because it places the most severe fault condition on the substation transformers for every vehicle related fault, regardless of the severity of the vehicle fault. The mechanical force produced by the magnetic fields of the transformer windings under high current levels causes elevated stresses on the winding insulation and clamping. It is logical to assume that this accelerates deterioration, however, it is impossible to quantify the effect.

It should be noted, however, that the established precedent of using the pneumatic grounder has not previously been identified as a problem with the older 25 Hz system. The substation transformers are approximately 40 years old and few have required major repair work. Further, the occurrence of vehicle faults represents only a small portion of the causes for substation breaker trips (1 in 7). The hazard of releasing the fault energy with a transformer on an MU car has previously been discussed and must be considered.

A proposed arrangement to deal with the limited on-board breaker capacity is to provide a protective relay which is set to detect current levels slightly below the limit of the breaker and arranged to inhibit operation of the breaker above that level. Faults within the capacity of the onboard breaker would be handled by that breaker. However when a fault in excess of the onboard breaker capacity occurred, the breaker would remain closed until the substation interrupted the fault. Following interruption by the substation, the onboard breaker would open to isolate the vehicle.

Taking this proposed arrangement a step further, the present pneumatic grounder could be retained and actuated by the proposed protective relay to assure tripping of the substation breaker. Because of the location of the grounder and its short circuit path from the pantograph to ground, this would offer a protective shunt path for fault current around the vehicle transformer.

Air blast Interrupters

The airblast circuit breakers which have been applied to railroad equipment operate on a two stage principle to provide circuit interruption and transient suppression. A current limiting resistor is connected in series with an auxiliary contact and operates in parallel with the main contacts. The breaking sequence begins with the main contacts opening under whatever load or fault current is present, drawing an arc between the contacts. A blast of air from a special reservoir is discharged between the electrodes, cooling and extending the path of the arc, which extinguishes at the next zero voltage point of a cycle. The resistor circuit remains closed across the main contacts momentarily to suppress switching surges, and is then disconnected by the auxiliary contact to complete circuit isolation.

In designs such as the Brown Boveri type DBTF circuit breaker the auxiliary contact is external to the airblast breaker and is in series with the main airblast contacts. The main airblast contacts are spring loaded and reclose after operating momentarily. The auxiliary contact is a low speed mechanical switch which opens sequentially during opening of the main contact. The suppression resistor remains connected across the main contacts. The auxiliary contact is used for circuit isolation and reclosing the circuit in addition to interrupting the circuit through the surge resistor. See Figure 4-1.

In the ASEA type HVA breaker the main and auxiliary contacts are internal to the airblast unit and are mechanically linked for sequential operation. A toggle mechanism holds the contacts in either the open or closed position.

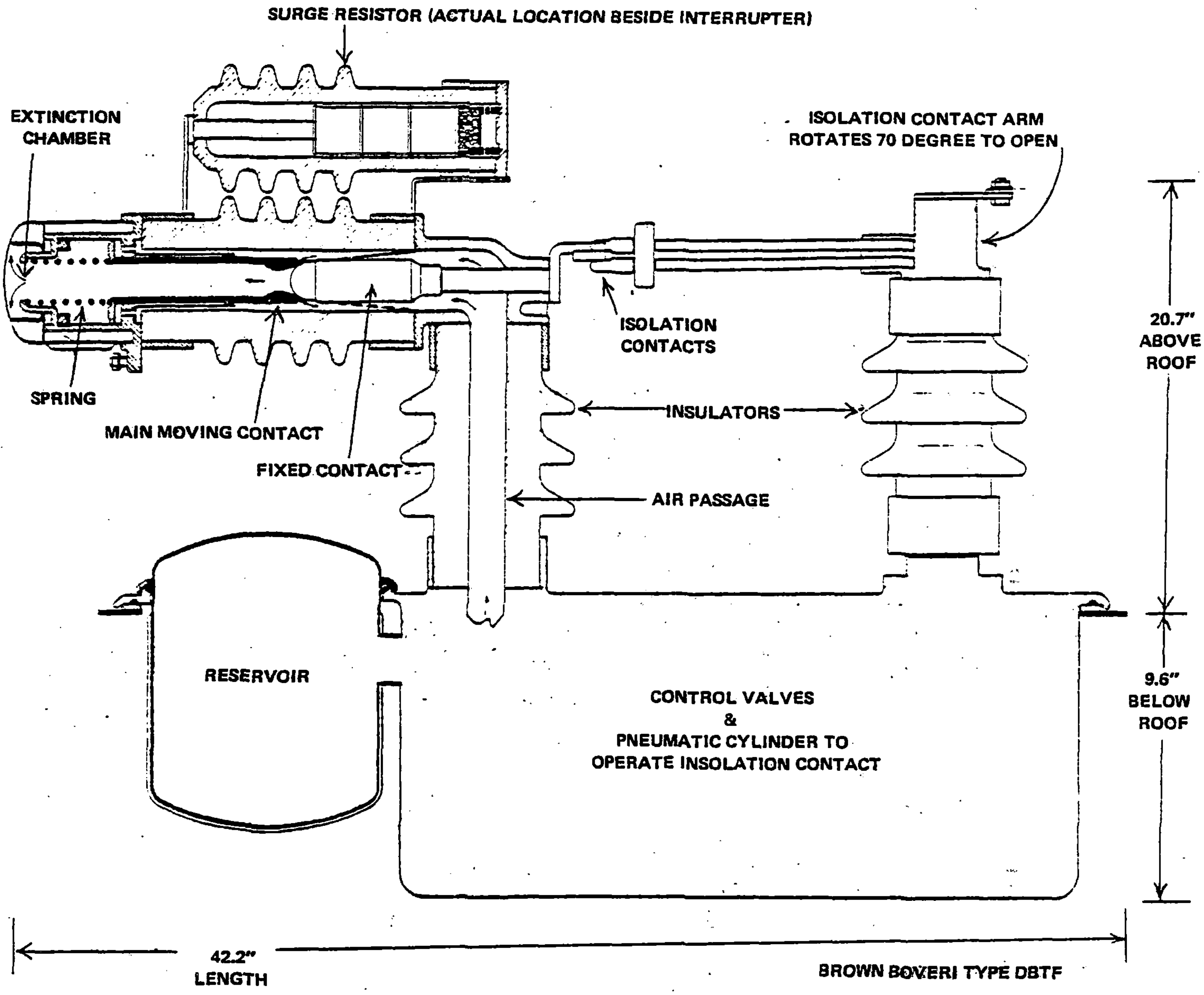
An important condition for operation of the airblast breaker is that circuit interruption is dependent on maintaining a sufficient supply of air to extinguish an arc. It is therefore necessary to provide a dedicated air reservoir for this purpose and to design safeguards to prevent closing the contacts unless the reservoir is sufficiently charged, as well as to open the breaker should the pressure fall to the minimum level required for operation under the rated fault conditions.

To energize a vehicle it is necessary to have a supply of air to close the breaker. In the case of the new Amtrak AEM7 locomotive (which has an ASEA airblast breaker and an air raised pantograph) a battery powered auxiliary compressor is provided. This type of compressor is also offered by BBC.

Another consideration is contamination of the air supply to the breaker by either oil or moisture. It is not only important to prevent the accumulation of contaminants in air lines and pilot valves and on insulator surfaces, but to prevent contaminants from increasing the ionization of the air blast which is used to extinguish the arc. In humid climates, such as the NEC, the air supply from an air compressor and after cooler will have excessive moisture and require further drying with a dessicant.

Vacuum Interrupters

Vacuum interrupter operation is dependent on the absence of ionized gas in a vacuum which prevents an arc from being sustained between contact tips through the zero current portion of an a.c. cycle. The interrupter element consists of a fixed contact and a movable contact both extending into a sealed



AIRBLAST CIRCUIT BREAKER

FIGURE 4-1

vacuum chamber composed of a ceramic or other insulating material. A flexible bellows seal is provided for the operating rod. A metal shield surrounds the contacts within the vacuum chamber and serves to condense vaporized material from the contact tips and to provide some shielding against the emission of X-radiation during the operating cycle. This is a condition which may occur when a sufficiently high voltage is applied across a gap in a vacuum and is influenced by the material of the electrodes but will not occur at rated voltage when the interrupter is in the fully open position. Figure 4-2 shows a vacuum interrupter element.

A vacuum interrupter circuit breaker is comprised of one or more vacuum interrupter elements connected to an actuating mechanism with insulators. Several of these elements can be connected in series to extend the voltage range of the breaker. Both General Electric and Joslyn rate their elements at approximately 15 kV each, with a two-unit breaker rated at 34.5 kV used for the nominal 25 kV electrification system. Figure 4-3 illustrates a vacuum circuit breaker.

The operating mechanism is a spring loaded device which assures rapid contact separation when the breaker is opened. A motor driven cam, a large solenoid, or a pneumatic cylinder provides the opening and closing force. The closing sequence first compresses the opening springs before moving the contacts to assure that the breaker is ready to trip. Some breaker designs such as the pneumatically operated unit applied to the Amtrak E60 locomotive have a separate trip function employing a solenoid latch which permits a fast spring opening sequence. This is faster than normal on and off operating speed and is used for overload protection.

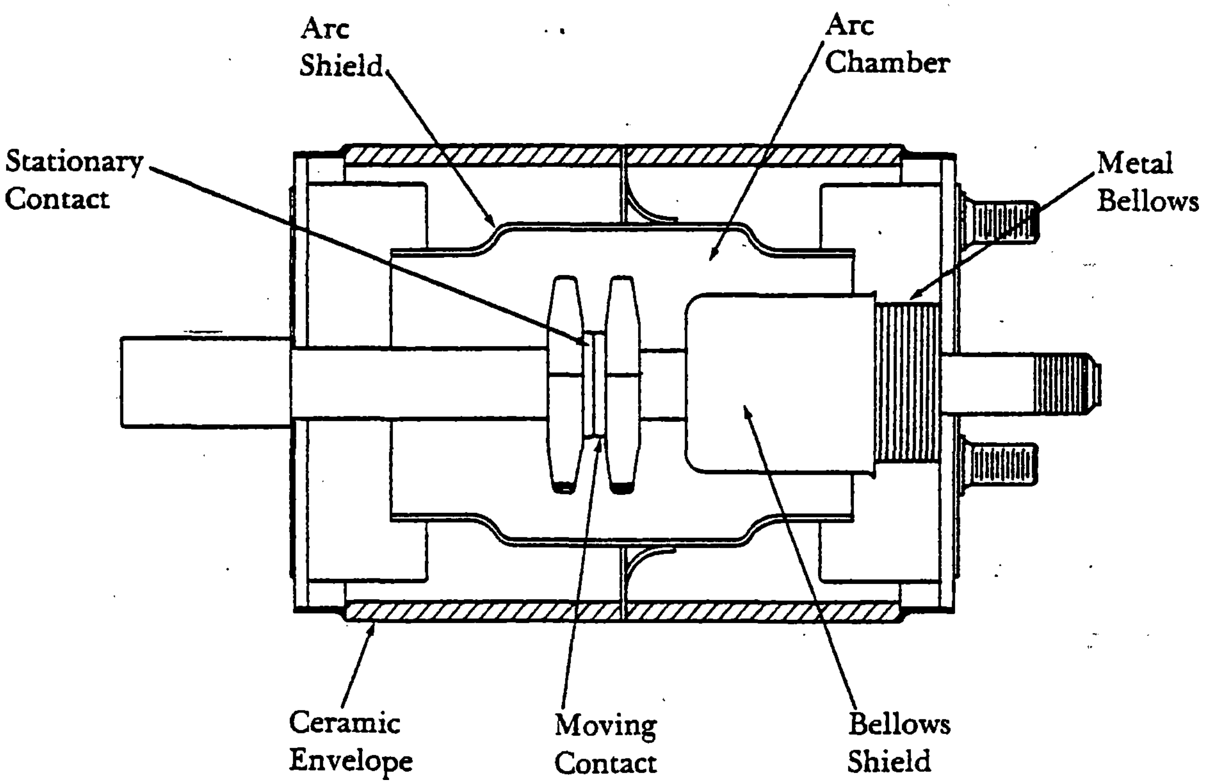
A manual back-up operation, using a ratchet mechanism to "cock" the opening springs, may also be provided on some models such as the Joslyn VBT breaker applied to SEPTA m.u. cars on the Reading Division.

The complete response time for opening of a vacuum breaker (including sensing of a fault, mechanical tripping of the breaker, and interruption of the arc) is on the order of 2 cycles or 0.03 second. Actual interrupting time is within a half cycle after the contacts have fully opened.

Duty Cycle Requirements

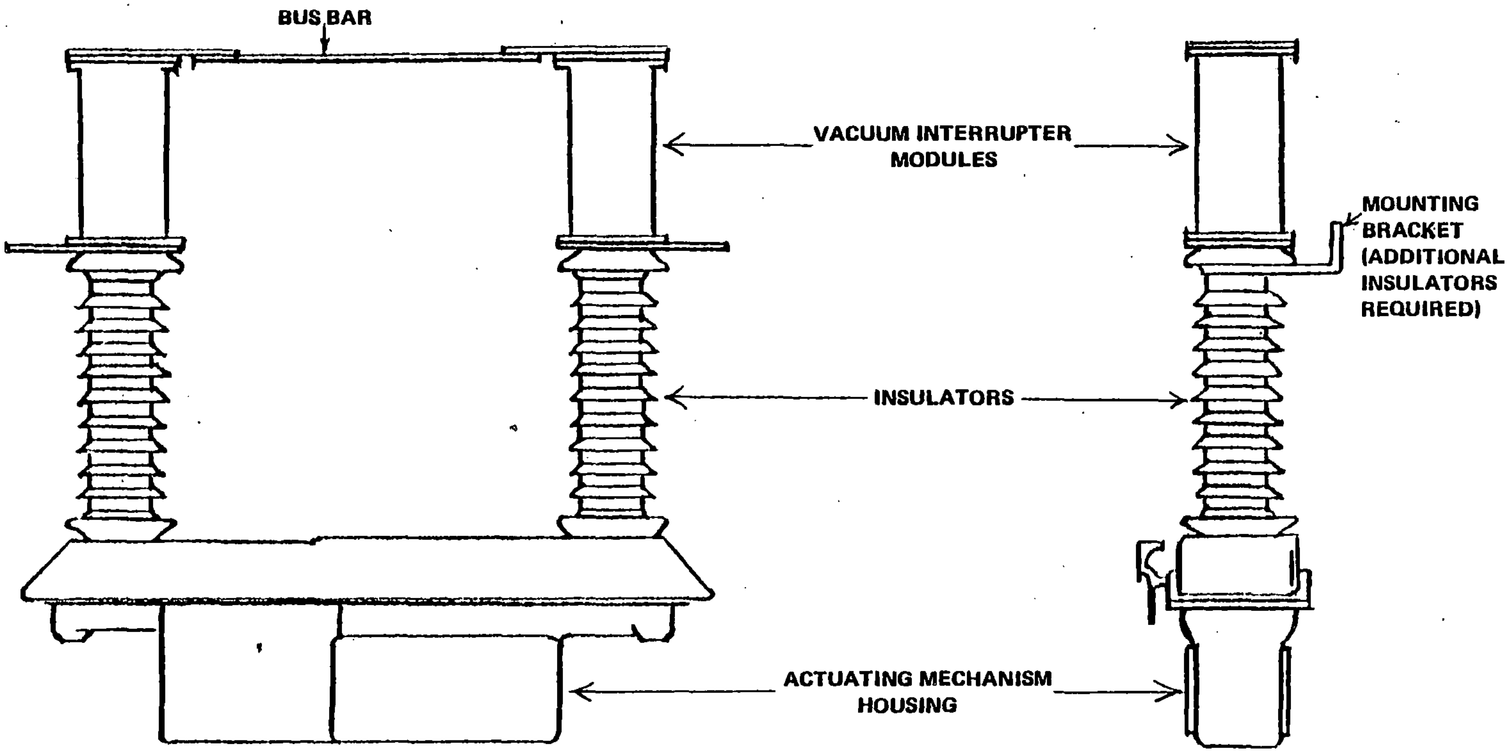
Two factors which affect the service life on any electrical switching device are the number of cycles of operation and the current level involved. The mechanical wear of the circuit breaker mechanism is virtually independent of the current involved while the contact erosion is proportional to the current interrupted and duration of arc. With approximately 80 section breaks between Boston and Washington and the layover and terminal inspection and test operation, the circuit breakers will be subjected to an average of 82 operating cycles per one way trip.

VACUUM INTERRUPTER MODULE



WESTINGHOUSE ELECTRIC

FIGURE 4-2



VACUUM CIRCUIT BREAKER

FIGURE 4 - 3

Based on the current Metroliner utilization of 12,000 to 15,000 miles per month, the number of circuit breaker cycles can be projected to vary from 2158 to 2698 per month. When the 34 upgraded cars are placed in service, the burden of the runs will be placed on them with an expected usage extending to 16,000 miles per month, corresponding to 2877 breaker cycles. Since this mileage will be accrued between the scheduled shop periods for monthly inspection and maintenance, the circuit breaker must be able to withstand at least this duty cycle without adjustment or repair.

Because the normal operating sequence will begin by removing propulsion power at a jerk limited rate, the current to be interrupted by the primary breaker will usually be limited to, only the auxiliary level. Even though this current is quite low, the frequent cycling of the breaker at phase breaks will tend to produce fairly rapid mechanical wear.

In the case of vacuum interrupters, both General Electric and Joslyn have tested their vacuum contact assemblies to 60,000 cycles. Joslyn gives a pro-rated guarantee of 40,000 cycles at rated current on their VBT breaker. A projected life expectancy of 100,000 cycles under very small loads has been discussed but cannot be assured since there is no substantiating test data. Presumably at that time the operating mechanism would be rebuilt and the contact assemblies replaced. The extent of contact wear can be determined by measuring the travel required by the moving contact. Adjustments are made as necessary up to the condemning limit. Contact life is affected both by the mechanical action of opening and closing and by the erosion of the current interruption. Because contact erosion is an inverse function of the current, the occurrence of faults will greatly reduce the service life of the contacts when compared with the life expenctancy under normal vehicle auxiliary loads. As the current levels will normally be quite low, it is quite possible that the fatigue life of the metal bellows seal on the contact assembly will be the controlling factor for overall service life of the unit. The life of the bellows is greatly affected by the speed of operation, particularly the mechanical shock of fast operation.

The application to the upgraded Metroliner is an example of a slow speed vacuum interrupter intended for maximum cyclic life. A motor driven Joslyn VBT breaker rated at 4 kA maximum interrupting current and 600 A continuous capacity was used. This breaker consists of a machinery housing with two vacuum contact elements mounted on insulators and connected in series for a rating of 34.5 kV. (It should be noted that other Joslyn commercial interrupters with 600 A continuous rating are given maximum interrupting current ratings varying from 3 to 8 kA, depending on the circuit characteristics of the particular application). Because the current rating of the breaker is well below the 17.2 kA potential fault current from the catenary, no attempt was made to use this breaker for fault interruption on the upgraded Metroliners. Instead, the old pneumatic ground switch and pantograph lowering sequence (as applied on the 25 Hz electrification) has been retained to trip the substation breaker.

This arrangement presents an apparent conflict with the fault protection philosophy outlined in the task 204 report of the NEC electrification program and will require resolution. The reason for selecting a breaker of 4 kA capacity is that larger size breakers, such as the one applied to the Amtrak E60 locomotives, are too large for application on the roof of an m.u. car. The same space restrictions also limit the size of airblast breaker which can be applied. Retention of the pneumatic ground switch is also in conflict with the 60 Hz substation circuit breaker design which makes use of a slower responding impedance measuring method of fault detection as compared with the rate-of-rise detection with the 25 Hz system.

ASEA rates the HVA series airblast breaker (which is to be applied to the new EMD AEM7 for Amtrak) at a mechanical life of 100,000 cycles without part replacement. Considering part replacement such as contacts and rubber-seals, the service life is projected to be in the order of 200,000 to 300,000 cycles. The normal maintenance cycle calls for disassembly, cleaning, lubrication, and repair after 10,000 cycles which corresponds to somewhat more than three months of projected NEC service (as discussed previously). This, of course, is based on operation of the breaker at reduced loads. Service life of the contacts under load or fault conditions will be shortened by erosion. The recommended inspection interval is reduced for operation under load and is 500 operations at rated current of 630 A, 50 operations at 2.5 kA, and 15 operations at 5.6 KA. (The maximum interrupting capacity is 8.3 kA.)

Comparison

Circuit interruption entails a transient voltage oscillation which occurs in an inductive device such as a transformer when it is disconnected. The inductive discharge of the transformer produces a potential opposite to the line potential, resulting in a voltage across the breaker which could be as much as three times the line potential. In the case of a transformer under load, the resistance of the load will tend to dissipate the inductive discharge of the transformer, however, if there is no load this transient voltage may be higher.

In order to control such transients, the airblast breakers applied to rail vehicles are arranged as two step switches with resistance in parallel with the main contacts for the initial step in the opening operation. In this way current is reduced to a low level before interruption takes place. Arc extinction is usually within one or two half cycles.

The vacuum interrupter does not have a transient suppression function and some concern has been expressed for the effect that rapid circuit interruption has in producing transients which may affect power semiconductor devices in the propulsion system and even carry over to the battery circuits and control devices. Foreign equipment suppliers provided several reactions on this subject to IPEEP representatives. ASEA expressed its concern that with a vacuum interrupter, circuit interruption may occur before the zero current point and that contacts bounce on closure. Both of these conditions can produce transients which may be avoided by the use of airblast breakers. Brown Boveri also indicated their preference for the airblast breaker which has extensive service experience and expressed no interest in vacuum interrupters which they feel would produce unacceptable transients. Alsthom also indicated a preference for airblast breakers. British Rail Engineering representatives expressed concern over problems they were encountering with vacuum interrupters on the APT prototype and indicated they were considering a change to airblast units.

In sharp contrast to the above testimony, Hitachi (which makes both airblast and vacuum interrupters) expressed confidence in their vacuum interrupter, having placed 590 units in service on the New Tokaido Line as early as 1968.

Information received in informal meetings with General Electric representatives indicates that the type of transformer used in m.u. cars and locomotives will not "ring" at the high frequencies and voltages which are characteristics of such a transient. The design of transformers with sufficient core material for 25 Hz operation contributes a very high impedance to the rate of voltage rise accompanying transient conditions. The results of the test programs with the E60 locomotives, the SEPTA Silverliners on the Reading Division, and the upgraded Metroliners have indicated that there is no hazard to semiconductors in secondary circuits. Service experience with the E60 confirms these conclusions.

The primary reasons for selecting vacuum interrupters for NECIP vehicle conversion as opposed to airblast breakers was the longer interval between maintenance events afforded by the vacuum interrupter and the resulting lower projected maintenance cost. Initial cost of an airblast breaker is also higher than for a vacuum interrupter.

High Voltage Fuses

Part of the primary fault protection system on the newer commuter m.u. cars operated by NJDOT and SEPTA on the NEC and connecting electrified lines, is the addition of a special high voltage fuse. These cars have not as yet been equipped with primary circuit breakers and a voltage change/phase breake negotiation system, although they were built with dual voltage transformers. The reason for the high voltage fuse is best explained by tracing the history of its application in a retrofit program.

A severe internal fault in a transformer often creates a shock wave within the cooling fluid which cannot be relieved fast enough through the normal pressure vents. As a result, the transformer tank walls are bulged and tank welds are broken. Such a violent mechanical reaction under an m.u. car is rather frightening to passengers and potentially hazardous as considerable energy is involved.

In July, 1974, a number of the 214 Silverliner IV and Jersey Arrow II cars experienced violent transformer failures in which the primary winding arced to ground near the "line end" without the current limitation of the transformer impedance. Design and manufacturing problems were blamed for the failure of at least 28 transformers which necessitated an expensive rebuild program under warranty. At that time, a primary fuse was installed on all of the cars in order to prevent fault currents from reaching catastrophic proportions. Even with the fuse, there was a later incident in which a transformer faulted, bulging the tank, breaking tank welds, and blowing the fuse.

Application of fuses became a recommended practice. However, in reviewing this recommendation and considering the fact that no other equipment built in the U.S. used such fuses, Amtrak rejected its application to the upgraded Metroliners. The upgraded cars have a vacuum interrupter and retain the pneumatic grounder to provide fault protection since the 4000 A rating of the vacuum interrupter is substantially less than the possible fault current.

It should also be noted that the foreign equipment designs reviewed by IPEEP do not make use of such fuses nor do they use pneumatic grounders, but rely entirely on the on-board circuit breaker and its protective relaying. The air blast breakers applied to the German type ET403 m.u. equipment have a rated capacity of 10,000 A, which is probably equal to that of the substations on the German 15 kV electrification but would not meet the new NEC requirements.

The addition of primary tap changers to car and locomotive transformers provides an internal location where the line and ground terminals are placed in close proximity in a manner not occuring on previous transformers. The chance of a failure in the contacts of the tapswitch increases the potential for a short circuit between the line side and ground without the current limiting effect of transformer impedance. This is far more severe than a short between turns and may even be introduced as a consequence of an overload caused by shorted turns. In view of this increased chance of catastrophic failure and the inability of the primary circuit breakers on m.u. cars to handle full catenary current, it appears to be reasonable to add the fuse on m.u. cars.

5. POTENTIAL AND CURRENT MEASUREMENT

Current Measurement

Measurement of primary current is used for transformer overload protection and is accomplished with a current transformer in which a voltage is induced in the secondary winding which is proportional to the current flow in the primary. The current transformers commonly used for high voltage railroad equipment are of the "window type" in which the secondary winding is assembled on the magnetic core and completely insulated, and an opening or window is provided for the primary conductor to pass through. For dual voltage operation, a tapped secondary is provided so that the sensitivity of the transformer can be reduced when operating on the higher current levels associated with the lower voltage.

On present NEC m.u. cars, a single current transformer is used to measure the high voltage current for overload protection. The current transformer is mounted around a short copper tube through which the high voltage lead from the pantograph circuit to the main transformer is routed. This tube serves as the ground path from the pneumatic grounder which functions to trip the substation breaker for fault interruption (See section 4) and permits the PL relay to measure both the ground and transformer currents. After a fault trip of the grounder, the pantograph lowering circuit delays until the combined currents disappear, indicating that the substation breaker has opened, before lowering the pantograph and releasing the grounder.

A second protective function of high voltage and ground current differential protection is provided on most locomotives in the NEC and on one of the IPEEP candidate m.u. car designs (The German ET403). An additional pair of current transformers are applied to the high voltage and ground connections of the main transformer and arranged, with a relay circuit, in a "buck" connection in which the two currents cancel each other. The differential protection circuit detects only an unbalance in primary current caused by an internal main transformer failure and is not affected by the normal current but only by the level of insulation leakage or failure. The differential circuit is therefore not affected by a conversion to dual voltage operation.

The only change in current measuring circuits necessitated by dual voltage operation is to apply a dual range or tapped current transformer and provide relay contacts in the propulsion control logic to select the range which corresponds to the main transformer primary tap changer position. The size and construction of a tapped current transformer remains unchanged from the single range type with the only difference being an additional terminal and connecting wire.

Potential Measurement

With a single voltage system the only purpose of catenary voltage measurement is to detect abnormal low limits at which point propulsion and auxiliary loads are reduced to minimize power consumption. This is done both to protect vehicle equipment and to unload the substation in the event of difficulty. This function is easily implemented by a relay circuit operating on one of the secondary windings of the main transformer and may be retained for the same protective function with a dual primary voltage system.

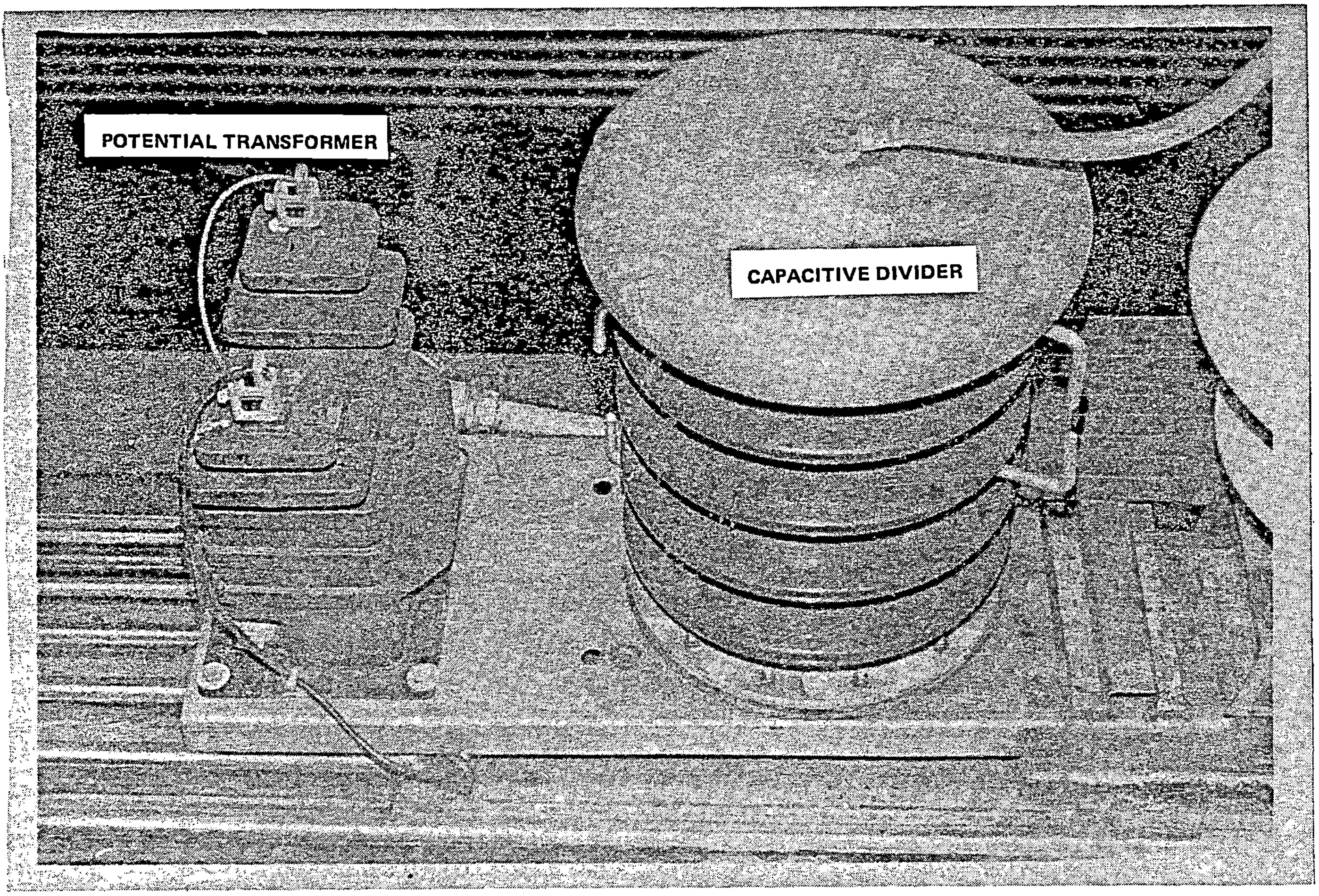
The introduction of a dual voltage electrification requirement necessitates on-board catenary voltage measurement to assure correct tap changer position. This measurement must be made while the main transformer is disconnected by the primary circuit breaker while passing through a voltage change/phase break in the catenary.

Two basic approaches to potential measurement are available based on commercial power techniques. Either a potential transformer operating directly from the high voltage circuit or a combination of capacitive coupling with a potential transformer may be used. The directly coupled potential transformer is a small capacity step-down transformer which reduces the line voltage to a level suitable for instrumentation. Unfortunately, while very accurate from the standpoint of voltage measurement and frequency response, the potential transformer is very large because of the insulation level required. An example of this is a transformer for 25 kV operation made by Hitachi which occupies an area approximately 21" x 38", stands 21" high, and weighs 463 lbs. This is much heavier than an airblast breaker and almost twice the weight of a vacuum interrupter.

The combination of a capacitive coupling with a much smaller potential transformer offers considerable reduction in bulk and weight of equipment.

An example of this type of circuit is the arrangement applied to the upgraded Metroliners. Figure 5-1 is a photograph of the capacitor and transformer which are mounted on the roof, forward of the pantograph.

Catenary voltage is applied to the top terminal of the capacitive divider and is reduced by a factor of 7.5:1. The intermediate voltage is taken from a terminal on the bottom of the capacitor unit and connected to the primary winding of the potential transformer. The potential transformer has a turns ratio of 30:1, giving an overall ratio of 225:1. The potential measuring relays in the voltage changeover logic then operate on a signal range of less than 115 volts. Equipment weights are 90 lbs. for the capacitor unit and 44 lbs. for the transformer.



CAPACITIVE DIVIDER AND POTENTIAL TRANSFORMER
AS APPLIED TO UPGRADED METROLINER
FIGURE 5-1

6. BUS COUPLINGS

Background

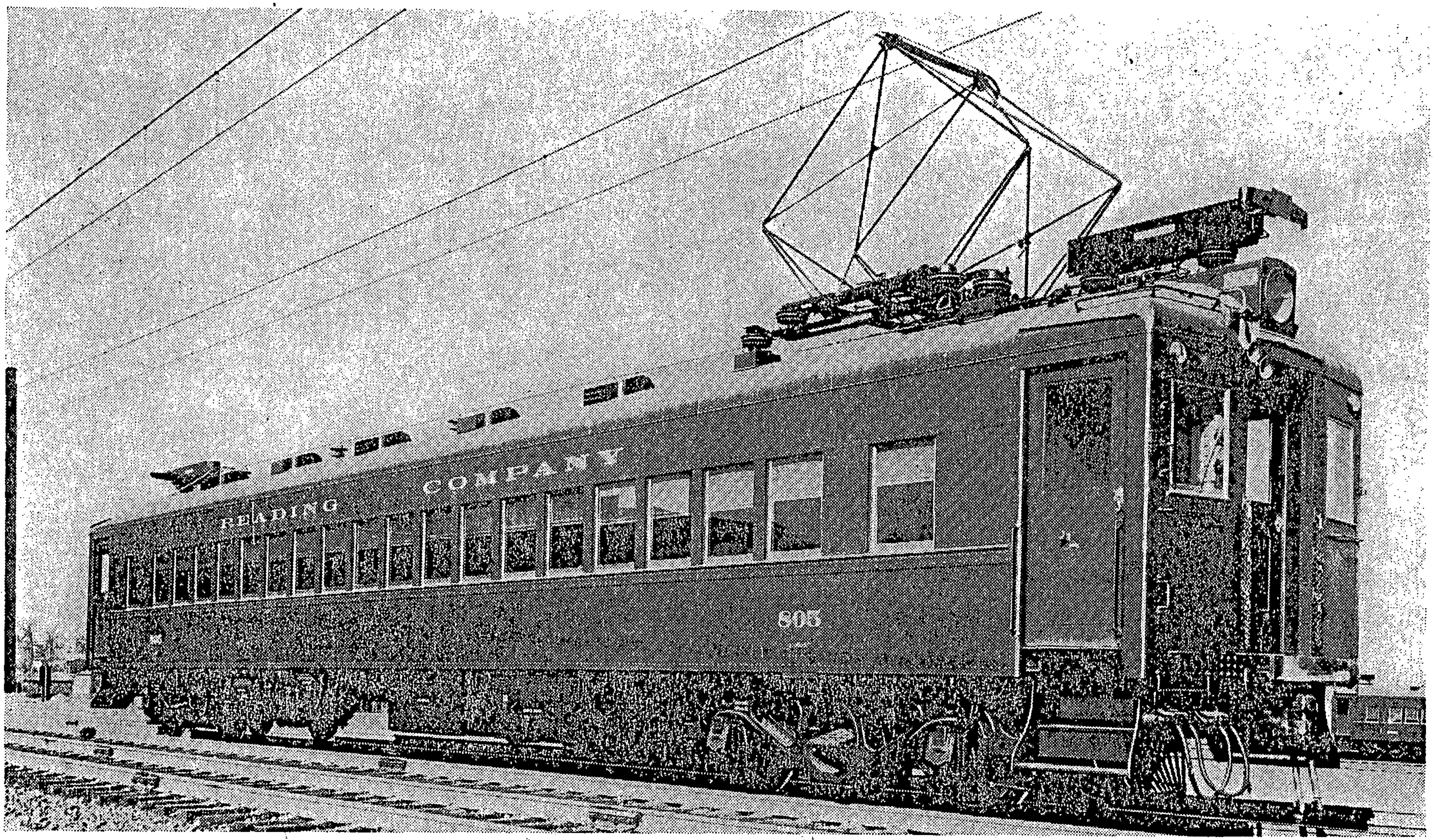
Interest in primary bus coupling between cars or locomotives operating as multiple units stems from the problems encountered with the operation of multiple pantographs, particularly at high speed. (Pantograph/catenary interaction is discussed in another IPEEP paper prepared for the FRA). Because of the obvious safety hazards of handling 11 to 25 kV, manually applied jumper cables present a time consuming operational problem. Automatic bus couplers therefore offer an attractive solution.

North American practice has generally neglected busing for high speed operation but has used such devices at lower speeds, ostensibly to reduce wear. The few moderate to high speed applications have been limited to the use of jumper cables to bus cars in pairs within a train. The Metroliners have bolt-on jumper cables between the adjacent non-cab ends of cars to permit use of only one pantograph for each of two otherwise independent cars. High performance commuter m.u. cars having independent propulsion systems but a dependent or "married pair" set of auxiliary systems have only one pantograph per pair with a bolted jumper cable between them. Examples are the New Jersey D.O.T. Jersey Arrow II, SEPTA Silverliner IV, and the MTA and CDOT type M-2.

Automatic Bus Couplers

The only North American application of automatic bus couplers on m.u. cars is on the older Reading Company commuter cars (now owned by SEPTA) in Philadelphia suburban service. A picture of one of these cars is given in Figure 6-1. These cars have a spring loaded buffer device on roof mounted insulators at each end of each car which is pneumatically extended to a contact position or retracted for bus isolation. A connecting bus bar, which is also on insulators, is tied directly to the transformer and pantograph. When the cars are coupled and the main air reservoir hose connections are made-up, the buffer faces of the connectors on adjacent cars are automatically extended to complete the circuit. The bus connectors can also be retracted to isolate a car in the event of a fault. When cars are bussed together in a train, the bus connectors are controlled by the pantograph lowering relay circuits (See Section 4) and are retracted following substation circuit breaker operation by the car-borne pneumatic grounder. Operating practices call for use of two pantographs on a train of two to seven cars and four pantographs for trains of eight to twelve cars. Pantographs on both ends of the train are used on the SEPTA Reading division.

The Great Northern Railroad, which also had an 11 kV, 25 Hz electrified division, made use of similar bus connectors which were added to the class Y-1 dual-service locomotives to reduce wear and arcing, particularly in severe weather. These engines were later sold to the Pennsylvania Railroad, however the bus connectors were removed.



SEPTA M.U. CAR WITH AUTOMATIC HIGH VOLTAGE BUS COUPLER

FIGURE 6 - 1

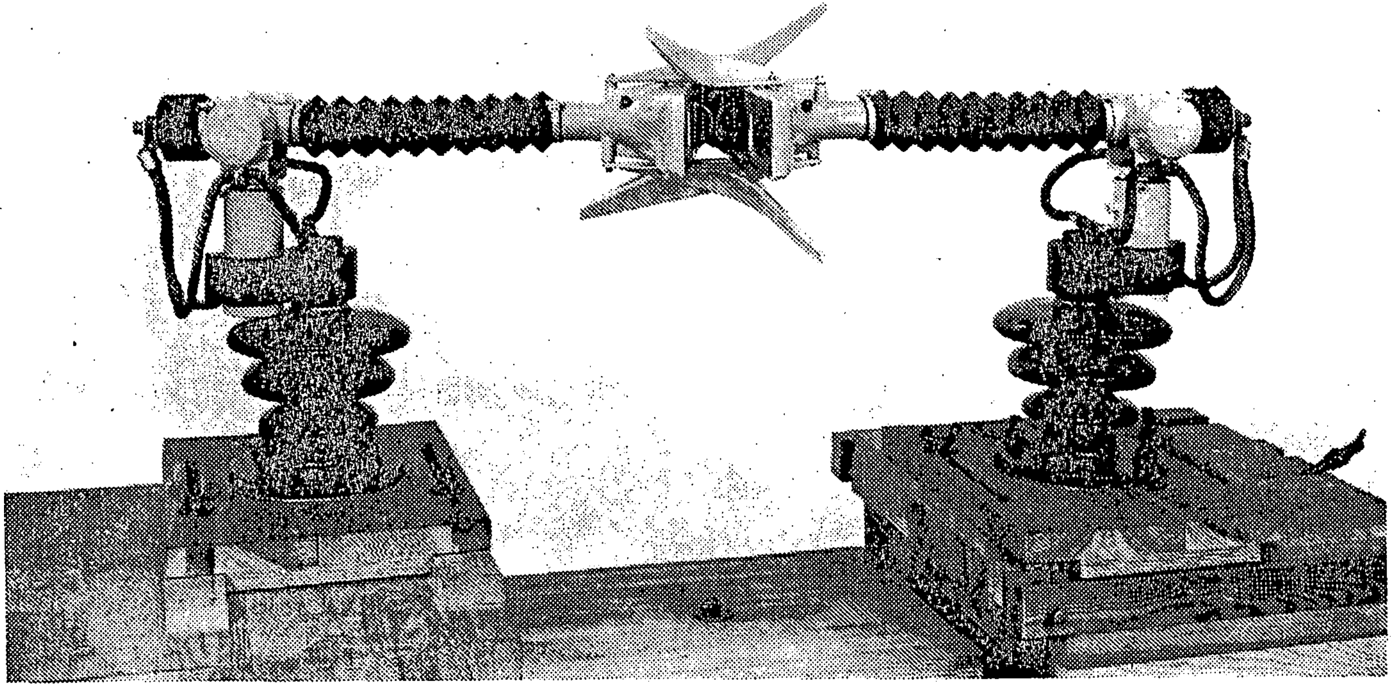
The German ET403 m.u. trains which was reviewed as an IPEEP candidate vehicle has an automatic bus connector manufactured by Brown Boveri. This device is illustrated in Figure 6-2. The coupler head has a spring loaded telescoping shank which is supported in a pivoted yoke to accommodate relative movement between carbodies. Two gathering horns project from each coupler head on a diagonal to provide alignment on curves of 820 ft. radius (7° curve) and to compensate for height variation.

The bus coupler is rated at 700 A continuous capacity with the qualification that air flow from train movement will maintain the desired operating temperature under high ambient temperatures. Since the catenary of the German Federal Railroad is rated at 700 A (at 15 kV, 16 2/3 Hz), there is no concern for potentail damage to the bus coupler when using two pantographs, thus placing the bus connection in parallel with the catenary.

Surge tests of the coupler have demonstrated its ability to withstand 27 kAs of energy, applied for a duration of 80 ms, without contact welding. Welding occurred at 39 kAs but the contacts are said to have sustained no permanent damage and functioned properly after separation of the weld. It is felt that this is adequate to survide a fault on the ET403 until a circuit breaker interrupts the current.

While the ET403 mounting insulator used is for 15 kV operation, a change for 25 kV operation should present no problem.

The use of bus couplers introduces the possibility of bridging catenary sectionalizing insulators should more than one pantograph be raised. With the existing single phase power distribution bus tie breakers are normally closed bypassing the insulators and there is no potential problem. With the introduction of phase breaks and voltage changes planned for the NEC, the potential for serious faults would exist. Trainlined interlocking circuits would be required to preclude such an error.



BROWN BOVERI

AUTOMATIC BUS COUPLER

FIGURE 6-2

7. INSULATION & MOUNTING

General

Because of the voltage transients (such as lightning) which may occur in the catenary transmission, it is necessary to maintain a high level of insulation in the primary circuit. While devices such as lightning arresters and primary switchgear may be mounted within locomotive carbodies, it is considered mandatory practice to keep these devices external to a passenger carbody for safety in the event of an electrical fire. Roof mounting of this equipment also offers less hazard of an electrical fire progressing into the passenger compartment than with underfloor mounting and avoids an unprotected cable run through the car body.

The pantograph supports, lightning arrester, primary switch, and terminator for the transformer lead-in cable are all constructed with porcelain insulators having a long surface path to ground to prevent leakage or flashover.

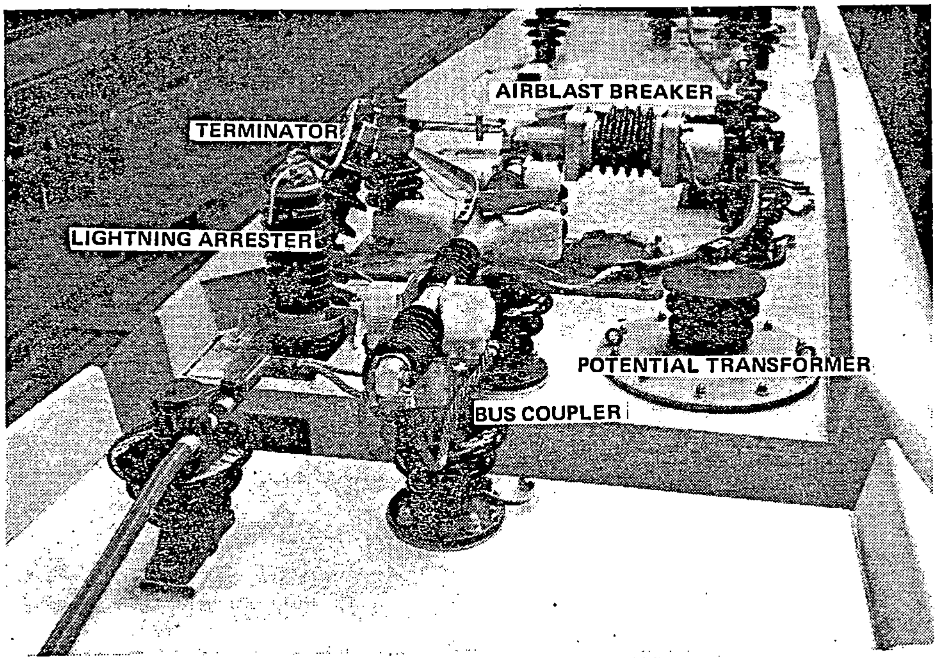
A second insulation consideration is the "strike distance" between high voltage equipment and the grounded carbody surfaces. The pantograph frame and mechanism, and any bus coupler or bus bar arrangement must all be located with sufficient clearance, not only to prevent an impulse flashover, but to preclude accumulation of snow and ice from closing the gap. The criteria observed with previous 11 kV equipment was generally 6 inches clearance with 4 inches permitted under certain circumstances, however with the increase to 25 kV, a distance of 8 inches must be maintained. By way of comparison, the German Federal Railways uses a gap of 5.9 inches with their 15 kV system.

The mounting of high voltage devices on the roof of a car presents a serious aerodynamic problem as the bulk of insulators and components offers considerable turbulence inducing frontal area. Because of the insulation level required and the potential problems with snow accumulation this equipment cannot easily be faired into the carbody.

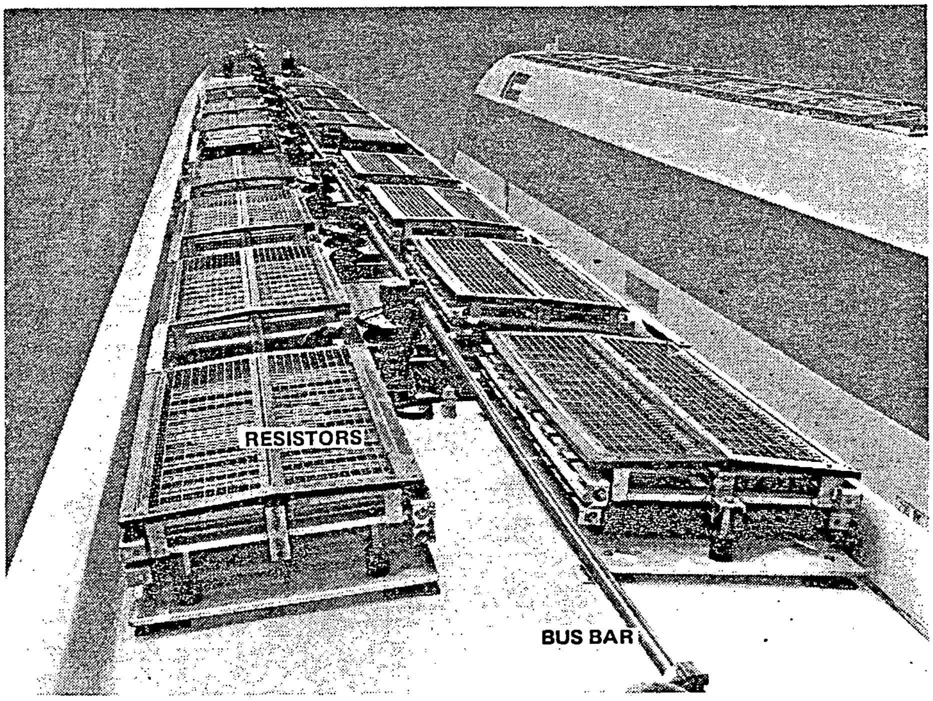
The German ET403 trainset, which was reviewed as an IPEEP candidate train, has a considerable amount of roof-mounted equipment including dynamic brake resistors, pantographs, airblast circuit breakers, and automatic bus couplers. This apparatus is arranged as close to the roof as possible and partly concealed from the sides by extensions of the car sides. This treatment is basically an esthetic consideration which forms an equipment trough running the length of the roof but does little to control the air turbulence caused by the projecting equipment. Figure 7-1 shows two views of the roof of the ET403.

The obvious disadvantage to extending the top of the sides in this manner is that it facilitates the accumulation of wet snow which could ground the high voltage apparatus or, worse still, permit a short between the high voltage bus bar and the

END OF CAR ROOF SHOWING BUS COUPLER, AIRBLAST BREAKER, POTENTIAL TRANSFORMER, LIGHTNING ARRESTER, AND LEAD-IN TO TRANSFORMER.



DYNAMIC BRAKE RESISTORS WITH 15 kV BUS BAR IN CENTER



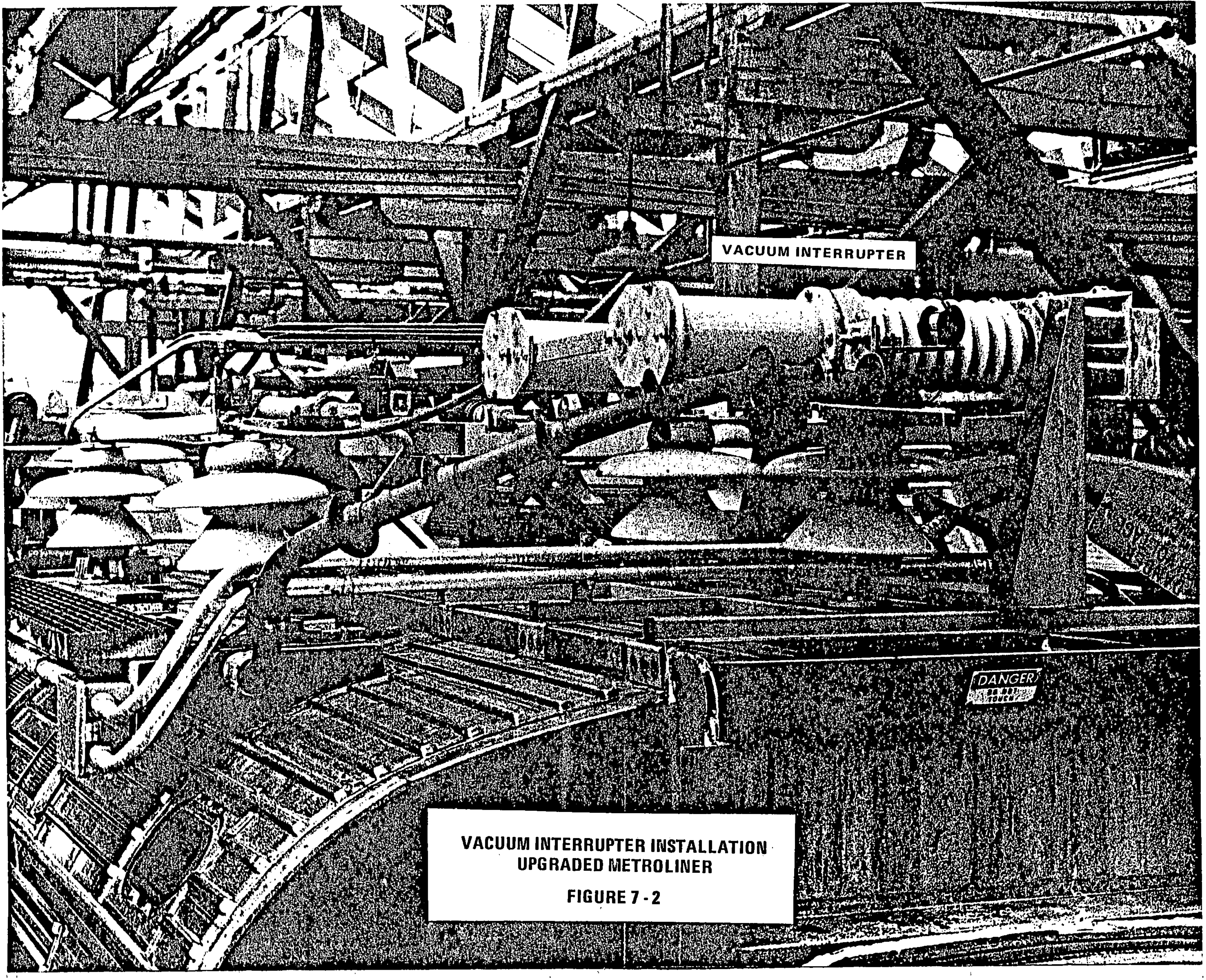
ROOF EQUIPMENT ON GERMAN ET403
FIGURE 7-1

dynamic brake resistors. In view of the history of snow problems in the NEC which has plagued the Metroliners and even affected GG-1 locomotives, such an esthetic practice should probably be avoided.

The French TGV train set, which was also reviewed as an IPEEP candidate train, has a fairly streamlined arrangement of roof mounted equipment. The power cars (or locomotives) are located at both ends of an articulated train set and have a bus cable to permit operation on one pantograph. Because of the unique dual power operation on the existing 3kv d.c. electrification within the cities and the new 25 kV, 50 Hz a.c. electrification on the high speed lines, each power car has two different pantographs.

Fairings are provided on the power car and on the adjacent car of the articulated car set to provide a windscreen ahead of and behind the pantographs to minimize turbulence. While a considerable amount of equipment including an airblast breaker and terminals must be left exposed, the installation represents the most streamlined installation of any of the IPEEP candidate trains. An insulated bus cable clamped directly to the car roofs is provided to avoid the protruding insulators normally associated with a bus bar.

Installation of roof equipment on the upgraded Metroliner is a conversion which represents many compromises. It is a "poor" example of the layout and installation of equipment because it combines the original pantograph and high voltage lead-in cable installation, the roof mounted dynamic brake resistor arrangement developed by a research and development program of 1973, and the more recent requirement for a primary circuit breaker and potential measuring device. Much of the mounting hardware is not an integral part of the structure but external add-on supports. Cable routing is circuitous because of the placement of devices in the available space and clearance restrictions. A view of the roof is given in figure 7-2 showing, in particular, the vacuum interrupter installation.



VACUUM INTERRUPTER INSTALLATION
UPGRADED METROLINER

FIGURE 7 - 2

speed allowed at that location) to open its primary circuit breaker in the interval between detection of marker M2 and entrance into the phase break. Ideally the vehicle receiver should be located in the same longitudinal position as the pantograph shoe, however, this is not practicable with any existing vehicle in the NEC. Pantographs are usually located close to truck pivot points to avoid lateral misalignment with the catenary. The truck itself precludes locating the receiver below the pantograph because of space limitations. Consideration must also be given to magnetic interference with the marker/receiver systems caused by the mass of truck components and motors.

For a single m.u. car which does not employ high voltage bus jumpers, the receiver will be located inboard of the truck at the pantograph end. This results in a longitudinal offset between pantograph and receiver of about seven feet. Other types of vehicles have greater offsets. In order to determine the location of wayside markers, allowance must be made for the "worst case" situation; that is the class of vehicle having the greatest offset. Figure 3-7, part A, illustrates a single m.u. car at a phase break showing the offset of the pantograph and receiver and the remaining distance available for "reaction" time of the VC/PB system before entering the phase break. Succeeding parts of this figure illustrate other m.u. car and locomotive pantograph and receiver arrangements.

Locomotives with closely spaced pantographs (such as the E60 and E44) present a situation nearly identical to that of the single m.u. car, as shown in part B of Figure 3-7. When a locomotive (such as the AEM-7) has widely spaced pantographs a compromise location of the receiver may be used to avoid the need for two separate sets of receivers. This is illustrated in part C of Figure 3-7.

Married pair m.u. cars which have a single pantograph mounted on one car of the pair are treated in the same manner as a single car. Part D of Figure 3-7 illustrates this arrangement. A common primary circuit breaker located on the pantograph equipped cars feeds the transformers on both cars and is controlled by one VC/PB system.

Separate cars (such as the Metroliners) which use a high voltage bus cable to permit two cars to share one pantograph present a more complicated situation. The VC/PB system can either be allowed to function separately on both cars of the bussed pair, accepting the error in pantograph location, or the VC/PB system on the car with its pantograph raised can be used to control both vehicles. The latter arrangement would require a number of additional trainline connections at the bussed ends. For this reason the first arrangement appears to be more suitable. This is illustrated in part E of Figure 3-7.

PART 4. NEC VEHICLE HIGH VOLTAGE PROTECTION AND SWITCHING CONTROL

Louis T. Klauder
and Associates

1. SUMMARY

The new electrification system for the NEC will distribute the single phase railroad loads across the three phase commercial power generation systems of the various utility companies between Boston and Washington. This introduces the need for phase to phase separation or phase breaks which is not a feature of the older single phase electrification between New Haven and Washington. The phase breaks will occur at an average of 7 mile intervals and will require that all powered vehicles be able to disconnect all propulsion and auxiliary loads while traversing each phase break.

During construction of the new electrification system, it will be necessary for all vehicles to have transformer characteristics and primary connections to permit operation on both frequencies and voltages. With the New York to New Haven segment of the NEC presently being converted to 12.5 kV, 60 Hz, this will involve three combinations of frequency and voltage requiring one transformer connection for 11 kV, 25 Hz or 12.5 kV, 60 Hz, and a second connection for 25 kV, 60 Hz.

The design of the new electrification system has progressed to the point of defining certain vehicle requirements for operation in the NEC including the application of automatic voltage change/phase break (VC/PB) negotiation systems and the application of high voltage primary circuit breakers for vehicle transformer switching and protection.

Catenary voltage detection and protective control will be required to permit connecting the transformer for the proper voltage range and to prevent application of excessive voltage to the transformer when configured for the lower voltage range.

The basis for the decision to employ on-board high voltage primary breakers in the NEC includes two considerations other than fault protection. The first is that the alternative approach of interrupting the auxiliary loads with the pantograph as it passes from the contact wire across an insulator would draw an arc which could cause erosion at the end of the wire and arc-tracking of the insulator. This would lead to higher maintenance of the catenary elements. Failure to remove propulsion power before entering the phase break would greatly aggrevate the situation. The second concern is that voltage changes will occur on the various routes on which the vehicles may operate (even after corridor conversion is complete). This will require that the vehicles be able to change transformer primary connections "on the fly". On-board catenary voltage measurement and assurance of correct transformer connection is considered mandatory prior to energizing the transformer in order to avoid apparatus damage. To comply with this requirement the transformer must be disconnected from the pantograph circuit until catenary voltage has been measured, the transformer configuration checked, and the transformer reconfigured if necessary.

Both manual and automatic negotiation of voltage changes and phase breaks have been considered. The decision to use an automatic system is based on a number of factors including the frequent occurrence of voltage changes or phase breaks at an average of 7 miles corresponding to average intervals of 4 to 5 minutes at the proposed NEC schedule. It is felt that manual operation of the voltage change/phase break system (VC/PB) at this frequency would cause an undersirable distraction which would invite error and divert attention from other operator functions.

In preparation for re-electrification of the NEC, specifications have been prepared for an automatic voltage change and phase break negotiation system. This system is being incorporated in the specifications for converting existing m.u. cars and locomotives for dual voltage/frequency operation as well as for new equipment. General Electric originally developed a VC/PB system having a control sequence which differs from the modified GE system now in the specifications. The original arrangement has been applied to the upgraded Metroliners, however, neither system has as yet been adopted. The original GE system was developed before requirements to minimize the time of auxiliary power interruption were imposed to prevent light flicker at low vehicle speeds. Comparative test simulations performed with upgraded Metroliners have demonstrated substantial reduction in auxiliary power interruption time with the modified GE system as compared with the original GE system.

A description of the operation of the automatic VC/PB system and the protective functions which it performs is presented in this paper to explain the vehicle compatability requirements imposed by the NEC Improvement Program.

In keeping with the wayside electrification design criteria, a revised arrangement of vehicle overload protection is also planned. This arrangement takes advantage of the high voltage primary circuit breaker added to each powered vehicle for phase break and voltage change switching.

Because of the expense involved in conversion for dual voltage/frequency operation, many commuter cars may remain unchanged even after the basic corridor electrification conversion is complete. These cars would remain in suburban service in Philadelphia on the former Reading lines and some of the former Pennsylvania branch lines which can be expected to remain electrified at 11 kV, 25 Hz. Certain commuter routes through Philadelphia would remain at 11 kV to permit unmodified equipment to enter the suburban stations which are separate from Amtrak. The possibility of misrouting of trains (which occurs with somewhat embarrassing frequency) could subject unconverted cars to overvoltage and overfrequency. Vehicle protection must therefore be considered for the unconverted cars.

2. INTRODUCTION

NEC Electrification Conversion

The program for replacing the present single phase 11 kV, 25 Hz electrification system in the NEC with a 25 kV, 60 Hz system operating directly from the commercial three phase 60 Hz network involves significant changes in the power distribution and the addition of vehicle-borne equipment not presently required. The distribution of the single phase loads across the three phase commercial network may place adjacent catenary substations on different phases. Thus vehicles will be required to disconnect electrical loads before crossing the insulated phase breaks in the catenary. This function will require the addition of high voltage switch gear and control equipment. In some locations a voltage change will also be involved and this will require the additional on-board function of transformer primary tap changing.

The phase breaks present a unique situation not required of the relatively simple electrical air breaks used in the original electrification for isolation of faults or maintenance sectioning. With the older section breaks, the ends of adjoining catenary sections extend beside each other for a short distance with each contact wire having a slight vertical ramp to permit the pantograph to pass from one to the other. The momentary contact path between the two wires through the pantograph is of no concern since both wires are energized in phase. With the new system, a difference in phase may be present across the electrical breaks, and it is vital that pantographs not be permitted to bridge the gap causing a phase to phase short. The proposed new phase breaks utilize two insulated spacers at each end of a short length of grounded wire to provide an isolated path for the pantograph. The middle section of wire is grounded so that if an arc is drawn by a pantograph it will discharge to ground in an easily recognized ground fault. This arrangement is illustrated in Figure 2-1.

A deviation from the objective of a total 25 kV power supply is the 12.5 kV, 60 Hz re-electrification program on the former New Haven Railroad between New York and New Haven, now in progress. This 12.5 kV electrification was planned by the states of New York and Connecticut before the inception of the NECIP program and may remain a permanent feature. In the course of upgrading work on the corridor, improvements will be incorporated in the 12.5 kV electrification which will be directed toward eventual conversion to 25 kV. Additional deviations from the 25 kV plan are numerous suburban branch lines and freight lines which are expected to remain at either 11 kV, 25 Hz or 12.5 kV, 60 Hz for the foreseeable future. These conditions along with the interim progression of re-electrification along the NEC impose requirements for dual voltage and dual frequency capabilities for virtually all powered vehicles.

To provide this dual voltage capability, the primary circuits of vehicle transformers must be arranged so that they can be connected with the proper turns ratio to provide the

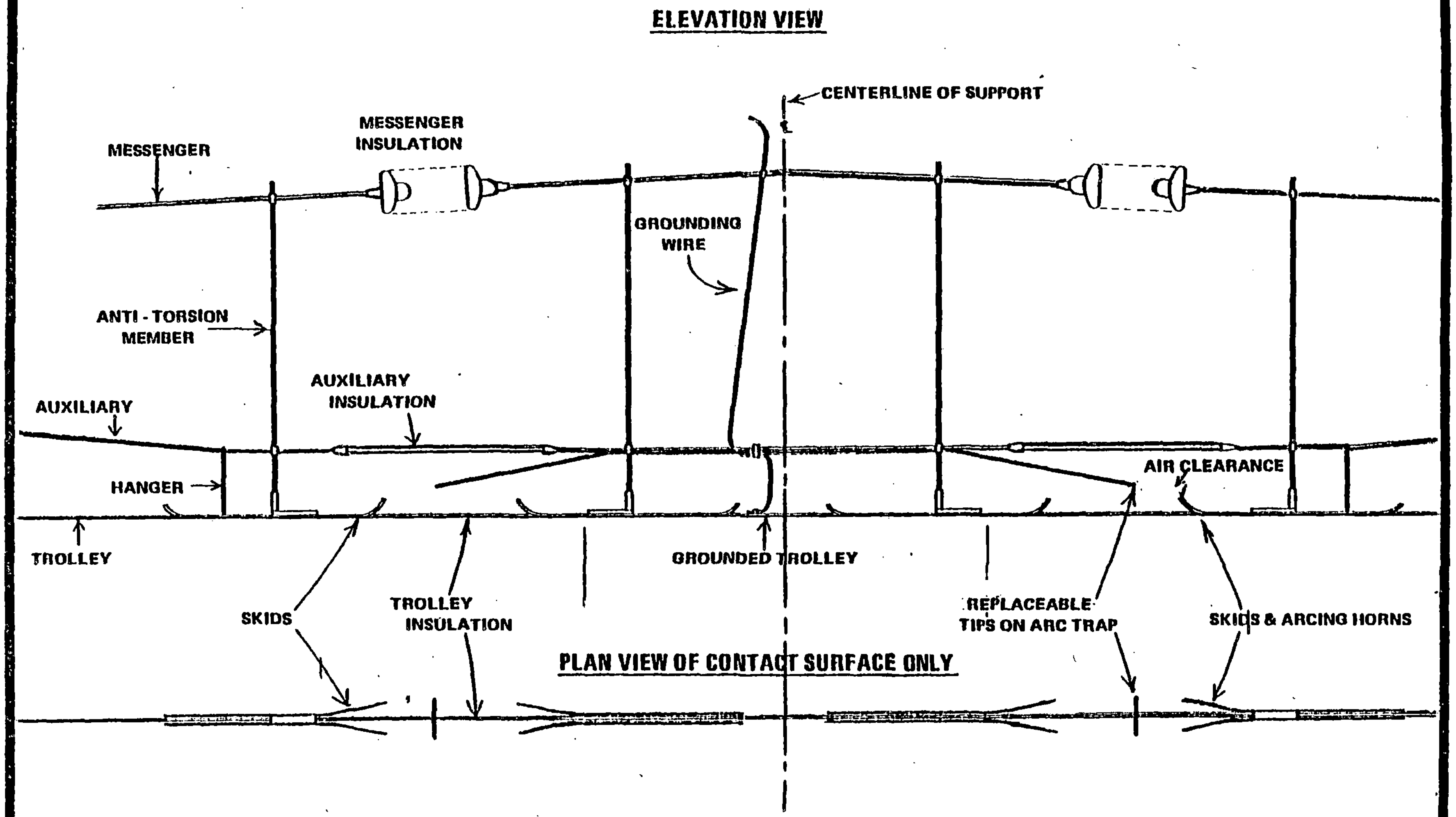


FIGURE 2 – 1
PHASE BREAK CONSTRUCTION

desired secondary voltages. Because of the simple two to one ratio of 25 kV and 12.5 kV when operating on 60 Hz, the transformers may be equipped with two primary windings having identical impedance (but different insulation levels) which are then connected in series for high voltage (25 kV) and in parallel for low voltage (12.5 kV). Because the impedances at 11 kV, 25 Hz and at 12.5 kV, 60 Hz are identical, equivalent secondary voltages are produced and no switching is required for this voltage and frequency change. Transformer switching between the high and low voltage connection is accomplished by an internally mounted tap changer.

Voltage Change/Phase Break (VC/PB) Negotiation

The new electrification arrangement will result in approximately 63 electrical breaks in the catenary between Boston and Washington at which a change in phase or voltage may occur. Operation through these section breaks will make use of an automatic control system and an on-board circuit breaker to deenergize the vehicle prior to passing between sections. Upon approaching a section break the following sequence of events must be performed by the automatic voltage change/phase break negotiation system.

- receive wayside signal
- remove traction power in a jerk limited manner
- reduce auxiliary loads
- open high voltage switch

At this point the locomotive or car is ready to cross the catenary break without the danger of having the transformer incorrectly connected for a voltage change and without drawing an arc at the pantograph. Upon entering the second catenary section the following sequence of events will be required of the vehicle-borne system.

- measure voltage on catenary
- assure correct transformer primary connection
- operate tap changer if required
- close high voltage switch
- reapply auxiliary loads
- reapply traction power in a jerk limited manner

In order to minimize the impact of a power interruption on the train while traversing a catenary break, the VC/PB negotiation sequence will be performed independently on each locomotive unit (whether operating singly or in multiple) and on each operating unit having a pantograph in a multiple-unit car consist, rather than on all cars and locomotives at the same time. This will result in a ripple effect of response through an m.u. train with each vehicle experiencing a power outage of minimum duration.

Vehicle High Voltage Circuits

Implementation of the VC/PB negotiation system requires basic changes to the primary high voltage circuits of locomotives and m.u. cars as well as the addition of control components. A change in primary overload protection will also be made, taking advantage of the new primary circuit breaker. Before addressing the individual subjects of automatic VC/PB negotiation and vehicle primary circuit protection, the revised arrangement of high voltage circuits should be introduced.

Because of space limitations, the arrangement of equipment on an m.u. car tends to be more complicated than on a locomotive and therefore will be discussed as an inclusive example. Figure 2-2 is a typical high voltage schematic for modified vehicles as presented in the specifications for "Modification of Multiple Unit Cars for Dual Voltage/Dual Frequency Operation in the Northeast Corridor". The specific car types are the Jersey Arrow I and II, and Silverliner II, III, and IV.

The arrangement of pantograph, pneumatic ground switch, lightning arrester, and current transformer remain basically unchanged from older practice. Operation of the ground switch and primary circuit breaker (vacuum interrupter in this example) for fault protection are discussed in Section 4 of this paper. Most of the more recent commuter cars also have the added protection of primary fuses as shown.

The key high voltage changes related to the NEC electrification include:

1. The addition of a primary circuit breaker.
2. The addition of catenary voltage sensing devices.
3. The conversion to a dual ratio current transformer.
4. The change to a dual voltage/frequency main transformer with integral tap changer.
5. The change of primary circuit components and clearances for 25 kV insulation level.

Additional low voltage control functions are also required in the form of the transformer tap changer actuator and the automatic VC/PB logic. Relatively minor changes in propulsion and auxiliary systems for dual frequency operation are also required to varying degrees on different vehicle types.

The operation of lightning arresters, high voltage circuit breakers, and potential and current measuring devices was covered in considerable detail in another paper, as part of the IPEEP study. It also includes an explanation of the changes to the basic electrification system.

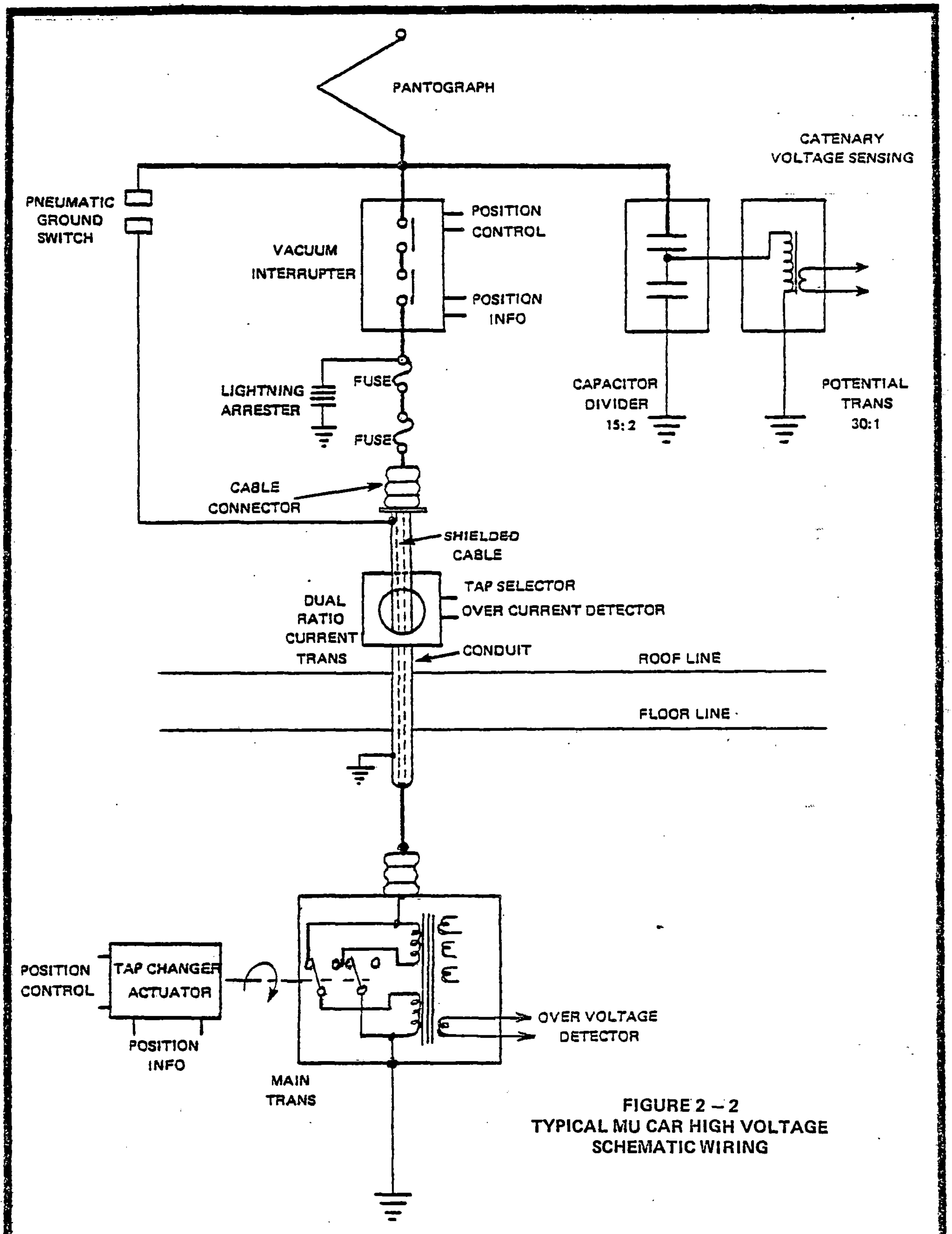


FIGURE 2 – 2
TYPICAL MU CAR HIGH VOLTAGE SCHEMATIC WIRING

3. AUTOMATIC VC/PB NEGOTIATION SYSTEM FUNCTION

General

The design of the VC/PB system must meet two very basic criteria governing operation of the system:

- Negotiation of VC's and PB's must normally be completely automatic with no action required of the engineman.
- Passengers must not be subjected to the irritation of light flicker caused by power interrupterions when operating at speeds above 15 mi/h.

The original GE system as applied to the upgraded Metroliners does not satisfy the low speed light flicker requirement which was imposed after the design had been developed.

Vehicle auxiliary systems must be altered to varying degrees (depending on the vehicle design) to permit sustained lighting during interruptions in power input to the auxiliary power supply while passing through VC's and PB's. One of two basic approaches must be taken, regardless of whether a motor-alternator set or static inverter is used. Either the lighting load must be sustained by energy stored in the auxiliary power supply apparatus, (whether in the form of rotating inertia or filter capacitor charge) or the lighting load must be transferred to a storage battery.

If energy stored in the auxiliary power supply is used it is necessary to shed all other auxiliary loads such as heating and air conditioning because of the limited energy storage capacity of the auxiliary power supply. For locomotive hauled cars with a head end power supply, the additional complication of trainlined load shedding controls is required unless battery sustained lighting is used.

In addition, several equipment protection criteria must be incorporated in the VC/PB system to minimize the chance of damage to vehicle apparatus and to the catenary.

- Redundant detection of wayside markers must be provided.
- Continuous voltage measurement and assurance of proper vehicle primary circuit configuration must be performed on each vehicle.
- Self diagnostic logic fault detection must be provided to detect VC/PB system errors.

Operation of the modified GE automatic VC/PB system which is included in vehicle conversion specifications differs from the original GE system applied to the Metroliners. The modified GE system is described here in detail followed by a brief summary of the original GE system. Test data contrasting the response times of both systems is also presented.

Modified GE System

The modified GE automatic VC/PB system utilizes wayside markers which are detected by sensors on each vehicle which has a pantograph. At each phase break there are four marker locations arranged symmetrically to permit operation in either direction. For convenience in describing the function of the vehicle system, the markers are designated as M1, M2, M3, and M4 in the direction of travel. M1 and M4 are identical as are the M2 and M3 markers. The M1 marker is an advance marker to permit gradual removal of power while approaching the phase break while the M2 marker is the signal to open the vehicle primary circuit breaker. The M3 marker is the signal to reclose the primary circuit breaker after the catenary break while the M4 marker serves as a reference to assure that the marker sequence has been detected properly.

The type of marker to be used has not as yet been established. Inductive coupling devices are being considered, however, initial preference has been indicated for fixed field magnets on the wayside which can be detected by vehicle sensors.

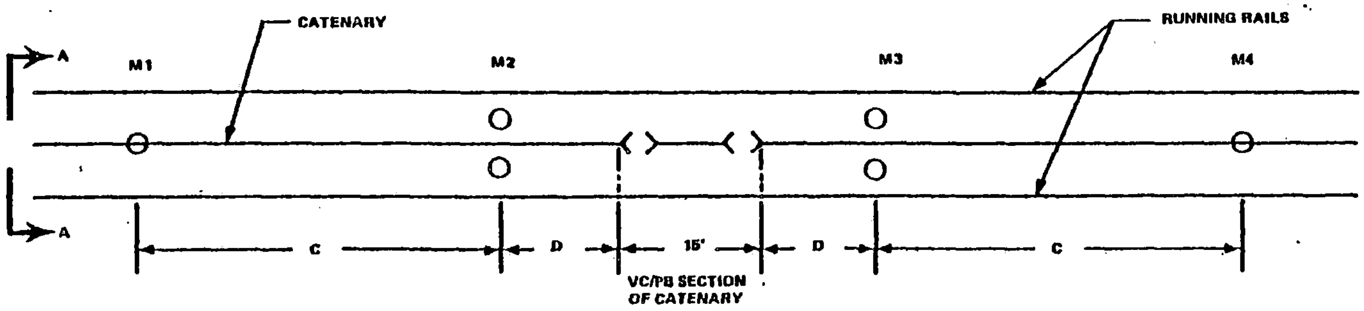
The markers and carborne sensors are positioned in such a manner as to provide distinct patterns for the M1/M4 markers and the M2/M3 markers. The M1/M4 marker has a single fixed field magnet located on the center of the track. The M2/M3 marker is also located between the rails and has two magnets abreast located near each rail. Sufficient space is provided between the paired magnets of the M2/M3 marker to preclude misreading by the vehicle sensor for the M1/M4 markers. The use of two magnets for the M2/M3 sensors also provides redundant detection of the M2 marker. This is very important since M2 has the most critical command; it opens the primary circuit breaker to protect the transformer against an overvoltage condition at a voltage change and to protect the catenary break against arcing.

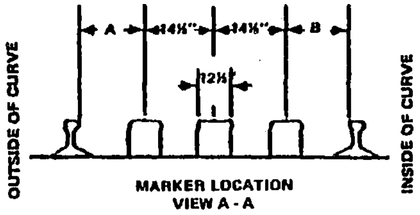
Location of the VC/PB markers is shown schematically in Figure 3-1. The distance from the catenary break to the markers will vary at different locations, depending on the maximum allowable track speed. The markers will be shifted slightly to the inside on curves to compensate for the chord effect.

In operation, the VC/PB control also performs a number of check functions to guard against error and protect the vehicle equipment. Failure to detect markers in the correct sequence or detecting only one of the two magnets at the M2 and M3 markers are among the possible errors.

There are also provisions to reclose the primary circuit breaker when operating at low speed before reaching the M3 marker in order to minimize the time of power interruption.

The logic of the automatic VC/PB system operates in a marker sequence count of four steps referred to as "relative location values". Steps "1", "2", and "3" correspond to detection





Maximum Allowable Track Speed	C FEET	D FEET
15	15	44
30	27	48
60	53	60
90	80	71
110	100	79
130	100	88
155	100	88

ALL DIMENSIONS APPROXIMATE

DEGREE OF CURVE	A INCHES	B INCHES
TANGENT	13–3/4	13–3/4
0° 30'	13–7/8	13–5/8
1°	14–1/16	13–7/16
1° 30'	14–3/16	13–5/16
2°	14–3/8	13–1/8
2° 30'	14–1/2	13
3°	14–5/8	12–7/8
3° 30'	14–13/16	12–11/16
4°	15	12–1/2
4° 30'	15–1/8	12–3/8
5°	15–1/4	12–1/4

FIGURE 3 – 1
VC/PB MARKER ARRANGEMENT

of the M1, M2, and M3 markers, while step "0" is the reset condition and occurs when M4 is passed, preparing the system for the next phase break or voltage change sequence.

At a voltage change or phase break the VC/PB logic always performs a catenary voltage measurement before closing the primary circuit breaker in order to determine whether the voltage has changed and operate the transformer primary tap changer as required.

The VC/PB logic also checks to assure that the primary circuit breaker opening devices are prepared for operation prior to closing the breaker. In the case of solenoid operated vacuum interrupters which use capacitors to operate the solenoids, the VC/PB logic checks to assure that the opening capacitors are charged before allowing the breaker to close. Most airblast breakers have an internal interlock which precludes closing the breaker unless the reservoir is charged.

The VC/PB control logic is designed to detect faults of three types, numbered in the order of increasing severity:

Type 1 fault - an error in detecting an M1 or M4 marker.
Type 2 fault - an error in detecting an M2 or M3 marker.
Type 3 fault - failure of the primary circuit breaker to open or detection of an overvoltage (measured on the secondary windings of the main transformer).

A VC/PB fault indication trainline is provided to warn the engineman when a failure has occurred in the train. A system of local indicator lights on each operating unit provides information on the status of the logic and identifies the type of fault.

The consequences of a type 1 fault are not very significant because detection of the M2 and M3 markers in the proper sequence will still permit safe opening and closing of the primary circuit breaker. A type 2 fault at a phase break could result in a power arc upon entering a catenary break. If an increasing voltage change is present, a type 2 fault would produce a type 3 fault by subjecting the transformer and all connected loads to twice their rated voltage. A type 3 fault involving failure of the primary circuit breaker to open on command would also produce an arc into the catenary break and could subject the transformer to overvoltage as well. The response of the system to the various faults will be discussed later.

Figure 3-2 illustrates the function of the VC/PB control logic in relation to the rest of the vehicle. The vehicle primary circuits and protective relaying are shown on the left while the interfaces with the VC/PB control logic are shown in the center. Information relayed to the logic includes catenary voltage and switching device position information. Commands issued to the switching devices are also identified. Interfaces between the logic and the trainline circuits and wayside marker receivers are shown to the right of the logic.

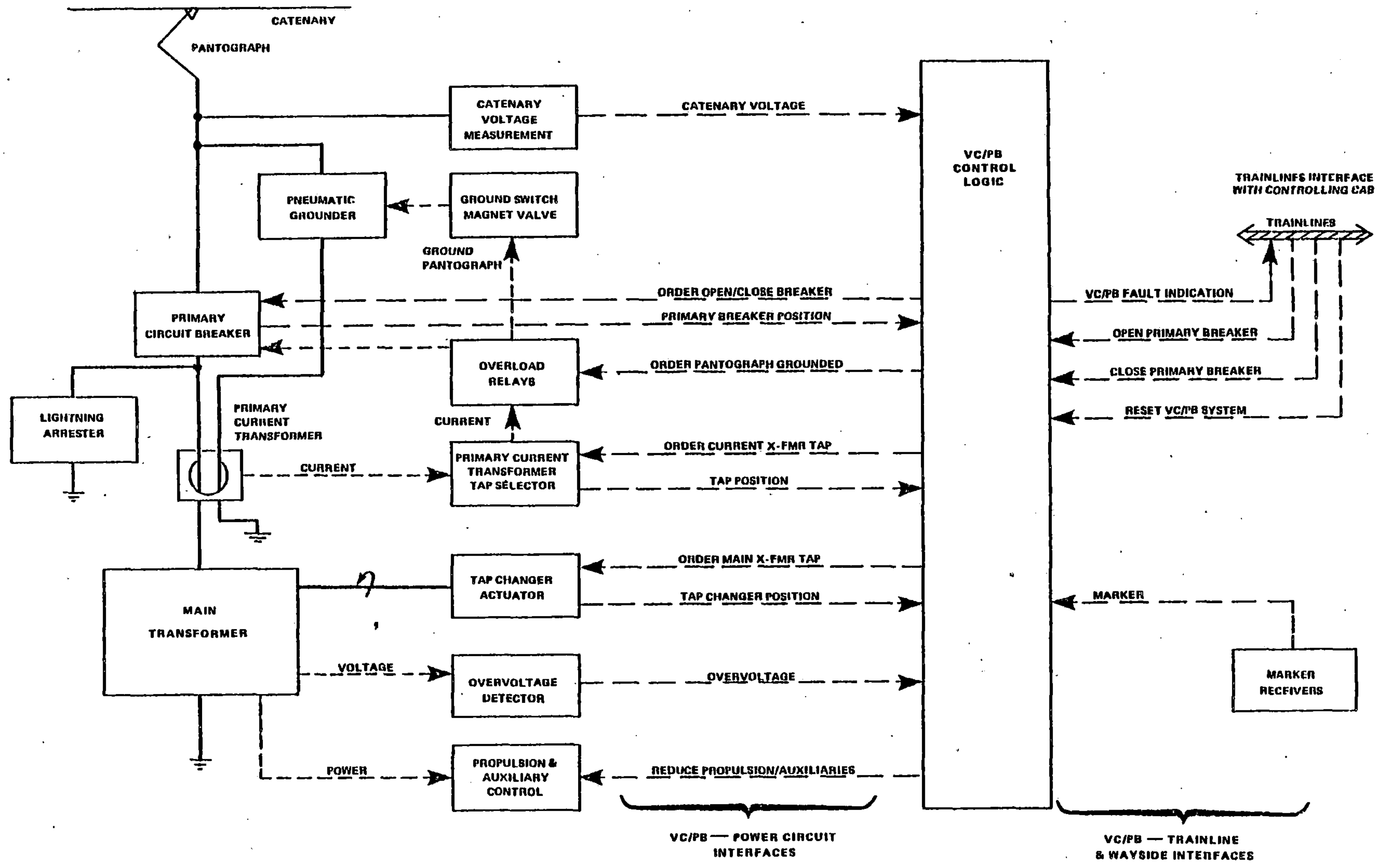


FIGURE 3 – 2 VC/PB SYSTEM

System Operation

M1 Marker Response

As a train approaches a VC/PB it encounters the advance marker M1 and the VC/PB control logic sequences from the reset or "0" location value to "1". At this time the propulsion system is instructed to reduce power in a jerk-limited manner. Unless lighting loads on passenger trains can be sustained by a storage battery it will be necessary to shed other auxiliary loads so that rotating inertia of rotary converters or the charge on filter capacitors in solid state inverters can sustain the lighting and avoid the irritation of light flicker to passengers. The location of the M1 marker will vary depending on the allowable track speed in order to provide sufficient time to reduce power but avoid a prolonged loss of propulsion.

Failure to detect the M1 marker will not be determined until the M2 marker is reached, at which time the location value will step from "0" to "2" and the VC/PB error indication trainline will be energized, turning on a light in the cab to alert the engineman. A local type 1 fault indicator will also light to identify the offending unit in a multiple unit consist of cars or locomotives. The system will continue to function but the warning light will remain lighted until the system is reset, either locally or by trainline.

M2 Marker Response

The second marker, M2, is located close to the actual catenary break, with the distance determined by the allowable track speed. Upon detection of the M2 marker the VC/PB location value will step from "1" to "2". In the event of a failure to detect marker M1, it will skip from "0" to "2". Location value "2" commands the primary circuit breaker to open and initiates several timing and catenary voltage detection functions in the VC/PB logic. The logic makes no assurances or checks prior to opening the breaker since the open condition is inherently safe.

M3 Marker Response or Phase Break Detection

The primary circuit breaker will normally remain open until marker M3 is sensed indicating that the catenary break has been passed. At train speeds below 30 mi/h this could result in a prolonged interruption of power on the vehicle because the M3 marker is located at a distance past the phase break sufficient to permit its use as the M2 marker for trains running in the opposite direction. For this reason provision is made to detect the live catenary on the exit side of the phase break without waiting for M3.

This is accomplished with a "minimum breaker open time" timer which starts after detection of the M2 marker, waits for 4 seconds (±0.5 second) and then looks for a catenary "no voltage" condition of at least 0.3 seconds indicating that a voltage or phase break has occurred. The timing sequence then commands reclosing the high voltage breaker upon sensing catenary voltage and assuring correct tap changer position without waiting for the M3 marker. This is illustrated in example "A" in Figure 3-3.

Because of the possibility of a momentary loss of catenary power on the vehicle due to a pantograph bounce or substation outage and reset occurring after detection of the M2 marker but before the catenary insulation break has been reached, there is a chance that the VC/PB control system can be "fooled". The VC/PB logic could mistakenly identify either the resumed pantograph contact with the catenary or the restoration of power to the catenary as the "other (exit) side" of the phase break. If there is an increasing voltage change across the break, this could be damaging.

For this reason a second timing sequence begins and is in effect until the M3 marker is passed, confirming completion of the voltage change or phase break and providing a second chance to correct an error in detection. If, during the interval between reclosing the breaker and sensing M3, there is an interruption of catenary voltage for more than 0.025 second (±0.008 second) the primary breaker is commanded to open again. Prompt reopening of the breaker will prevent the transformer from being subjected to overvoltage in the event that the first closure was in error.

This 0.025 second time interval is very short and may conceivably result in some nuisance tripping of the primary breaker due to pantograph bounce. However, such a short time is necessary because this interval combined with the breaker opening time must not exceed 0.233 second. This is the time that will elapse in crossing a catenary break at a speed of 29 mi/h, and is therefore the minimum time available to open the breaker. The likelihood of a nuisance trip because of pantograph bounce is not very great at speeds below 29 mi/h and is not considered to be significant.

Overlapping protection is provided at speeds greater than approximately 22 mi/h by the "minimum circuit breaker open time" timer (which initiated the timing sequence). The 4 second timer interval is the time required to cover the distance from the M2 marker to the exit side of the phase break at speed over 22 mi/h thus precluding operation of the phase break detection sequence over this speed.

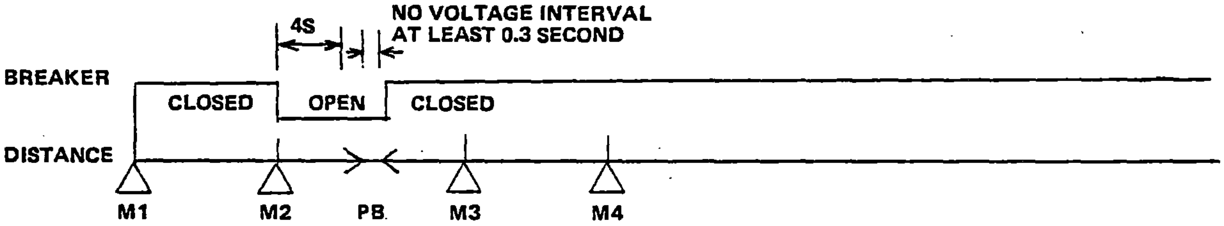
The vehicle speed at which the VC/PB logic shifts between M3 marker control and phase break detection control varies with the distance between the phase break and the M3 marker. The distance from marker M3 to the phase break (given in Figure 3-1) varies according to the maximum allowable speed of the track. The vehicle speed at which the VC/PB logic shifts its mode of operation will increase up to a maximum of 30 mi/h in proportion to increasing track speed.

FIGURE 3 – 3

MINIMUM CIRCUIT BREAKER OPEN TIMER FUNCTION

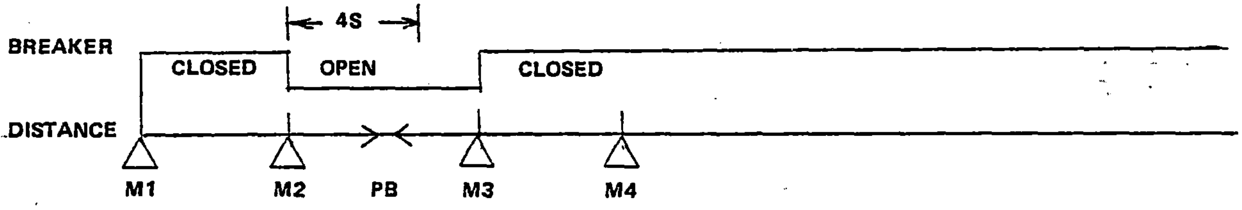
A. **15 mi/h**

VEHICLE DOES NOT REACH BREAK IN 4 SECONDS, DETECTION OF BREAK BY NO VOLTAGE CONDITION GOVERNS RECLOSURE.



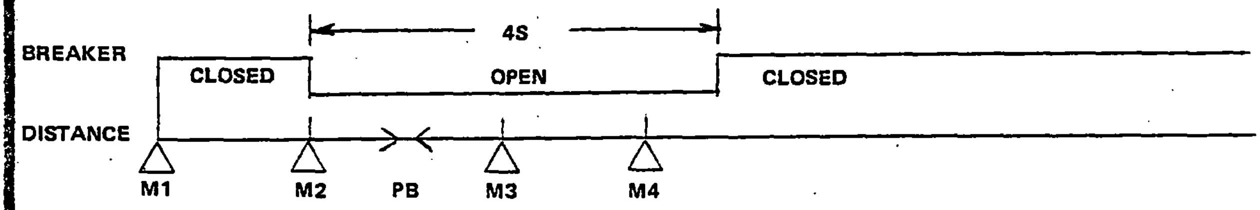
B. **30 mi/h**

VEHICLE PASSES BREAK WITHIN 4 SECONDS, MARKER M3 GOVERNS RECLOSURE.



C. **60 mi/h**

LOGIC HAS RESET AND VEHICLE HAS PAST MARKER M4 BEFORE 4 SECONDS HAVE ELAPSED, TIMER GOVERNS RECLOSURE.



When the VC/PB logic is controlled by the M3 marker, the primary breaker will close as soon after detection of the M3 marker as the "Minimum Breaker Open Time" timer will permit. Figure 3-3, examples "B" and "C", illustrate this function. In "B", the train is moving at 30 mi/h and has passed the phase break within 4 seconds but has not yet reached marker M3. The breaker will therefore remain open until marker M3 is passed. Example "C" represents a train traveling at a speed of 60 mi/h or more in which case both the M3 and M4 markers are passed within 4 seconds. The VC/PB logic will progress in accordance with the marker sequence, however the breaker will remain open until the 4 second interval has elapsed.

It should be noted that the 4 second delay is also slightly longer than the time required to reset or recharge the circuit breaker for re-opening. The reset or recharge sequence is necessary in order that the circuit breaker will be prepared to trip in the event of a fault when it is reclosed. For this reason there is also a minimum breaker open interval imposed by the response time of the breaker mechanism and it is not possible to reclose the breaker immediately after detecting the M3 marker when traveling at high speeds.

Another separate timing function in the VC/PB logic serves to assess a possible failure to detect the M3 marker by measuring a time interval of approximately 90 seconds (adjustable from 30 to 120 seconds). If the relative location value does not progress past "2" in this interval as a result of sensing of M3 or recognizing the phase break (by no voltage), the VC/PB control will reset to "0" and register a type 2 fault. This time interval is short enough to prevent the sensing of the M2 marker at the next phase break from being misinterpreted as the M3 marker. Such an error would result in reclosure rather than opening of the primary breaker at M2 before entering the second catenary break, causing a power arc and possible voltage mismatch.

Circuit Breaker Closure Logic

In normal operation at speeds of 30 mi/h or more the primary circuit breaker will remain open until the vehicle has passed the catenary electrical break and detected marker M3. At this point the VC/PB logic steps to location "3" and instructs the primary circuit breaker to reclose subject to the following mandatory and limited conditions to assure safety and protection of the vehicle:

Mandatory Conditions for Circuit Breaker Closure

- No type 3 fault may be present. (A type 3 fault is a failure of the primary circuit breaker to open or detection of an overvoltage on the main transformer.)
- The breaker reopening mechanism or circuitry must be prepared to trip in the event of a fault on reclosure.

- The "Minimum Breaker Open Time" interval of 4 seconds (plus or minus 0.5 second) must have elapsed since the primary circuit breaker last opened in order to preclude reclosure of the breaker prior to reaching the next VC or PB when traveling between about 20 mi/h and 30 mi/h. (This timing is not effective at speeds below about 20 mi/h, however overlapping protection is also provided in the range up to 29 mi/h by the timing circuit which looks for catenary power interruptions greater than 0.025 seconds in the interval between reclosure and sensing marker M3. This overlap allows for tolerances in the timing circuits and differences in marker spacing.)

- Voltage must be present on the pantograph and must be satisfactorily identified as either "low" (> 5 kV but < 15 kV) or "high" (> 15 kV).

- The transformer tap changer and primary current measuring devices must be configured for the proper voltage.

- There must not be a trainline command present to open the primary breaker. (Any opening command will prevent closure.)

- The local primary breaker opening switch on a particular vehicle must not be in the open position. (Any open command will prevent closure.)

<u>Limited Conditions for Circuit Breaker Closure</u>

- The relative location logic and related timers must progress to <u>one</u> of the following <u>three</u> conditions:

  a. The relative location logic must change to "3" indicating that the other side of the phase break has been reached (Normal sequence).

  or:

  b. There has been an interval of 0.3 seconds with no voltage sensed while the relative location logic is still at "2" (which will allow primary circuit breaker reclosure upon reaching live catenary). (Normal sequence at speeds below 29 mi/h.)

  or:

  c. The relative location logic must reset to "0" by manually resetting the control system. (Manual override)

- The VC/PB control system must not be "locked out" by an excessive count of type 2 faults. (Type 2 faults involve errors in detecting M2 and M3 markers. A counter in the VC/PB logic will keep track of the occurrence of type 2 faults. When the number of faults exceeds a preset variable value, the primary circuit breaker will be "locked out" in the open position awaiting corrective maintenance.)

- The VC/PB system must not have had a preset number of type 2 faults since the last time the control was reset, either locally or by the reset trainline. (The number of unreset type 2 faults may be set at either 0 or 1.)

It should be noted that the last three listed limited protective functions involving the relative location values and the count of type 2 faults can be overridden by the Manual Reclose Circuit Breaker Trainline. Operation of the manual controls will be discussed later. Actuation of the manual close command while moving into a catenary break could result in a power arc into the catenary break but does not override any of the basic voltage connection and other safety interlocks.

M4 Marker Response

The conclusion of the normal operating sequence is the sensing of the M4 marker which resets the relative location value to "0". The relative location value will also be reset to "0" whenever the VC/PB reset trainline is energized or whenever the primary circuit breaker close trainline is energized. Use of either manual command while moving in a phase break or voltage change can result in a power arc into the catenary break.

Failure to detect the M4 marker will result in the relative location logic remaining in location "3". If the M1 marker of the next phase break is the next center marker which is detected, the relative location will reset to "0". Subsequent detection of the M2 marker out of apparent sequence will step the relative location to "2" and register a type 1 fault. The type 1 fault is indicated by the local indicator light on the VC/PB control and in the operator's cab by energizing the VC/PB error trainline.

Failure to detect both the M4 marker and the next M1 marker will result in the relative location value changing directly from "3" to "2" and will also register a type 1 fault on the local VC/PB control and in the cab.

The most serious failures which can occur are the two, type 3 fault conditions involving failure of the primary circuit breaker to open or an overvoltage condition. The response to a type 3 fault will vary somewhat depending on the primary overload protection arrangement on the locomotive or multiple unit cars. The arrangement called for in m.u. car conversion specifications requires operation of the pneumatic ground switch which grounds the pantograph. After the substation circuit breaker opens, the pantograph is lowered to isolate the fault. This sequence of fault protection is discussed in more detail in Section 4.

Newer locomotive designs do not incorporate a ground switch. In this case the response to an overvoltage condition is restricted to opening the primary circuit breaker. Failure of the breaker to open has no automatic recourse.

Trainline Controls

There are three basic trainline controls provided in each operating cab which permit "opening" and "closing" all primary circuit breakers and "resetting" the automatic controls of all cars. Lights indicating the status of the open and close trainline switches and a trainline fault indicator are also provided. The basic functions of the controls are as follows:

- Primary Circuit Breaker Open and Close Switch. This control may use one or two switches but is arranged so that all breakers may be opened in one step. To guard against inadvertent operation closing the breakers, two distinct steps are required for closing. The open command immediately opens all breakers while the close command will be subject to the following Mandatory Conditions on a local car basis.

    - No type 3 fault may be present
    - The breaker reopening mechanism must be prepared to trip in the event of a fault.
    - The "Minimum Breaker Open Time" interval of 4 seconds must have elapsed.
    - Voltage must be present on the pantograph and identified as "low" or "high".
    - The transformer tap changer and primary current measuring devices must be configured for the proper voltage.
    - There must not be a trainline command present to open the primary breaker.
    - The local primary breaker opening switch must not be operated.

  Provision is also made to seal the close switch. In normal operation neither open nor close trainlines are energized and the individual VC/PB systems function independently.

- VC/PB System Reset. This is a trainline reset function which resets the relative location value to "0" in all operating units in the train, thus causing the primary circuit breakers to close if the Mandatory Conditions (listed above) are met. Resetting will cancel the register of type 1 faults and reset type 2 faults up to the preset value. Any VC/PB system which has been locked out by an excess of type 2 faults or by a type 3 fault will not reset. Use of the reset switch requires caution because resetting between an M2 marker and the catenary break will result in a power arc drawn into the break.

The indicator lights in the cab have the following functions:

- Primary Circuit Breaker Open and Close Trainline Lights: These lights will be lighted when the open or close switches are in the respective positions. In normal operation, neither command will be given and both lights will be out.
- Fault Light: The fault light will be lighted if any operating unit in the train has experienced any of the following fault conditions:
  - a type 1 fault since last reset
  - a type 2 fault since last reset
  - a VC/PB lockout caused by an excess count of type 2 faults or one type 3 fault
- A lamp test switch will also be provided for checking the indicator functions.

Local Controls

To facilitate diagnostic efforts on the road as well as maintenance testing, the VC/PB control system on each operating unit will have a control panel with the following local controls:

- Primary Circuit Breaker Open Switch - Operation of this momentary contact switch opens the primary circuit breaker and resets the minimum open time timer (4 seconds). The relative location logic continues to function and will resume control after the switch is released.
- Primary Circuit Breaker Close Switch - momentary contact. Operation of this switch resets the relative location value to "0" and closes the breaker if the Mandatory Conditions (discussed under the trainline close function) are met.
- Reset VC/PB System. Operation of this switch also resets the relative location value to 0 and will cause the primary breaker to reclose if the mandatory conditions are met. Resetting will cancel the count of type 1 faults and reset type 2 faults up to a predetermined total. This switch will be sealed because operation between an M2 marker and the catenary break will cause a power arc to be drawn into the break.

- Reset Type 3 Fault. This switch resets the inhibiting condition after a type 3 fault involving either failure of the primary breaker to open on command or detection of an overvoltage condition. It does not reset the overload and protective relays which ground and lower the pantograph. (These are discussed in Section 4 of this paper.)

- Set Count Of Type 2 Fault Counter. This control resets the number of type 2 faults counted by the VC/PB logic. The counter can count up to 10 faults and is also reset by successful negotiation of a VC/PB sequence. This count is not reset by the VC/PB system reset controls.

- Set Number Of Type 2 Faults Permitted Before Lockout. This is an adjustable value from 1 to 10 which initially will be set at 3. When the number of type 2 faults exceeds this number, the VC/PB logic continues to function normally except that primary circuit breaker operation is locked out in the open position.

A display of lamps and counters is also provided to monitor the key elements in the VC/PB logic. These generally will include the following items:

- Status of commands to remove propulsion power and shed auxiliary loads except lighting.

- Pantograph voltage measurement status, "zero", "low", or "high".

- Primary circuit breaker status, "open" or "closed".

- Status of fault conditions.

    - type 1 fault since last reset
    - type 2 fault since last reset
    - elapsed count of type 2 faults up to 10
    - inhibition of automatic primary circuit breaker closure caused by a preset number of type 2 faults since last reset or a total number of type 2 faults in excess of a predetermined value.
    - type 3 fault

- A lamp test circuit will also be provided for checking all indicator light functions.

Original GE System

The original GE system for automatic VC/PB negotiation differs principally in that it removes power and opens the primary breaker following detection of marker M1 and recloses the breaker only upon detection of marker M3. The M2 and M4 markers serve purely to provide redundant detection of markers M1 and M3. There is no timing sequence to enable detection of the phase break itself since the original system was developed prior to the imposition of the requirement to minimize auxiliary power interruption at low speed to prevent light flicker. Failure to detect any marker will result in a VC/PB negotiation system logic fault which will open the primary breaker and require manual resetting.

Like the modified system, the arrangement of wayside markers in the original GE system is also symmetrical around the phase break for bi-directional traffic but differs in that single markers are utilized at each of the four marker locations rather than a combination of single and double markers. Right and left marker orientation with respect to the track center line distinguishes between the controlling markers (M1 and M3) and the redundant or "check" markers (M2 and M4). Figure 3-4 illustrates the marker arrangement and the negotiation sequence.

A tabulation of marker location distances has not been developed for the original GE system. Since both systems must consider the time required to remove propulsion and the pantograph/receiver relationship, the marker locations can be assumed to be virtually identical.

A brief summary of the operating sequence of the original GE system follows.

M1 and M2 Marker Responses

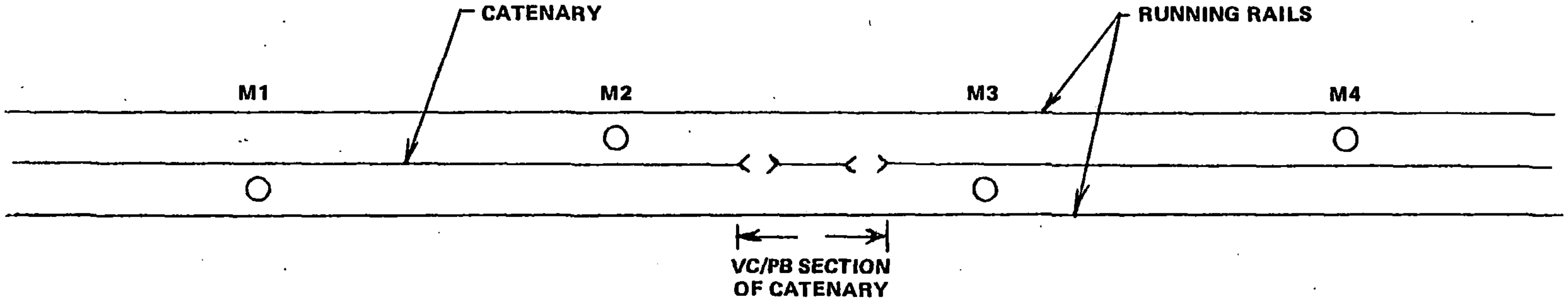
Upon detection of the M1 marker, the propulsion system reduces power in a jerk limited manner and all auxiliary loads except lighting are removed then, after a one second delay, the primary breaker is opened.

The M2 marker serves purely as a check to assure detection of marker M1. Failure to detect the M1 marker will result in a logic fault when M2 is detected and the primary breaker is opened without the benefit of jerk limited propulsion power removal. Failure to detect the M2 marker between M1 and M3 will also result in a logic fault.

The M1 marker also starts a timer which is set to run from 70 to 90 seconds, during which time the entire VC/PB sequence must be completed. Failure to complete the sequence in this interval will result in a logic fault.

M3 and M4 Marker Responses

The primary breaker remains open until the M3 marker is detected at which point it will close after identification of pantograph voltage, assurance that the transformer is configured correctly and recharging of the breaker operating circuitry. The voltage measurement and vehicle circuit configuration logic is in effect at all times with redundant protection provided by an overvoltage relay on the transformer secondary winding.



NORMAL MARKER RESPONSE SEQUENCE

M1 – SHUT DOWN PROPULSION AND AUXILIARY LOADS. OPEN PRIMARY CIRCUIT BREAKER IN 1 SECOND.

M2 – CHECK DETECTION OF M1 MARKER.

M3 – CLOSE PRIMARY CIRCUIT BREAKER AFTER ASSURING PROPER VOTLAGE CONFIGURATION.

M4 – CHECK DETECTION OF M3 MARKER.

FIGURE 3 – 4

GE VC/PB MARKER ARRANGEMENT AND SEQUENCE

Failure to detect the M3 marker in sequence between M2 and M4 will result in a logic fault. Failure to detect the M4 marker after detecting the M3 marker within the 70 to 90 second total time interval will also result in a logic fault.

Comparison

Tests have been run with upgraded Metroliners to determine the behavior of the propulsion and auxiliary loads when subjected to the VC/PB operating sequence using both the modified GE system in the vehicle modification specifications and the original GE system. Particular emphasis was placed on the point at which the motor-alternator slows sufficiently to cause flickering of the fluorescent lights. Light flicker is particularly annoying to passengers, and the avoidance of this irritation has become an important criteria in the design of vehicle auxiliary systems for phase break negotiation. The 15 mi/h speed permitted under a "restricting" signal has been tentatively designated as the slowest speed required for phase break negotiation without light flicker.

Figures 3-5 and 3-6 contrast the interruption in primary power supply to the vehicle transformer caused by the time that the primary circuit breaker is open. Marker locations corresponding to a high speed phase break were used and are shown along the horizontal distance scale. The elapsed time from the first marker is plotted vertically. The lines plotted for several speeds have a gap which represents the time that the primary breaker is open. The points at which light flicker occurs are indicated approximately 7 seconds after opening the primary breaker. It should be noted that temporary auxiliary load shedding modifications were incorporated into the test Metroliner to prolong the lighting.

Light flicker occurred with the original system when negotiating phase breaks at speeds of 26 mi/h or less with complete loss of lighting at 18 mi/h. In contrast, the modified system was able to operate satisfactorily at 15 mi/h with flicker noted only in a 10 mi/h test.

The two dashed lines across the top of both Figures 3-5 and 3-6 represent the points at which the air conditioning system and propulsion system are restored to full operation following the interruption in vehicle primary power. The air conditioning system is the last of the auxiliary loads to be reapplied to the motor alternator following its restarting sequence. Restoration of propulsion is also dependent on the M.A. restarting sequence since the equipment cooling blowers are driven by the M.A. The propulsion control is interlocked with the blowers to assure adequate cooling air.

Vehicle Receiver Location

The location of wayside markers and vehicle receivers must assure that every vehicle has sufficient time (at the maximum

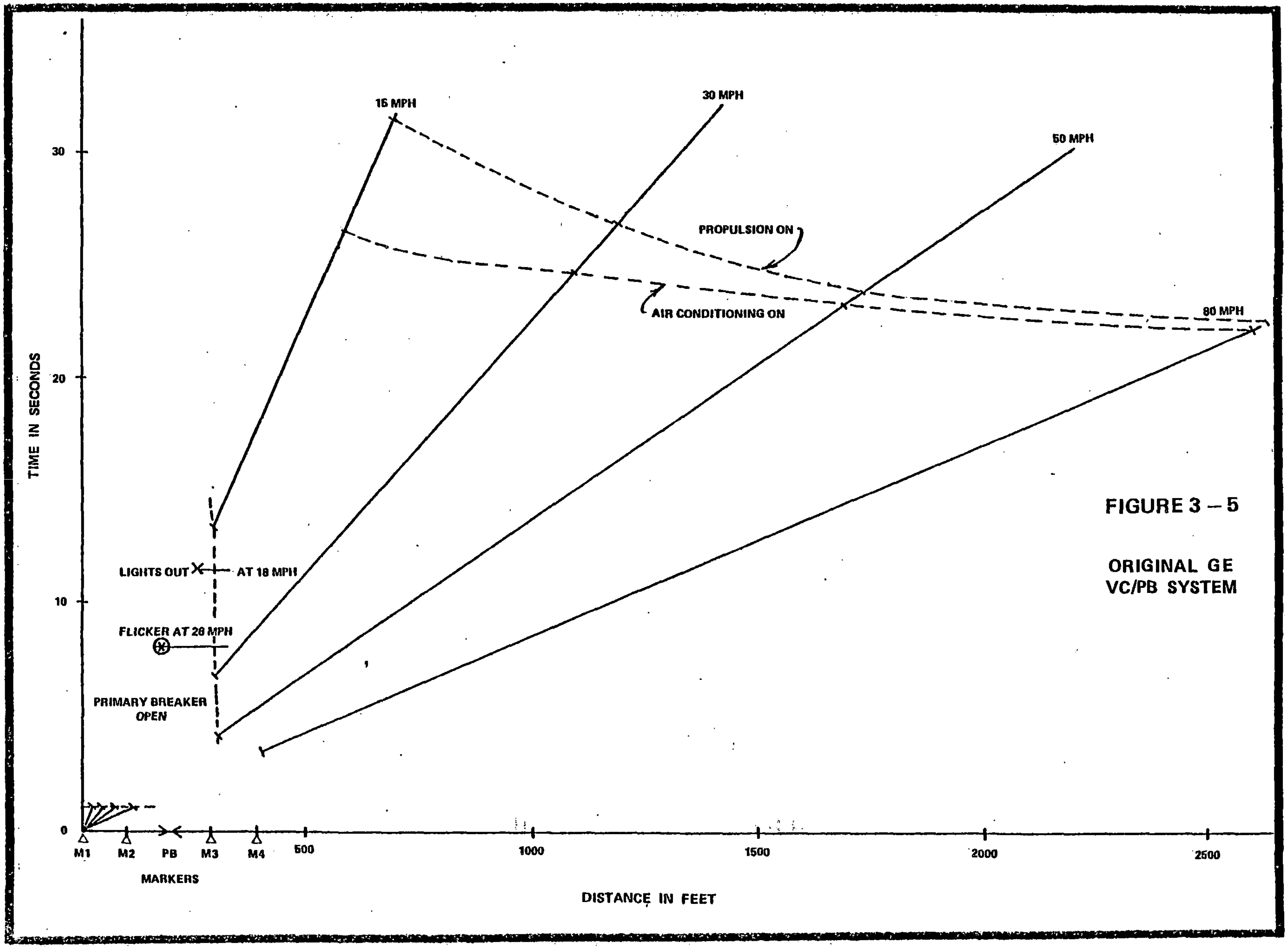


FIGURE 3 – 5

ORIGINAL GE VC/PB SYSTEM

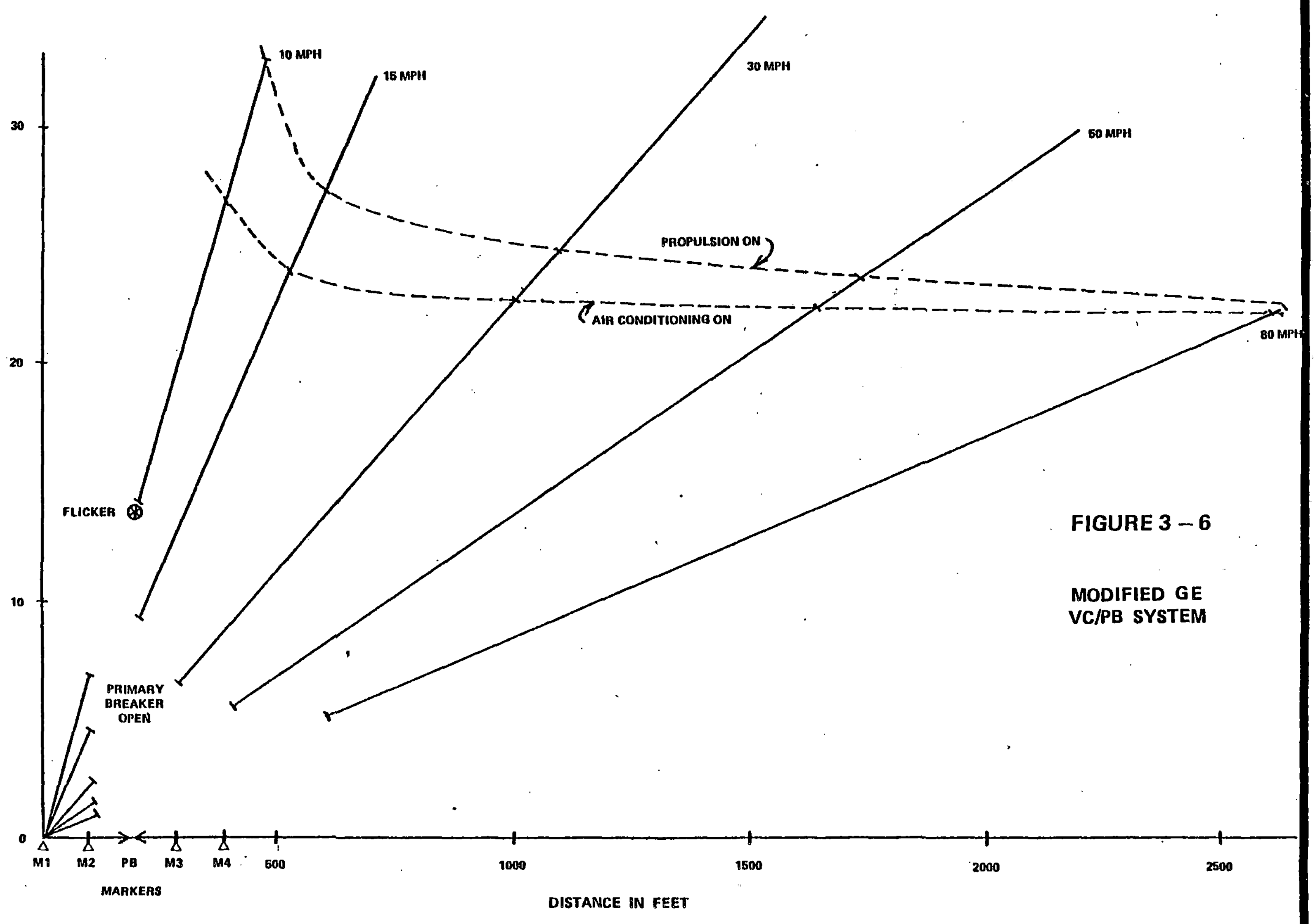


FIGURE 3 – 6

MODIFIED GE VC/PB SYSTEM

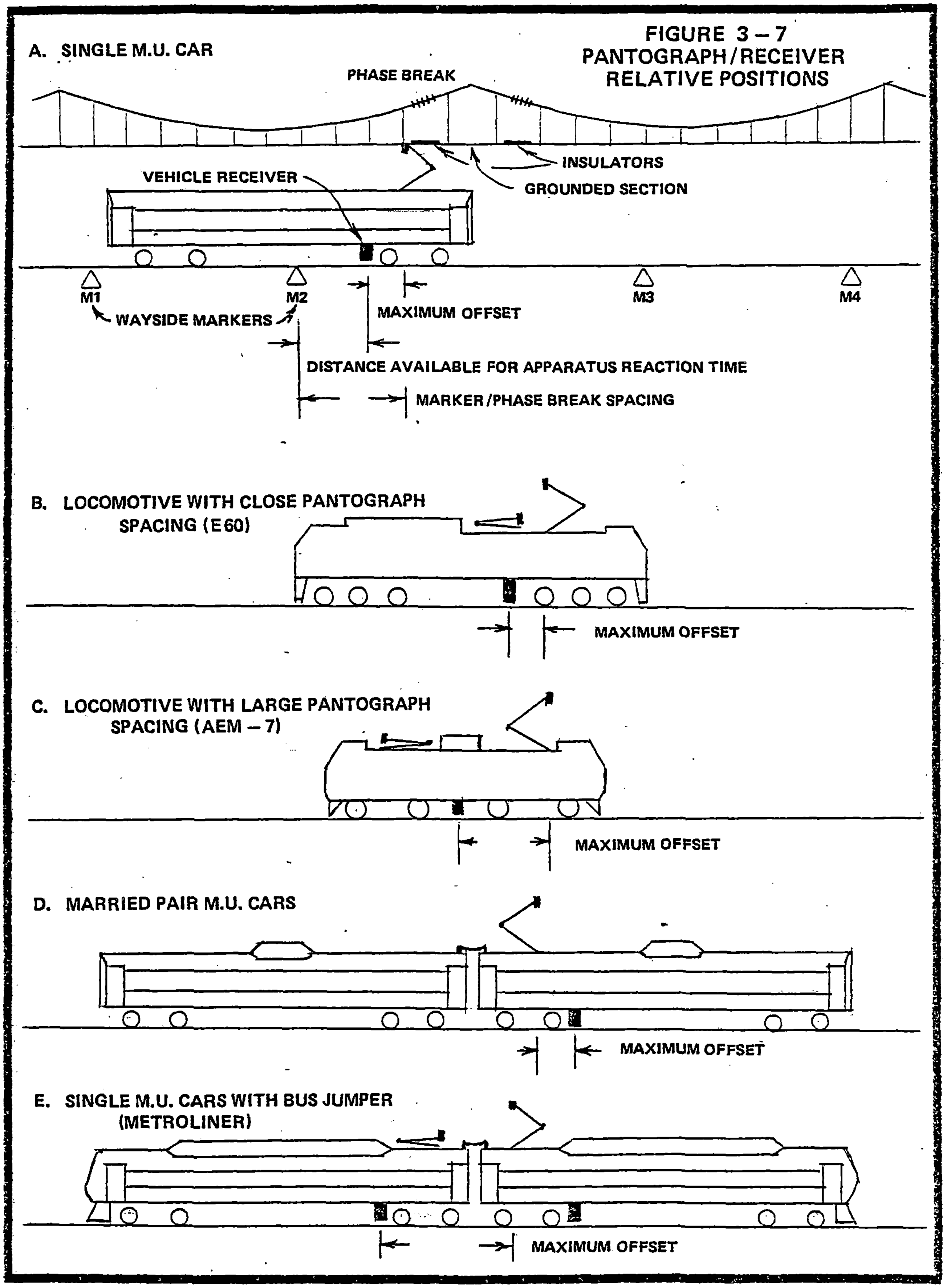


FIGURE 3 – 7
PANTOGRAPH/RECEIVER
RELATIVE POSITIONS

A. SINGLE M.U. CAR

B. LOCOMOTIVE WITH CLOSE PANTOGRAPH SPACING (E60)

C. LOCOMOTIVE WITH LARGE PANTOGRAPH SPACING (AEM – 7)

D. MARRIED PAIR M.U. CARS

E. SINGLE M.U. CARS WITH BUS JUMPER (METROLINER)

In either case some precaution will be required to prevent operating with both pantographs raised since the distance between the pantographs is great enough to bridge a VC or PB.

4. VEHICLE PRIMARY OVERLOAD PROTECTION

Background

The philosophy of vehicle fault protection which is currently used on the 25 Hz electrification is based on use of the substation circuit breaker to interrupt the fault current and then lowering the vehicle pantograph to isolate the condition. This is done by applying a deliberate ground fault to the catenary by means of a pneumatic ground switch. The resulting current surge trips the impulse breaker at the substation which remains open for 15 to 30 seconds before automatically reclosing. During this delay, the vehicle pantograph is lowered, isolating the fault. If the fault is not cleared and the breaker trips upon reclosure, it remains tripped until reset by supervisory control.

The philosophy applied to the new 60 Hz electrification involves the addition of a vehicle primary circuit breaker which not only provides transformer isolation while configuring the transformer for the correct voltage, but serves to interrupt fault conditions on the vehicle. The limited space available prohibits installation of a vehicle circuit breaker of sufficient capacity to handle all possible vehicle faults, particularly on m.u. cars. A compromise solution is required.

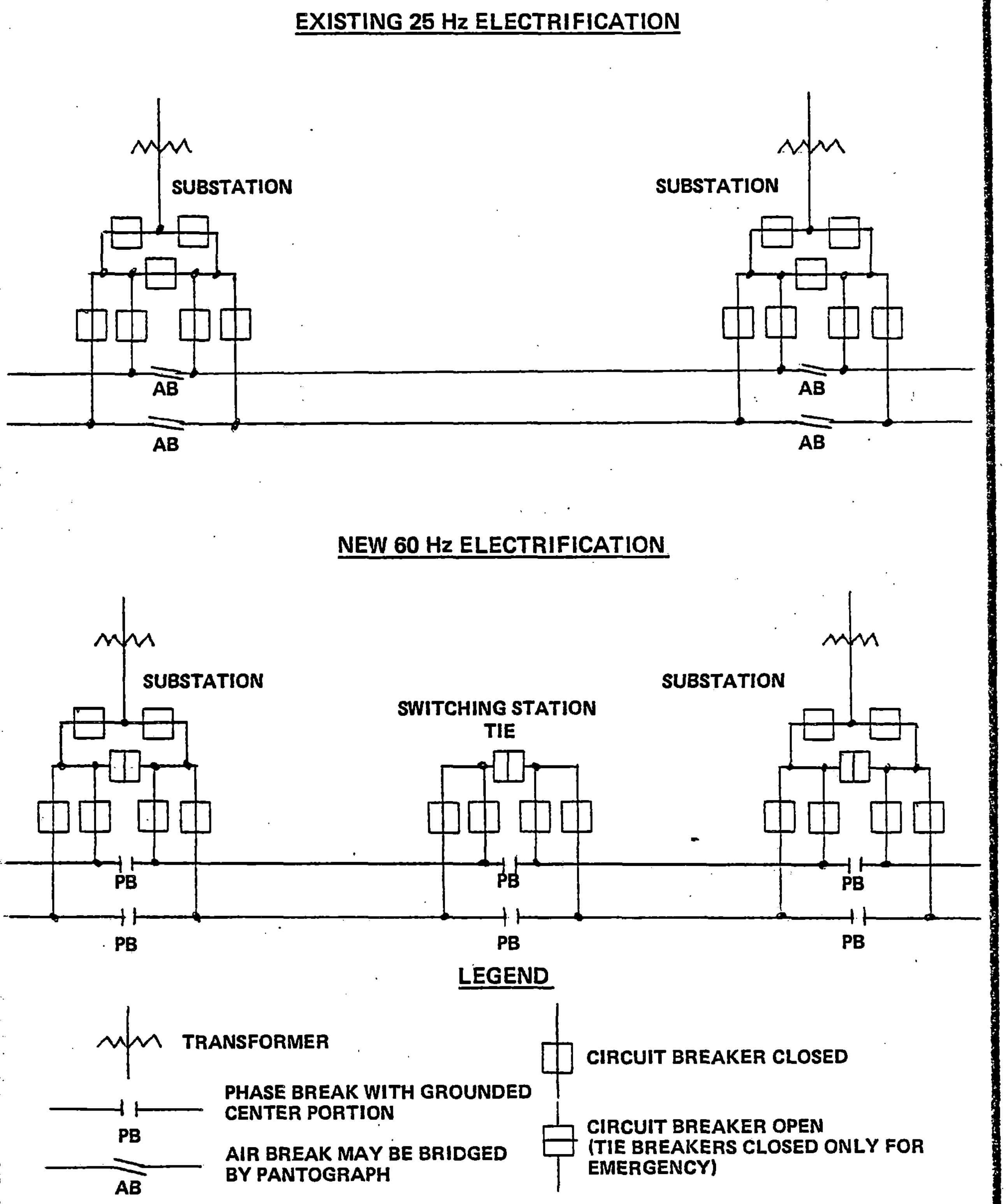
The maximum possible fault current level of the new electrification will approach 20 kA, (one 30 MVA transformer with its secondary shorted). Depending on the location of the vehicle and the impedance of the intervening catenary the fault currents resulting from a vehicle fault could be as high as 17.2 kA.

The circuit breaker arrangement of both the existing 25 Hz electrification and the new 60 Hz electrification are shown in Figure 4-1.

With the present 25 Hz electrification, each section of catenary is fed at both ends by two substations. Each of the substation breakers is set to trip an impulse of 5000 A in 1/2 cycle (0.02 second) and backup impedance measuring is also provided. Typical faults occurring in the middle of the catenary section are cleared by the breakers at both ends opening within 1 cycle (0.04 second). In the case of a fault at one end of the catenary section, the adjacent breaker will trip within 1/2 cycle while the distant breaker will clear in 2 to 4 cycles (0.08 to 0.16 second). The current level from the distant breaker will be substantially reduced by the impedance of the intervening catenary.

With the new 60 Hz electrification each section of the catenary is fed from only one substation which is located at one end of the section. All parallel sections of catenary fed from the same substation are connected by tie breakers at the switching station at the far end. This minimizes transmission losses and results in a feed to any vehicle from both ends of the catenary

FIGURE 4 – 1
CIRCUIT BREAKER ARRANGEMENTS



section. By placing circuit breakers in series, a complex fault detection system is necessary which requires the use of zone type impedance measuring relays to permit selective isolation of faults. For this reason the impulse breaker feature of the older 25 Hz system cannot be used.

The 60 Hz protective relaying operates in a timing sequence which depends on the location of a fault in a catenary section. Faults in the middle 70% of the catenary section lie within zone 1 of the impedance measuring relays of the breakers at both ends. The zone 1 relay response is "instantaneous" (0.01 to 0.02 second) and, combined with the breaker operating time of 0.007 to 0.008 second, produces a total trip time of 0.017 to 0.028 second. Figure 4-2 presents the response sequence of a single wayside impedance relay and breaker. In the case of a fault at one end of the catenary section, the fault will be in zone 1 for the adjacent breaker which will trip "instantaneously" in 0.017 to 0.028 second. The impedance measuring relay at the far end of the section will "see" the fault in zone 2, which comprises the distant 15% of the catenary section. Zone 2 involves an additional relay delay of 0.10 to 0.15 second which will result in a total distant trip time of 0.117 to 0.178 second.

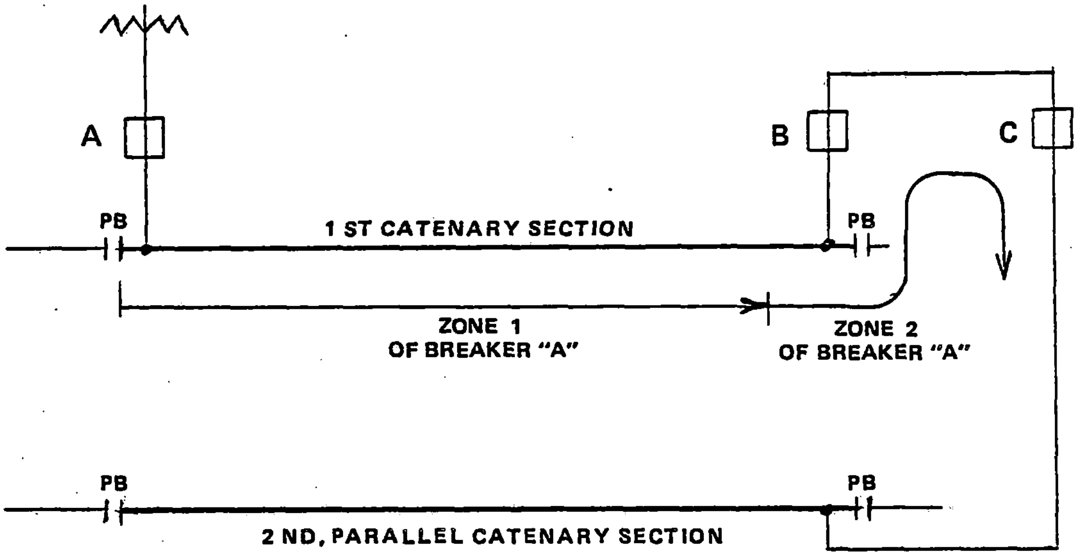
Due to space limitations, it is difficult (or impossible) to apply a high voltage circuit breaker of sufficient interrupting capacity for the maximum possible fault current to the primary circuit of each locomotive or m.u. car. Although the primary current caused by overloads and other faults on the secondary side of the vehicle transformer would tend to be limited by transformer impedance, severe primary faults such as the failure of the tap changer or roof mounted equipment ground downstream of the breaker could develop a current in excess of the vehicle breaker's capacity. Thus the substation circuit breakers must be relied upon to interrupt the fault current under these conditions.

The older arrangement of using on a pneumatic ground switch to "relay" a fault to the substation could assure this function, however there is a serious objection to continuing the use of this method because it introduces a full ground fault on the substation transformer for every vehicle related fault, regardless of its severity. The mechanical force produced by the magnetic fields of the substation transformer windings under such high current levels causes severe stress on the winding insulation and clamping. However, this system insures the recognition of vehicle faults and protects the vehicles from the serious damage which could result from a low level primary fault.

The transformers used in the original electrification have apparently not been degraded from this type of fault protection. They are approximately 40 years old and few have required major repair work. It is also significant to note that the occurrence of vehicle faults represents only a small portion of the causes for substation breaker trips (1 in 7). Further, the most common vehicle faults are ground faults resulting from incidents such as pantograph damage. Because these faults occur

FIGURE 4 – 2

WAYSIDE IMPEDANCE RELAY AND BREAKER SEQUENCE



FOR BREAKER "A":

ZONE 1 – EXTENDS 85% OF THE LENGTH OF THE 1 ST CATENARY SECTION.

ZONE 2 – COVERS DISTANT 15% OF THE 1 ST CATENARY SECTION AND EXTENDS THROUGH TIE BREAKERS "B" AND "C" INTO THE 2 ND, PARALLEL CATENARY SECTION. THE PROTECTIVE RELAYS AT "B" AND "C" PROTECT THE 2 ND CATENARY SECTION on the catenary side of the vehicle primary breaker, the addition of vehicle breakers will not protect the substations from such faults.

The design criteria used for the transformers in the older electrification reflected the abuse expected in the application, and the transformers were "overdesigned" accordingly. New transformers will, for reasons of economy, follow established commercial power equipment standards rather than special railroad design and construction criteria. As a result, they can be expected to be less suited to the existing type of fault protection. It is therefore considered preferable <u>from the standpoint of wayside equipment</u> to use a vehicle circuit breaker instead of a grounder.

A compromise in vehicle circuit breaker size to fit space limitations can result in situations in which a fault exceeds the breaker's capacity. Under the circumstances an arc will be sustained through that breaker until the wayside breaker interrupts the fault. This situation is comparable to commercial power distribution practices for branch circuits and is also followed by contemporary European railroad electrification systems. In U.S. railroad electrification this arrangement is used on the two experimental Conrail freight locomotives (GM6C and GM10B) and on the Amtrak AEM7 and E60 locomotives. The Conrail experimentals and the AEM7 are built by EMD and are equipped with ASEA air blast primary circuit breakers. The E60 is by G.E. and has a GE vacuum interrupter.

Some concern has been expressed for the potential hazard of a catastrophic transformer fault on an m.u. car and the tremendous amount of energy which might have to be dissipated in the confined area under the car floor below the passenger compartment. Presumably such a fault will be in excess of the interrupting capacity of the vehicle circuit breaker. If the train is at the extreme end of a catenary section there is a delay in wayside breaker opening imposed by the sequence of operation of the distant impedance measuring relays at the substation. For this reason the pneumatic grounder is to be retained on m.u. cars as a "belt and suspenders" approach to fault protection.

<u>Fault Protection System</u>

The fault detection circuitry which is planned for the conversion of m.u. cars for operation with the new electrification system is similar to that which is currently in use. An additional relay will be provided to distinguish between faults within the capacity of the vehicle circuit breaker and faults in excess of this capacity. The planned circuit is based on use of the same protective relay, the Pantograph Lowering Relay (PLR), which is currently in use. A description of the basic PLR operation with the grounder is included here.

The PLR has a distinctive two step operation for sequentially operating the grounder and then lowering the pantograph after the fault current has been interrupted.

An overload or primary fault on a locomotive or m.u. car is first detected by the PLR by means of a current transformer in the primary circuit. Activating the PLR first causes the pneumatic grounder contact to strike the pantograph frame imposing a dead ground on the catenary. The resulting ground current is also measured by the PLR which retains the grounder against the pantograph frame and delays lowering the pantograph until the current drops to zero, indicating the substation breaker has opened.

A mechanical latch which holds the moving contacts in their normal operating position is released when the PLR has moved to the fault position. After the current drops to zero (substation breaker open), the PLR contacts travel past the normal position to the tripped position, releasing the pneumatic grounder and lowering the pantograph. Manual reset of the PLR to its normal operating position is required.

The modified fault detection circuit for the conversion of m.u. cars will add a second current measuring relay, the Fault Current Relay (FCR), which is identical in design to the existing PLR. The FCR is to be set to trip at the upper limit of the vehicle circuit breaker's capacity and will serve to operate the pneumatic grounder whenever a fault occurs which cannot reasonably be interrupted by the primary circuit breaker. The PLR will operate in much the same manner as with the older arrangement except that it will operate the primary breaker instead of the grounder.

In the case of the vacuum interrupter under consideration for use on converted m.u. cars which has a rated interrupting capacity of 4000 A, the FCR will be set at 3750 A,

The protective relay system for an m.u. car will be arranged as shown in Figure 4-3. Primary current is measured by a dual voltage range current transformer which surrounds the cable connecting the transformer to the primary circuit breaker. The ground current path from the pneumatic grounder also passes through the current transformer, enabling the current measuring relays to measure this fault current as well. A tap changer relay, TCR, selects the proper current transformer tap to correspond to the proper voltage - 25 kV, 60 Hz or either 11 kV, 25 Hz or 12.5 kV, 60 Hz. The TCR relay is mechanically "bi-stable" and remains in position even when electric control power is turned off. The FCR and PLR current measuring relays and the THR thermal overload relay are in turn connected across the current transformer.

In the event of an overload or other vehicle fault, the PLR first picks up and energizes the vacuum interrupter trip relay (TVIR) commanding the breaker to open. Upon sensing the loss of primary current, regardless of whether the current was interrupted by tripping the vehicle or wayside breaker (or both), the PLR then drops to its tripped position energizing the pantograph down magnet valve (PDMV). This lowers the pantograph, isolating the vehicle from the catenary.

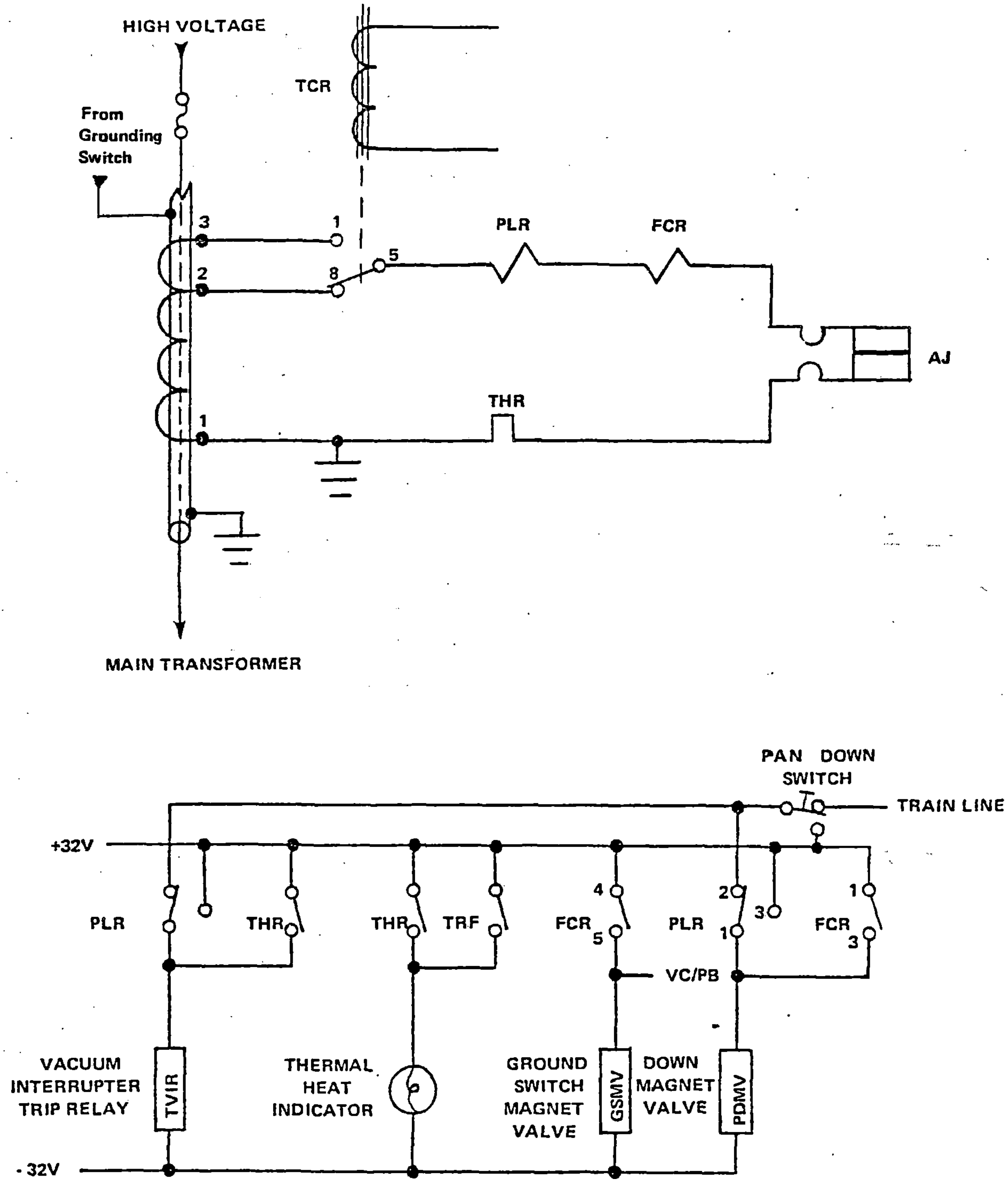


FIGURE 4 – 3
PRIMARY FAULT PROTECTION SYSTEM

FCR	FAULT CURRENT RELAY	MANUAL RESET
PLR	PANTOGRAPH LOWER RELAY	MANUAL RESET
THR	THERMAL RELAY	MANUAL RESET
TCR	TAP CHANGER RELAY	
TRF	TRANSFORMER HOT THERMAL SWITCH	

At the same time the FCR measures the fault current to determine whether it exceeds the capacity of the breaker. If the fault current is within this capacity, the FCR will not pick up, and only the PLR operating sequence will occur. If the fault current is excessive, both the FCR and PLR will pick up. The FCR will activate the ground switch magnet valve (GSMV) at the same time that the PLR is attempting to open the primary circuit breaker. When the combined transformer fault and ground currents fall to zero, both the PLR and FCR relays will drop out to the trip position. The pantograph will then be lowered by the PLR energizing the down magnet valve as previously described.

Both the PLR and FCR relays require manual reset within the control enclosures.

Because the pneumatic grounder sequence requires a minimum of 0.24 second, (Measurements taken on Metroliners obtained PLR/grounder reaction times varying from 0.24 to 0.80 seconds.) it is unlikely that the grounder will make contact before both the vehicle breaker and the substation breakers have tripped. The substation transformers will therefore not be subjected to the severe jolt of a ground fault except in rare situations. Because the FCR relay will release the ground switch magnet valve as soon as the fault is interrupted, the pneumatic grounder may not actually contact the pantograph frame. In the event that it does make contact, the grounder will merely serve to discharge any remaining capacitive charge in the catenary.

If a fault is in excess of the vehicle breaker's capacity, an arc will be sustained through the breaker until either the wayside breaker trips or the pneumatic grounder makes contact with the pantograph.

Prolonged overloading on the primary circuit, at current levels below the trip point of the PLR, will cause heating in the thermal relay (THR). When the THR trips, the primary circuit breaker is opened and a local thermal indicator warning light is turned on. Manual reset of the THR is required within the control enclosures.

An additional complication to vehicle protection is presented by vehicle faults involving pantographs, buss cables, and insulators where the fault current does not pass through the current measuring transformer. The wayside circuit breakers must then be depended upon to detect and interrupt such faults. Breakage of pantographs and entanglement with the catenary are relatively common incidents and usually produce a ground fault which is easily recognized by the substation protective relaying.

There remains a chance of a high impedance fault which may escape recognition by both the substation and vehicle protective relaying. Conditions of this sort are beyond the capabilities of existing automatic overload detection systems and require human intervention. Several alternatives are available to the crew. The first is to attempt to lower the pantograph, thus breaking the circuit. This will only be successful if the pantograph lowering mechanism is functional and if the catenary is high enough to permit extinguishing the arc. A second alternative is to radio the tower operator, who in turn must call the power director and request shutdown of the catenary. In some locations tower operators have a direct catenary control.

There is room for improvement in giving all tower operators direct control of catenary breakers. This should be given consideration in establishing operational criteria for wayside control since it would provide a fault protection backup for all circumstances including those involving vehicles. It would also be possible to provide a local "panic button" in the operating cab to operate the pneumatic grounder. There is however, a level of complexity with alternate devices and controls which may produce a greater chance of circuit failure than the original problem.

5. OVERVOLTAGE PROTECTION

Potential for Damage

The Philadelphia area presents a unique situation in which a number of commuter lines will remain at 11 kV, 25 Hz indefinitely after the basic NEC re-electrification change is complete. A problem presented by this dual voltage territory is the hazard of subjecting unconverted (11 kV, 25 Hz) cars to overvoltage/overfrequency should they stray into 25 kV, 60 Hz territory. This event could occur as a result of misrouting at the two interlocking plants, Arsenal and Zoo, which control traffic entering and leaving 30th Street Station.

There is also the chance of raising a pantograph on an 11 kV only car while in yard or shop areas (such as Wilmington shops) with catenary energized at 25 kV.

The effect of overvoltage and overfrequency imposed by subjecting the vehicles' 11 kV, 25 Hz primary circuit to 25 kV, 60 Hz has varying consequences. Presumably the condition would last for only a few seconds before the PLR relay trips. The double voltage condition is the most serious since it overstresses insulation levels. The effect of both conditions on various types of devices is discussed here in general terms. Individual vehicles can be expected to respond differently as the age and existence of weaknesses in insulation will have a significant effect on their ability to survive.

The 15 kV lightning arrester can be expected to break down under 25 kV and provide a low resistance path from the pantograph to ground, however there is a distinct probability that the arrester could burn out without tripping the substation. It should therefore not be relied upon for protection against overvoltage (other than very short lightning transients).

The main transformer would experience limited risk since the inrush and excitation currents would tend to be reduced because of the higher impedance at 60 Hz, offsetting much of the effect of doubled voltage. The transformer insulation would be severely stressed at the higher voltage (the normal withstand test voltage is only 1.75 times the working voltage) however it is unlikely that this would cause damage if the exposure were limited to a few seconds. Wire and cable insulation can also be expected to withstand twice the working voltage for a brief period.

Rotating machinery is relatively insensitive to brief overvoltage conditions because the insulation test levels are high and the machines are designed to handle high starting currents. Series or compound wound commutating motors will accelerate to a higher speed when the voltage is doubled. However, the load characteristics of blowers and compressors will tend to hold motor speed down with an increase in current.

The older Silverliner I, II, and III m.u. cars have induction motor driven auxiliary devices operating at 25 Hz. Subjecting these motors to 60 Hz would cause them to attempt to overspeed by a factor of 2.4, however the various loads would limit the speed actually reached and high currents would be drawn.

The components which are most susceptable to damage from an overvoltage condition are the power rectifiers and those other solid state control devices which operate directly on the secondary voltage from the transformer. The power rectifiers include "ignitron" mercury vapor rectifiers, which are often used as phase controlled rectifiers, as well as solid state, silicon rectifier devices. All of these devices are sensitive to the peak (instantaneous) inverse voltage to which they are subjected. At some level above the rated p.i.v., solid state devices will break down to a direct short. Because this is virtually an instant destructive failure with solid state devices, there is no time for fuses to function to protect them. Ignitrons have an inherently high internal resistance and would probably survive the resulting "arc back" long enough for protective devices to operate.

Because of their higher cost, devices with p.i.v. ratings high enough to withstand twice their normal working voltage are not generally used, therefore a high incidence of failure could be expected under double voltage conditions.

Vehicle Protection

The design of the VC/PB system offers inherent protection against overvoltage in that the control logic requires three basic checks before closing the primary circuit breaker:

1. Catenary voltage must be present and identified ("high" or "low").
2. The main transformer tap changer must be in the correct position (11 kV or 25 kV).
3. The current measuring transformer tap relay must be in the correct position (11 kV or 25 kV).

Unmodified vehicles will not have a primary circuit breaker and therefore will not have this level of protection.

Additional protection is provided on converted m.u. cars by an overvoltage relay applied across one of the main transformer secondary windings. Occurrence of an overvoltage condition will cause the VC/PB logic to operate the pneumatic ground switch directly. The resulting ground current will trip the PLR and FCR relays and then lower the pantograph, as described in Section 4 of this paper.

A modification has been proposed to protect single voltage (11 kV) locomotives and m.u. cars against overvoltage as a result of misrouting. These vehicles could be equipped with the VC/PB sensors to detect the presence of wayside markers preceeding a voltage change. The PLR relay could be operated by the signal from the VC/PB sensor and in turn tripped, operating the pneumatic grounder causing the wayside circuit breakers to open and the pantograph to be lowered. While this would not prevent the train from entering the wrong route, it would intervene to protect against overvoltage. No protection would be provided against raising the pantograph against a 25 kV wire under other circumstances.

While this arrangement is somewhat complex, it offers the most secure protection short of adding a primary circuit breaker and controls. By preventing even a brief exposure to overvoltage, it protects passengers from risk due to a consequential transformer fault or electrical fire. It does not guard against errors made by yard crews or shop personnel in raising the pantograph to the wrong voltage.

Another safeguard may be made available in conjunction with the new NEC signal system. There is a proposed signal arrangement for the NEC which would employ a special intermittent signal system at each point of entry to the corridor. This signal system would serve to activate the automatic train control (ATC) apparatus when entering the corridor and deactivate the ATC when leaving. Two-way data transmission between the vehicle and wayside would be provided by a high frequency inductive type interface which would confirm activation of the ATC prior to clearing the signal for the train to enter the NEC. The inductive coupling would employ a short vehicle antenna and a long track mounted antenna array.

While only in a preliminary design stage at present such a system could be used to prevent unmodified vehicles from entering 25 kV territory by requiring that voltage capability as well as ATC activation be confirmed before clearing the signal.

An alternate, but less effective proposal involves "no voltage" and "overvoltage" relays across one of the transformer secondary windings. The no voltage relay would open the propulsion and auxiliary circuit contactors upon loss of transformer voltage which would occur in the insulated section of a catenary break. The no voltage relay would have a delayed reclosure to permit the overvoltage relay to determine whether the voltage was excessive before permitting the auxiliary and propulsion contactors to reclose. Sensing of an overvoltage condition would be used to trip the PLR.

Auxiliary devices such as the rectifier for DC motor driven MA sets which do not have a contactor would be protected by an additional SCR switch having sufficient blocking capacity to prevent overstressing the fixed diodes in the rectifier bridge. This arrangement could also serve to improve auxiliary load regulation in normal service.

The obvious drawback to such a scheme is that it permits the transformer to be subject to excess voltage, even if only for a short time, and risks a consequential fault.

PART 5. PANTOGRAPHS

Louis T. Klauder
and Associates

PANTOGRAPHS

Problems in high speed power collection for electric trains in the Northeast Corridor first occurred with early Metroliner tests run at speeds up to 160 mi./hr. Serious deficiencies with both the existing catenary construction and conventional pantographs were identified which had not presented a problem below 100 mi./hr. Similar problems have also been identified in high speed train development testing and operation in other countries, and development programs addressing the subject have been instituted in those countries as a part of continuing railroad development.

Foremost among initial Metroliner pantograph problems and corrective action taken for each were:

1. Initial operation was with pantographs raised on all cars. This resulted in excessive disturbance of the catenary at maximum speed and loss of contact. This situation was corrected by busing the cars in pairs, and running with one pantograph per pair. This change, of course, doubled the current per pantograph and required that each pantograph collector shoe have three lines of carbon rather than two. The corrective action taken here halves the number of working pantographs and increases their spacing, and is in accord with the recommendations discussed in Section V.5 of this paper.

2. Aerodynamic corrections were made in the collector shoe assembly to minimize excessive uplift at higher speeds which occurred after the adoption of the PRR standard carbon type collector. This was done by the addition of fairing which incidentally, added 2 lbs. of the weight to the shoe assembly. This problem and corrective action are discussed in Section V.3 of this paper.

As part of the Northeast Corridor Improvement Program, the catenary system will be extended to Boston, and the existing catenary west of New Haven will be modified for operating speeds over 125 mi./hr. This will probably require advanced pantograph designs. Many of the IPEEP candidate trains have new pantograph designs which are intended for operation in this speed range while retaining compatibility with existing electrification systems and the variation in contact wire height encountered in these systems because of right-of-way clearances. These new designs are worthy of consideration for U.S. application.

Alternatives to overhead wire-pantograph power transmission systems have been suggested, such as rigid conductor (third rail) systems, and non-contact types of collection, as exemplified by the plasma arc, or by capacitative or electromagnetic coupling. However, with the current state of the art, none of these systems are serious competitors of the catenary-pantograph system, and they will not be discussed further in connection with the proposed high speed service.

The objective of this discussion is to provide a summary of available pantograph designs for the IPEEP review. The report will not attempt to make an analysis of pantograph behavior for in-depth study, but will confine itself to a discussion of the simple mechanics of pantograph operation and the hardware available from various manufacturers.

Before proceeding with the main topic, the characteristics of the most commonly used catenary systems, and their influence on and reaction to pantograph action will be briefly discussed.

I - CATENARY SYSTEMS

Overhead contact systems for heavy traction applications have commonly used simple, stitched or compound catenary suspension, comprising a contact wire or wires, and one or more suspension wires, supported in spans which typically are from 200 to 300 feet in length. Figure 1 illustrates these basic constructions, and defines the nomenclature of catenary components.

Ideally, a catenary system should have a uniform stiffness throughout its length. That is, the contact wire should deflect uniformly when subject to the pantograph force, thereby reducing pantograph vertical movement under level wire to a minimum.

It is to more closely approach this ideal situation that the more complex catenary constructions, such as stitched and compound, are used rather than the simple.

Simple catenary has a tendency to be more stiff at the supports than at mid-span, although this condition can be controlled to some degree by varying dropper design and spacing, by increasing mid-span sag, and by increasing tension. Introduction of stitch wires at the supports will reduce stiffness at these locations, but will add considerably to the number of catenary components, and to the difficulty of making catenary adjustments.

The compound design, by introducing an auxiliary wire immediately above the contact wire, accomplishes much the same purpose as the stitch wires, but without the introduction of many separate segments. The auxiliary wire also adds to the current carrying capacity of the catenary system.

Either the introduction of stitch wires, or an auxiliary wire, together with proper dropper design and spacing, and proper sag will result in a catenary with approximately uniform stiffness or compliance.

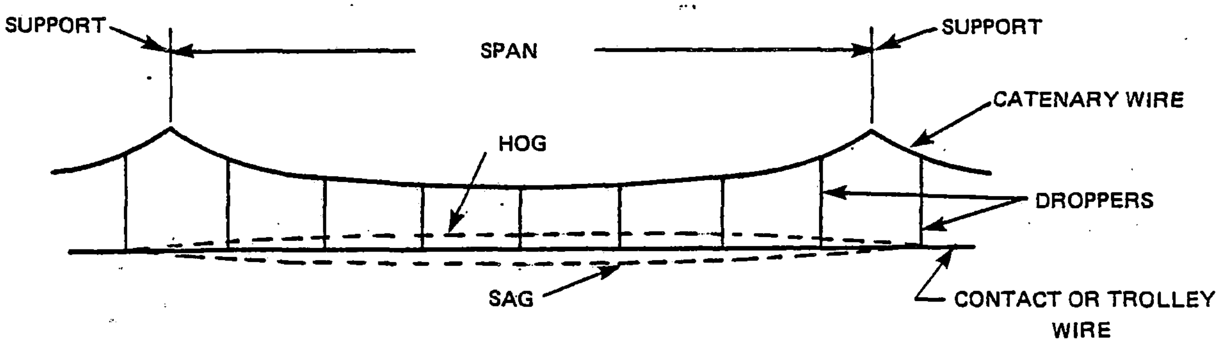
Composite compound-stitched designs have also been used in a number of applications.

With fixed tension catenary, as is presently used on the Northeast Corridor, each length of catenary is fixed at its extremities and adjusted to a predetermined tension. Thus, ambient temperature increase will cause catenary tension to decrease, and temperature decrease will cause it to increase.

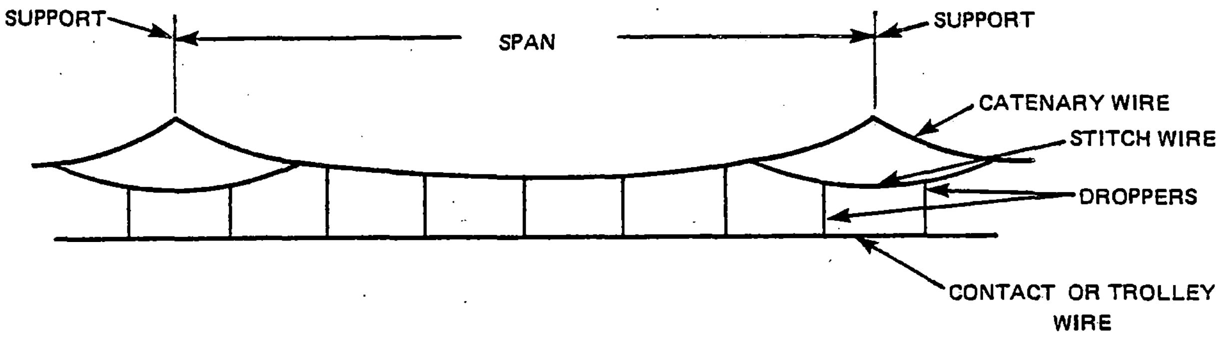
Constant tension catenary is commonly used overseas. Lengths of up to about one mile of wire are usually tensioned at both ends with a mid-point anchor. There are usually three spans of overlap, the span in the middle being the overlap where the pantograph rides on two contact wires simultaneously, and the end spans where the wire is sloped upward and to the side and attached through an insulator to the tensioning equipment. For single and

CATENARY – DEFINITIONS & NOMENCLATURE

SIMPLE CATENARY



STITCHED CATENARY



COMPOUND CATENARY

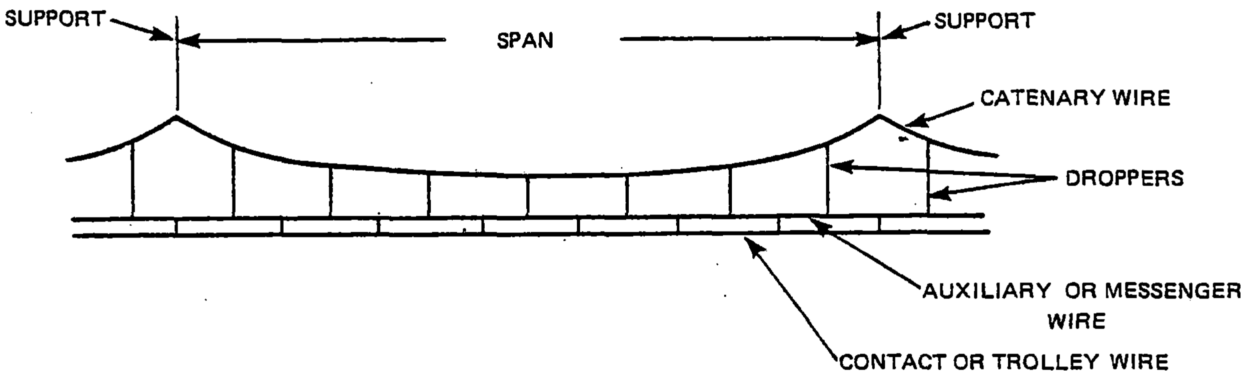


FIGURE 1

double track, the tensioning equipment usually is a relatively simple weight and pulley arrangement attached to a pole. For more than two tracks where bridge construction is used, the weights are located in the columns of the bridge with cables going up and around pulleys across the bridge, and then around pulleys above each track to connect through insulators to the corresponding sets of catenary wires. This results in a rather complicated arrangement for four or more tracks.

Pneumatic-hydraulic tensioning devices are sometimes used in lieu of weights, particularly where space is restricted.

The maintenance of optimum and uniform wire tension has a very definite effect on catenary performance. The use of weight or mechanical constant tensioning devices is essential if good performance is to be obtained at both extremes of ambient temperature. However, fixed tension catenary of the type presently installed in the Northeast Corridor can be adjusted to perform acceptably over an approximate 50 degrees F temperature range.

II - PANTOGRAPHS AND THEIR WORKING ENVIRONMENT

The pantograph is the link between the overhead contact system and the power circuit of the vehicle through which the power is transmitted. This power is collected through a rudimentary form of contact consisting of a simple collector strip on the pantograph sliding along a bare contact wire of the overhead system.

The pantograph has to work at varying speeds, under every climatic and wind condition, on varying stiffnesses of overhead equipment which arise due to differences in equipment design along a route (tensioned vs. non-tensioned catenary, for example), as well as various design features within each section length (dropper spacing or wire size, for example). These factors, and the differing riding qualities of the vehicle at various speeds result in widely varying dynamic conditions, which affect the contact force between the collector strip and the overhead contact system. A positive force at all times is essential to avoid loss of contact and sparking, yet this force must be as low as possible to ensure, in conjunction with the choice of collector strip material, the minimum wear of the overhead contact wire.

It can be seen, therefore, that the apparently simple device of the pantograph has to perform a very difficult task indeed.

The main feature of a pantograph may be described as follows and as shown on Figure 2:

1. A bottom frame is mounted to the vehicle through insulators.
2. Above the bottom frame is a flexible jointed framework which presses the wearing contact surface against the contact wire of the overhead distribution system. This framework must have sufficient rigidity to be mechanically stable both laterally and longitudinally.
3. Operating springs which ensure that the force exerted by the contact strip on the contact wire, over the prescribed range, is within certain design limits and relatively constant at all working heights.
4. A control mechanism to enable the pantograph to be raised or lowered.
5. A collector head or shoe fitted with collector strips which have minimum wearing effect on the contact wire of the overhead distribution system, yet are able to collect the required power without excessive overheating and burning.

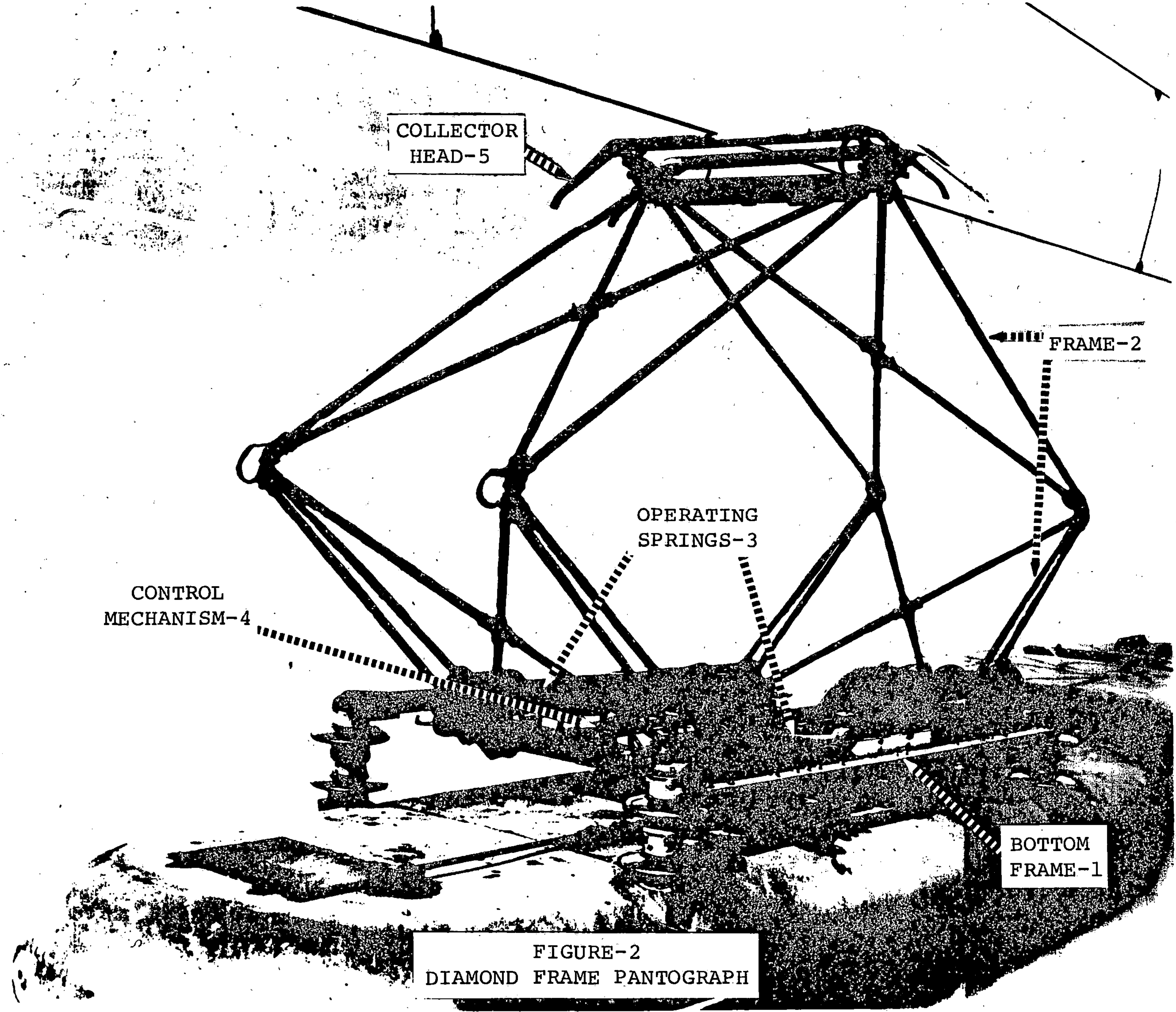


FIGURE-2
DIAMOND FRAME PANTOGRAPH

Probably the simplest form of structure which satisfies the above requirements is the classic diamond frame pantograph shown in Figure 2.

Pantographs of this type are in universal use on both d.c. and a.c. overhead contact systems in the United States and overseas. Usage of this type of pantograph on Northeast Corridor equipment is as listed on lines 1-7 and 15 and 16 of Figure 3.

In recent years, a number of other pantograph designs have come into use. The most widely used of these designs is the single arm type manufactured by the L. Faiveley Co. of France and their licensees (General Electric Co. in the U.S.A.), and by August Stemmann OHG of Germany (type BS-87).

Faiveley designs have been applied to much of the Northeast Corridor equipment built in the past 15 years. This design is illustrated in Figure 4, and usage of this design on Corridor equipment is listed on lines 8-11 and 17 and 18 of Figure 3.

A modernized lightweight pantograph of the diamond frame type is manufactured by Stemmann and is illustrated in Figure 5. This pantograph is used on recent Corridor equipment which did not receive the Faiveley design, as shown on lines 12-14 of Figure 3.

Another modern variation of the basic diamond frame pantograph is the crossed-arm pantograph illustrated in Figure 6, and which is manufactured by the General Electric Co., Ltd. of Great Britain.

Two-stage pantographs have been designed by the L. Faiveley Co. of France, in cooperation with SNCF, for the TGV and other high speed tests; and by the USSR Railway Administration of Russia. Two-stage designs make possible the separation of the compensation for deformation of the contact wire from the compensation for height variation of the contact wire. The first function is assumed by a pantograph of short travel (0.3 to 0.4m) (12 to 16 in.) fixed to the upper part of a pantograph of conventional travel which performs the second function. The Faiveley design is illustrated in Figure 7 and the Russian design in Figure 8. Tracking of the contact wire at high speeds is improved by these designs since only the low-mass short travel pantograph must respond to small variations in contact wire height.

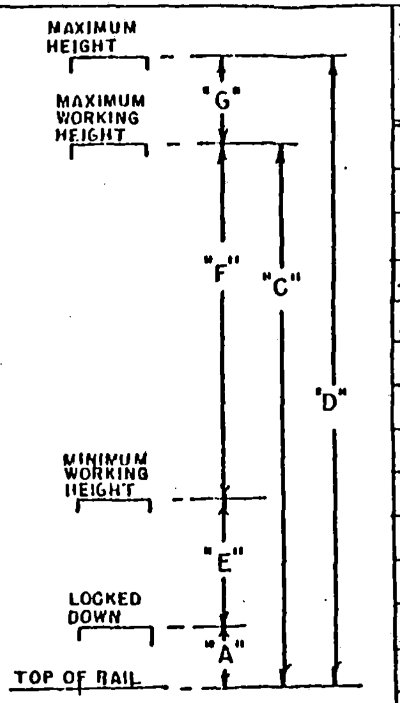
The Faiveley design is simply two independent pantograph frames whose characteristics are selected so that they function together in the desired manner. The upper and lower frames of the Russian design are, however, connected by a pneumatic servomechanism which causes them to maintain a correct relationship.

The SNCF's use of the two-stage pantograph is not dictated by their totally new high speed Southeast line, where

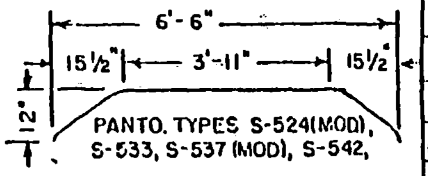
PENN CENTRAL-A.C. ELECTRIFICATION-PANTOGRAPH DESIGN DATA
ELECTRIC LOCOMOTIVES AND MULTIPLE UNIT CARS

SK. EE-2046 FIG. 3

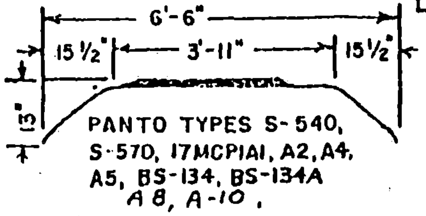
DIRECTOR-EQUIP. ENGINEERING
REDRAWN 8-15-74 (HMB)



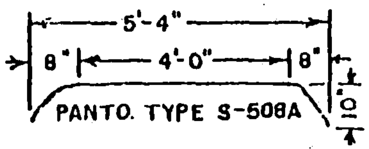
LINE NO.	PANTO. TYPE	USED ON		OPERATING HEIGHTS ABOVE RAIL				INTERMEDIATE DIM.		
		CLASS	EQUIPMENT DESCRIPTION	"A" LOCKED DOWN	"B" MINIMUM WORKING	"C" MAXIMUM WORKING	"D" MAXIMUM HEIGHT	"E"	"F"	"G"
1	US-137	MA9B, C, E	FORMER PRR RED MU (SEPTA)	15'-0 7/8"	15'-3 7/8"	23'-4 7/8"	23'-10 7/8"	3"	8'-1"	6"
2	S-508A	MA4A, MB4A, MC4A	" NEW HAV. MU (MTA)	14'-6"	14'-9"	23'-2 1/4"	23'-7 1/4"	3"	8'-10 1/4"	5"
3	S-524 S-524(MOD)	MA9B, C MA9C, E }	" PRR RED MU (SEPTA)	15'-0 7/8"	15'-3 7/8"	25'-0 7/8"	25'-4 7/8"	3"	9'-9"	4"
4	S-533	MA9C, D	" " " " (")	15'-0"	15'-3"	25'-10 1/8"	26'-3 7/8"	3"	10'-7 1/8"	5 3/4"
5	S-537(MOD)	MA9E	" " " " (")	15'-0"	15'-3"	26'-0"	26'-5"	3"	10'-9"	5"
6	S-542	MA9B, C, E, F	" " " " (")	15'-0"	15'-3"	25'-9 1/8"	26'-2 7/8"	3"	10'-6 1/8"	5 3/4"
7	S-570	MA1D	BUDD PIONEER MU (")	14'-10"	15'-1"	25'-9"	26'-2"	3"	10'-8"	5"
8	17MCPIA2 17MCPIA4	MA1B MA1C	" SILVERLINER MU (") ST. LOUIS " MU (")	14'-11 1/8"	15'-3 5/8"	25'-7 5/16"	25'-11 5/16"	4 1/2"	10'-4"	4 1/2"
9	17MCPIA5	MG1A, MS1A	BUDD-GE METROLINER (AMTRAK)	14'-10 3/4"	15'-3 1/4"	25'-6 3/4"	25'-10 3/4"	4 1/2"	10'-3 1/2"	4"
10	17MCPIA8	MA1G MA1E, MA1F	GE. SILVERLINER IV MU (NJ DOT) " " " " (SEPTA)	14'-11 11/16"	15'-3 11/16"	25'-7 11/16"	25'-11 11/16"	4"	10'-4"	4"
11	17MCPIA9	M-2	GE NEW HAVEN MU (MTA)	14'-9 3/4"	15'-1 3/4"	25'-5 3/4"	25'-9 3/4"	4"	10'-4"	4"
12	BS-134	MR1A	WEST. METROLINER (AMTRAK)	14'-10 3/4"	15'-3 1/4"	25'-6 3/4"	25'-10 3/4"	4 1/2"	10'-3 1/2"	6 1/2"
13	BS-134A	MA1A	ST. LOUIS JERS. ARROW (NJ DOT)	14'-11"	15'-3 1/2"	25'-7"	25'-11"	4 1/2"	10'-3 1/2"	6 1/2"
14										
15	S-540	E-40, GG1	ELEC. LOCO'S. AMTRAK & P-C	15'-0"	15'-3"	26'-0 1/4"	26'-5 1/4"	3"	10'-9 1/4"	5"
16	S-540	E-33	" " (FRT. ONLY) (P-C)	15'-4 1/4"	15'-7 1/4"	26'-4 1/2"	26'-9 1/2"	3"	10'-9 1/4"	5"
17	17MCPIA1	E-44, E-44a	" " (" ") (")	15'-0"	15'-4 1/2"	26'-1 1/2"	26'-6"	4 1/2"	10'-9"	4 1/2"
18	17MCPIA10	E-60	" " (GE-AMTRAK)	14'-7 1/2"	14'-9 1/2"	25'-3 1/2"	25'-6 3/4"	2"	10'-6"	3 1/4"



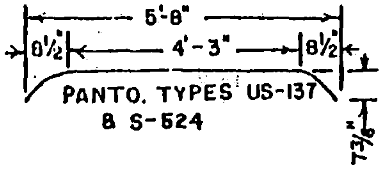
PANTO. TYPES S-524(MOD), S-533, S-537 (MOD), S-542,



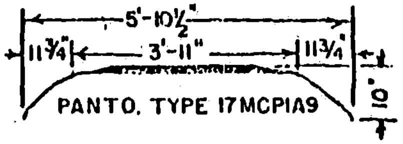
PANTO TYPES S-540, S-570, 17MCPIA1, A2, A4, A5, BS-134, BS-134A A8, A-10,



PANTO. TYPE S-508A



PANTO. TYPES US-137 & S-524



PANTO. TYPE 17MCPIA9

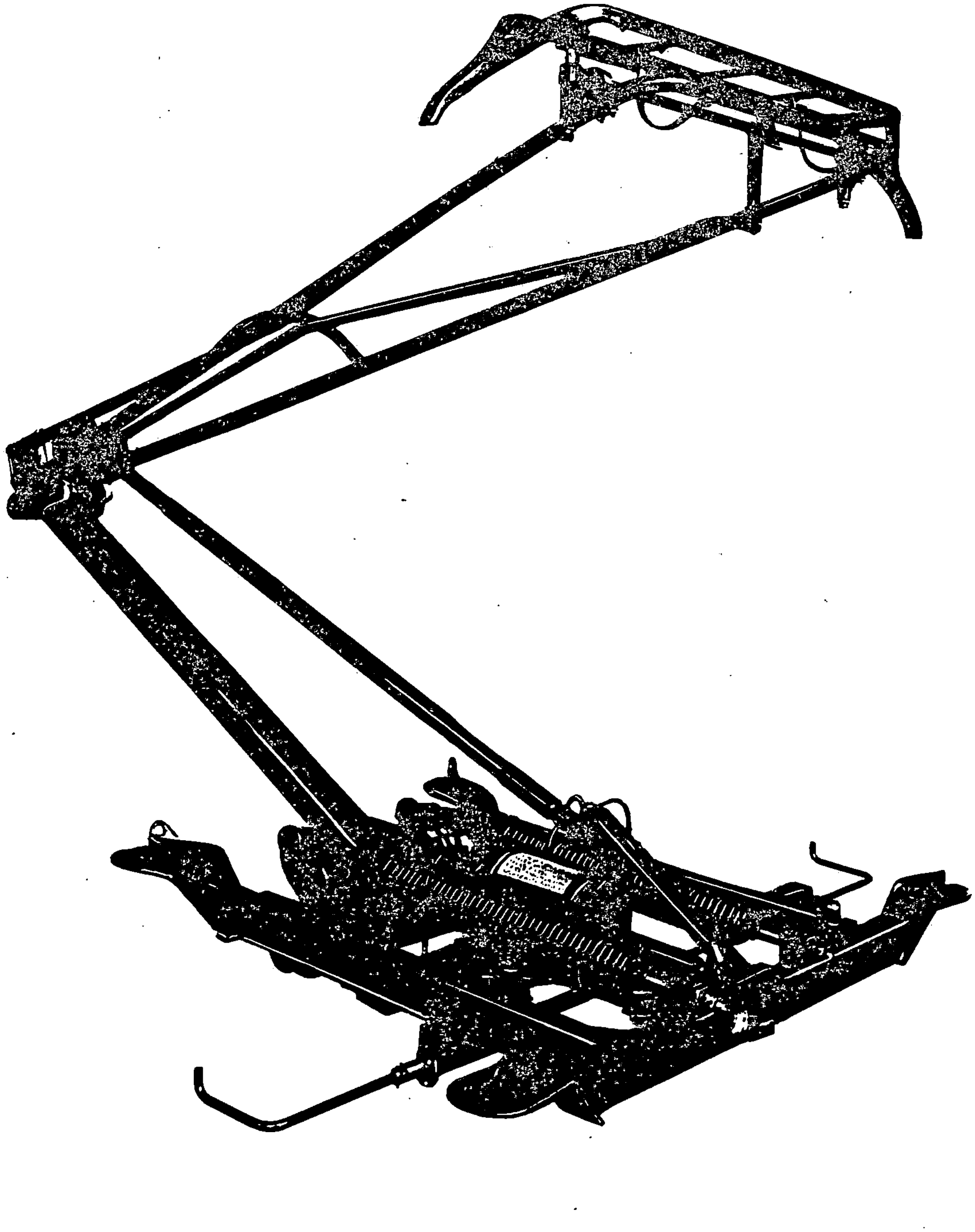


Figure 4 Faiveley Pantograph

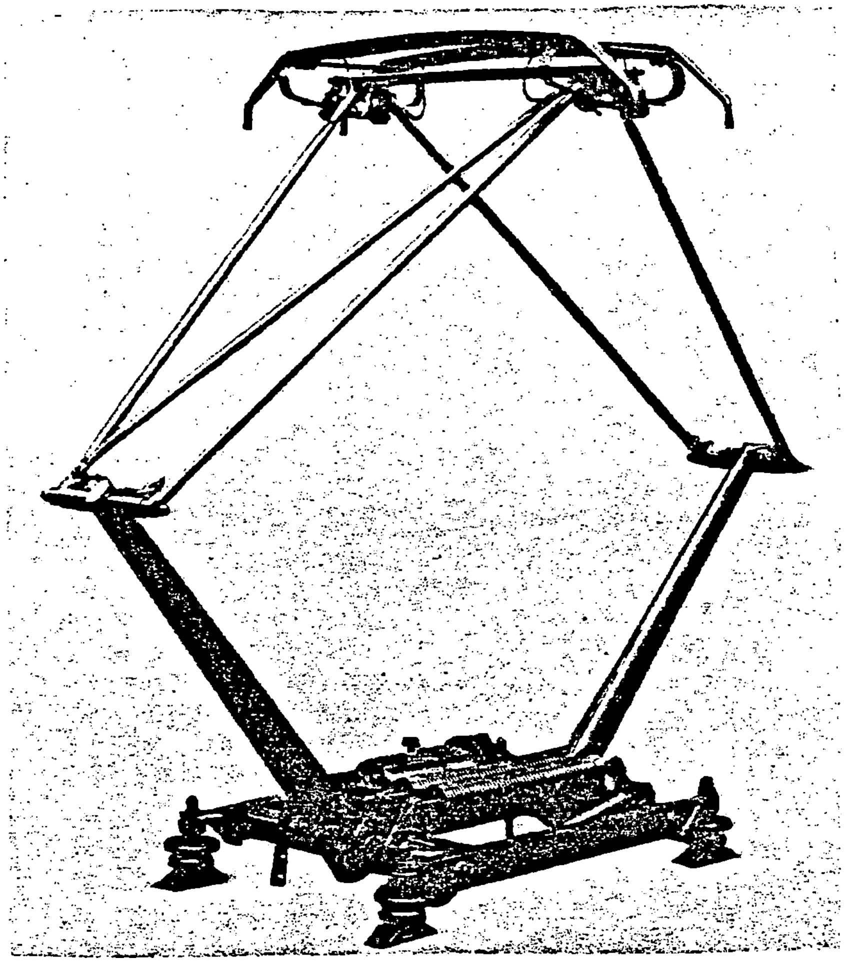


Fig. 5 Stemmann Pantograph

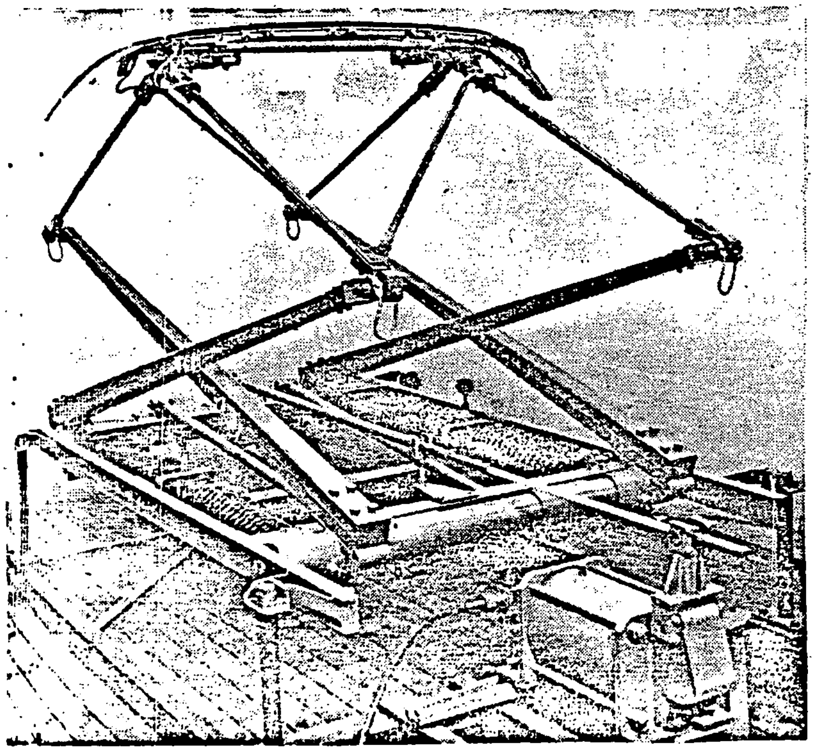


Fig. 6 Crossed-Arm Pantograph

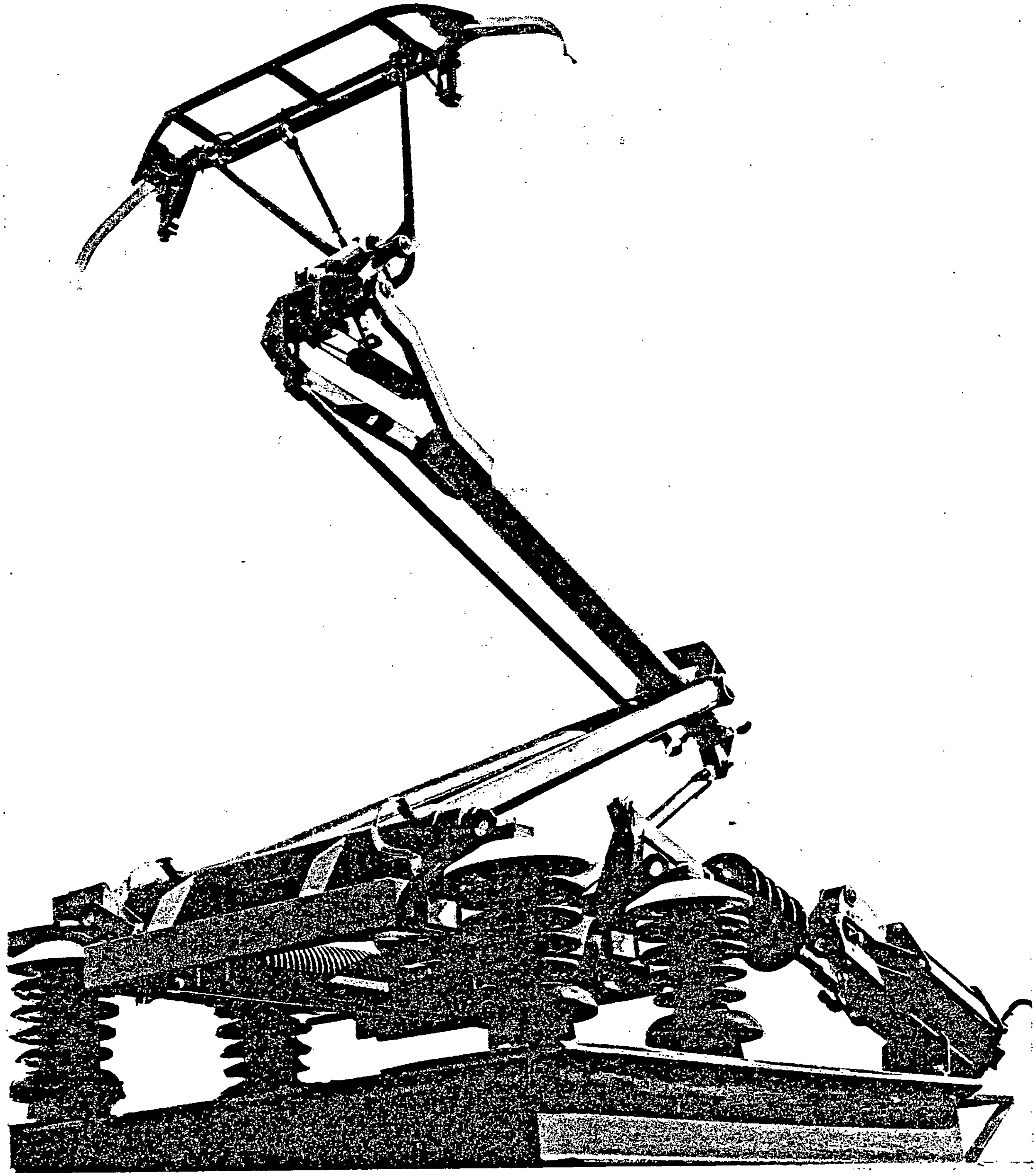


Fig. 7 Faiveley AMDE 2-Stage Pantograph

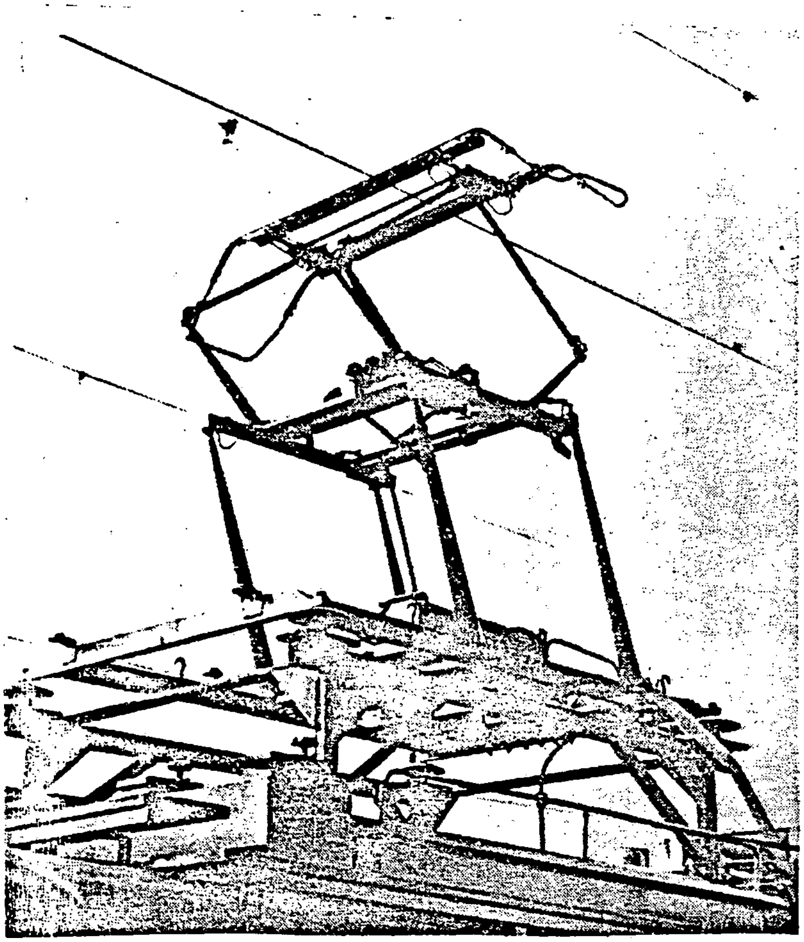


Fig. 8 TC-IM 2-Stage Pantograph

catenary height will be maintained nearly constant. Rather, it is to permit the new high speed equipment to be also used on the older lines where relatively poor catenary and track conditions may exist.

Additional details of the several pantograph designs may be found in the appendix.

III - PANTOGRAPH - CATENARY INTERACTION

The moving pantograph deforms the trolley wire in the contact zone, and a deformation wave propagates along the overhead catenary system. If the speed of the pantograph increases until it equals or exceeds the wave propagation velocity (Vw), the trolley wire will attain the properties of a rigid wire. Under these conditions considerable forces arise between the pantograph and contact wire which may lead to the destruction of the pantograph, or the catenary, or both. Therefore, the wave propagation velocity of the contact wire is the maximum speed at which normal current collection may be attained. As a practical matter, this speed reduced by approximately 20% can be assumed as the maximum permissible speed (Vp) for the movement of electrically propelled vehicles, that is, Vp = 0.8Vw.

The deformation wave propagation velocity in the overhead wire (Vw) may be determined quite precisely by the formula

$$Vw = \sqrt{\frac{Z}{M}}$$

where

Z = total tension in overhead wires, N(Newtons) ($kg \cdot m/s^2$)

M = mass of one meter of overhead wires, kg/m

This equation is derived from the general relationship for the propagation of a longitudinal wave in a tensioned string.

It is seen that once the wire size is selected, the value V_w is mainly influenced by the total tension of the catenary wires. Thus, for example, for a simple catenary consisting of a bronze 65 mm^2 catenary cable and a 107 mm^2 copper trolley wire with a total tension of 19.6 kN (4400 lbs.) (9.8 + 9.8) and a unit mass of 1.6 kg/m (1.1 lbs./ft.), Vw is 399 km/hr (248 mph) and Vp = 0.8 Vw = 319 km/hr (198 mph). Similarly, for a compound catenary consisting of a steel-copper 95 mm^2 catenary cable, a steel-copper 50 mm^2 auxiliary wire, and a 100 mm^2 copper trolley wire with a total tension of 35.3 kN (7940 lbs.) (15.7 + 9.8 + 9.8) and a unit mass of 2.16 kg/m (1.45 lbs./ft.), Vw is 461 km/hr (287 mph) and Vp = 0.8 Vw = 369 km/hr (229 mph).

A major problem of high-quality current collection at high speeds is to extend the service life of contact wires and pantograph contact strips. This depends on the parameters of the catenary and the pantograph, and the matching of these parameters.

Tests carried out in the USSR with carbon strips have shown that when the force of a pantograph against the contact wire is less than 40 N (9 lbs.), the number of momentary separations between contact shoe and contact wire increases noticeably, with an accompanying increase in average contact resistance, and in generated radio interference. Accompanying these phenomena is a considerable increase in arc burning (electrical wear) of the contact wire and pantograph contact strips due to sparking. Conversely, an excessive contact force, while it will decrease electrical wear, will increase mechanical wear by as much as a factor of two. Intermediate, there is an optimum pressure level at which overall wear will be minimized.

To ensure stable contact force, it is necessary that the catenary have a uniform elasticity and a uniform mass throughout the span length, and the following characteristics should be avoided:

1. It should not have abrupt changes in contact wire slopes due to large sags in the span or different heights of suspension at the poles.
2. It should also not have an abrupt decrease in elasticity anywhere in the span or concentrated masses in the contact wire, i.e., "hard" spots.
3. The pantograph should have a small mass interacting with the contact wire and a good amplitude-frequency characteristic.
4. The "catenary-pantograph" system should be free of any resonant oscillations of the component masses of the system.
5. The natural frequencies of the pantograph should not coincide with any frequencies of the vehicle on which it is mounted.

Simple and compound catenaries have a maximum elasticity in the middle of the span, and a minimum at the pole supports. The elasticity of the catenary depends on the span length, the tension in the wires, the location and spacing of the droppers, and the sag of the contact wires.

With a high contact force on the contact wire it is possible that one or several droppers of the catenary may become unloaded and this will lead to a change in the elasticity of the catenary and its dependence on the pressure of the pantograph.

Since the elasticity of the catenary changes along the span, the pantograph will perform periodic vertical oscillation when moving with a frequency

$$Fr = \frac{Vr}{L}$$

where Fr = frequency of pantograph vertical oscillation
Vr = velocity of pantograph in m/sec.
L = length of span in meters

That is, the frequency of vertical oscillation is equal to the number of spans traversed per second.

Moving from one span to the next, the pantograph force acts against the catenary with a frequency Fr. Under the action of this force the wires of the catenary perform vertical oscillations.

At low speeds, the pantograph forcing frequency Fr is considerably less than the natural frequency of the catenary Fn and the oscillations of the catenary when the pantograph passes are small. As the speed increases, the frequency Fr increases, and as it approaches the natural oscillation frequency of the catenary Fn, the quality of current collection deteriorates.

The speed of the pantograph at which the amplitude of the catenary vertical oscillations maximize is called the critical speed Vcr.

Assuming in $Fr = \frac{Vr}{L}$ that Fr = Fn and Vr = Vcr, the expression for critical speed is

$$Vcr = (L)(Fn)$$

After the pantograph exceeds the critical speed the amplitude of vertical oscillations of the catenary decreases and the quality of current collection is improved.

The free oscillation frequency of the catenary may be closely approximated by the formula

$$Fn = \frac{K}{L} \sqrt{\frac{Z}{M}}$$

where

K = the coefficient determined by the design of the catenary supporting unit; with spring droppers K = 0.46; with simple droppers K = 0.50.

L = span, in meters
Z = total tension in catenary, N (kg·m/sec.^{2})
M = mass of 1 meter of catenary, kg/m

Combining the last two formulas,

$$Vcr = K \sqrt{\frac{Z}{M}}$$

and it can be seen that once the wire size has been selected, the critical speed at which resonance begins depends mainly on the total tension in the catenary.

Thus, for example, for a simple catenary composed of a 65mm^2 bronze catenary cable and a 107mm^2 contact wire having a total tension of 19.6 kN (4400 lbs.) and mass per meter of 1.6 kg

(1.1 lbs./ft.), the critical speed Vcr is 199 (124 mph) km/hr. For a similar simple catenary but with a 70mm^2 steel-copper catenary cable and a 100mm^2 contact wire having a total tension of 29.4 kN (6610 lbs.) and mass per meter of 1.54 kg (1.0 lbs./ft.), the critical speed will be 248 km/hr (154 mph).

For a compound catenary consisting of a 95mm^2 steel-copper messenger cable, a 50mm^2 steel-copper auxiliary cable, and a 100mm^2 bronze trolley wire having a total tension of 42.2 kN (9490 lbs.) and a mass per meter of 2.16 kg (1.45 lbs./ft.), the critical speed will be 251 km/hr (156 mph).

From these examples it is seen that the critical speeds for typical catenaries are practically equal to the maximum speeds of contemporary electric vehicles, or in other words, the catenary and pantographs operating on an electrified high speed line are likely to be at or near resonance. Therefore, in order to avoid violent and uncontrolled oscillations, the design of the catenary and its tension should be carefully selected so that the critical speed is at least 15% greater than the maximum service speed.

Pantograph-catenary contact performance near resonant speed is improved if viscous dampers are applied to the catenary and/or pantographs. For ease of maintenance, it is preferred that dampers be applied to the pantographs only. Here they are more readily accessible for servicing, and are limited in number.

Multiple pantograph operation on one train has been found to be detrimental to good current collection at high speed, with the quality of collection deteriorating with the passage of each successive pantograph. That this condition arises is not surprising, since, as previously mentioned the critical speeds of typical catenaries are not far removed from the maximum speeds of contemporary electric vehicles, and the passage of each successive pantograph will tend to force the vibration initiated by the first. For acceptable collection performance, experience has shown that for a given consist of vehicles the number of operating pantographs should be kept to a minimum, and that as a general rule these pantographs should be spaced by at least a span length.

Demonstrating this condition, a dynamic performance computer study of three pantographs operating on the Washington-New York catenary in the 65 mph to 150 mph speed range and the -10 degree F to 110 degree F temperature range showed the following:

1. The first pantograph had power contact loss of less than 2% over all speeds and temperatures. (Satisfactory)

2. The second pantograph showed power contact loss of 2% to 5% over approximately 9% of the speed and temperature range (intermediate) and power contact loss of 5% or greater over approximately 2% of the speed and temperature range. (Unacceptable)

3. The third pantograph showed power contact loss of 2% to 5% over approximately 11% of the speed and temperature range (intermediate) and power contact loss of 5% or greater over approximately 2% of the range. (Unacceptable)

All of the less than satisfactory power collection conditions occurred in the temperature ranges below 35 degrees F or above 90 degrees F, and at speeds above 95 mph.

When the Japanese Tokaido line was constructed for operation with MU vehicles (up to sixteen cars with eight pantographs), a composite compound catenary with damping was installed. This construction proved to have a large vertical amplitude of vibration, as well as a tendency to be displaced laterally by wind loading. Later Shinkansen lines were built with a heavy compound catenary under greater tension (500 mm^2 total cross section, 53.9 kN_2(12,100 lbs.) total tension), and the original catenary (230 mm^2 total cross section, 29.4 kN (6,600 lbs.) total tension) on the Tokaido line is now being replaced with this type. The Japanese apparently are satisfied that heavy compound catenary, highly tensioned, is one answer to the problem of current collection with multiple pantographs.

The Tokaido line experience parallels that on the Northeast Corridor when the route was being prepared for the original Metroliner operation. At that time, the high speed tracks had a mixture of 4/0 (212 MCM)(107 mm^2) and 336 MCM (170 mm^2) contact wire. It was found necessary to completely replace the light contact wire with the heavier wire on the high speed tracks in order to obtain satisfactory catenary performance. In addition, it was necessary to adjust wire slopes, junctures between wire sections, and wire tension.

British Rail obtains satisfactory operation of 12 car high speed multiple unit trains by raising only four pantographs per consist and by remarshalling the cars to give maximum distance between pantographs. Current is collected satisfactorily up to 100 mph without spurious no-voltage relay operation.

Decreasing the number of operating pantographs on multiple unit trains has side benefits also. Train air resistance is decreased as the number of pantographs is decreased, as is wire wear, which is proportional to the number of pantograph passes.

IV - PANTOGRAPH DESIGN CONSIDERATIONS

In determining the design parameters of a pantograph, the following requirements must be considered:

1. The provision of a point of electrical contact between the moving vehicle and contact wire;
2. The minimum disturbance of a lightly damped overhead catenary system;
3. The function of dissipating kinetic energy and so reducing oscillation of the pantograph/overhead system.

Pantograph design is aimed at the best compromise which will comply with all of these sometimes conflicting demands. In order to cause the least disturbance to the overhead equipment, the pantograph mechanical impedance should be as low as possible and the contact force kept to a minimum. The basic parameters to be considered are mass, elasticity and damping. The impedance characteristic is dependent on the magnitude of these parameters and can be modified by variation of their values and mechanical configuration.

The pantograph mass is made up of the effective mass of the main frame and the mass of the head. There is a limit to the possible reduction in mass of the structure in order to retain sufficient rigidity to support the contact strips within the required range. There are also constraints on the materials of which the contact strips are composed. As inertial impedance is proportional to mass, every effort must be made to achieve minimum mass in order to attain maximum contact point acceleration for a given contact force.

Elasticity is introduced into the pantograph structure at the secondary suspension and in the contact strips, to reduce high frequency mechanical impedance by minimizing the mass that is required to follow the contact point trajectory.

Damping can be introduced into the pantograph structure between the base and the main frame and between the main frame and the pantograph head, to reduce resonance of the pantograph mechanism and to assist in reducing the amplitude of oscillations in the overhead system. Frame damping is limited to about 25% of critical by the large changes in forces which would otherwise occur when the pantograph is ascending or descending contact wire gradients. It has been found beneficial to arrange the damping differentially, so that there is a much higher rate when the pantograph is descending than when it is ascending, since heavy damping when ascending will cause a reduction of the mean contact force and an increased possibility of contact loss. The consequent reduction in electrical erosion on rising wires is expected to outweigh the increase in mechanical wear on falling wires.

Aerodynamic forces acting on the pantograph members can also produce a net vertical resultant force at the point of contact, changing the contact force and hence affecting current collection. These forces generally increase as the square of the air speed and so become much more significant at higher speeds. If the normal mechanically-produced contact force is substantially reduced by a negative aerodynamic force, then loss of electrical contact is a distinct possibility. However, experience has shown that a significant positive increment is also undesirable and the dynamic performance of the pantograph under the wire suffers. The aerodynamic lift characteristic should therefore be as near neutral as possible for all wind speeds and operating heights. It should also be symmetrical for either direction of travel. Further, any aerodynamic uplift forces contributed by the main frame and the head of the pantograph should separately be as small and as nearly equal as possible, so that the secondary suspension is in the middle of its design range throughout.

A non-symmetrical pantograph such as the Faiveley design does not exhibit symmetrical aerodynamic characteristics. Figure 9 shows the actual lift forces measured on Faiveley pantographs operating with knuckles leading and with knuckles trailing.

It is also interesting to note that seemingly insignificant changes in shoe configuration can produce very significant changes in aerodynamic uplift force on the shoe, as illustrated in Figure 10. (Figures 9 and 10 from "Test Results of GE-Faiveley Pantograph for High Speed Operation". R.T. Gray, General Electric Co., Dec. 1967.)

Mounting of pantographs to vehicles is generally straightforward. The bottom frame is supported on insulators which are attached to the vehicle roof as close as possible to a truck center line, in order to minimize lateral displacement on curves. Clearance requirements between energized and grounded parts of the vehicles for common voltages are:

50KV	21"
25 KV	10-1/2"
12.5 KV	7"

An exception to these simple roof mountings is found when the vehicle is of the tilt-body type. On this equipment, the pantograph may be supported on a truck mounted framework so that it will remain approximately on the vertical center line of track regardless of car body position. An alternative to this arrangement is used by ASEA of Sweden on the X-15 test vehicle and is shown in Figure 11. Here the pantograph is fixed to a roof-mounted slewing mechanism which is linked to the trucks below the tilting arrangement. Thus, tilting of the car body will cause the pantograph to slew against the tilt and remain on the vertical center line of truck. A similar arrangement, except that the roof-mounted slewing mechanism has the form of a parallelogram, is used on the British APT.

Figure 9

AERODYNAMIC LIFT TESTS - NOVEMBER 6, 1967

Standard G.E.-Faiveley Shoe 

Shoe 25" Above Base (or About 18 ft. Above Rail)

Knuckles Forward, Eastbound ————————

Knuckles Trailing, Westbound — — — — —

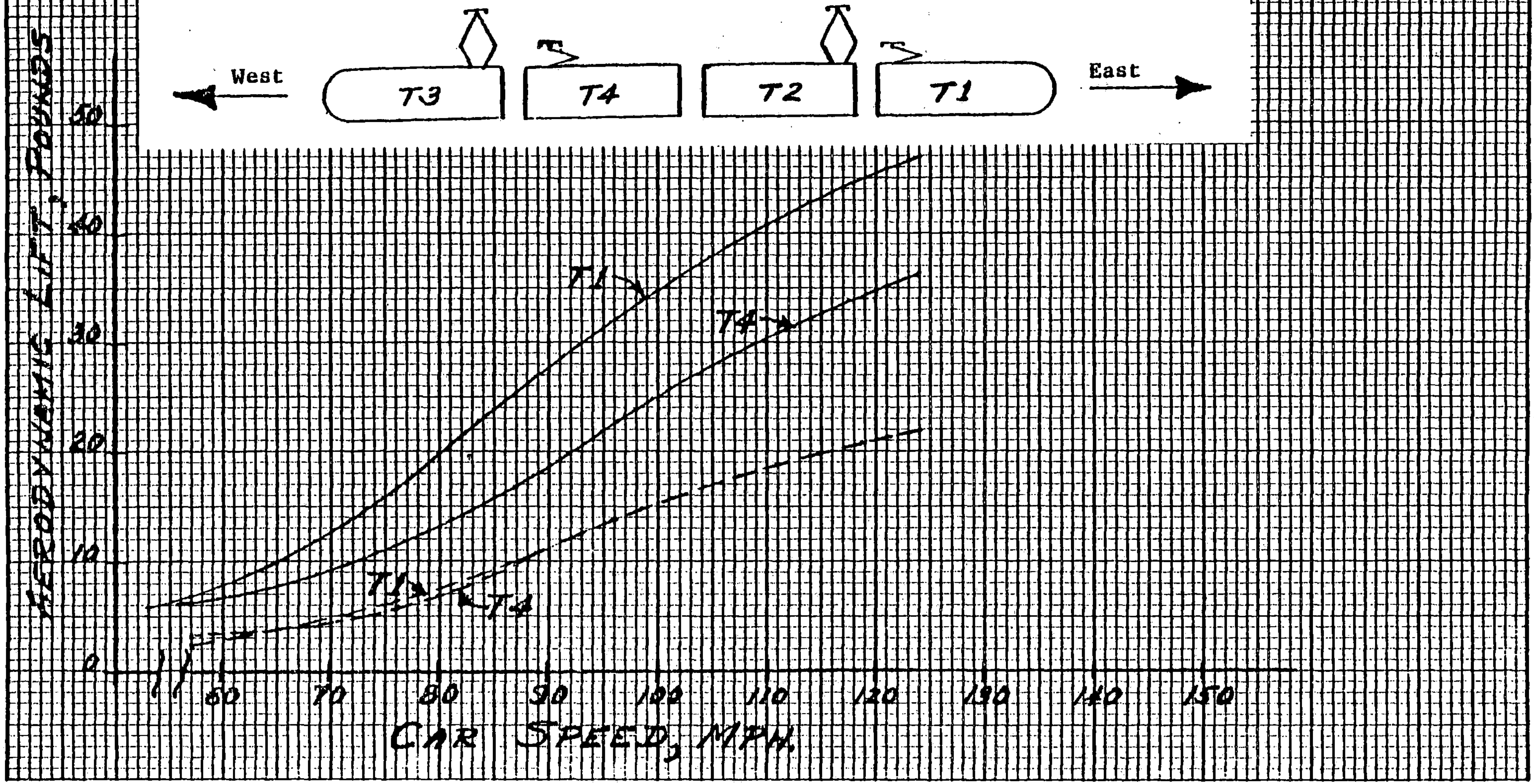
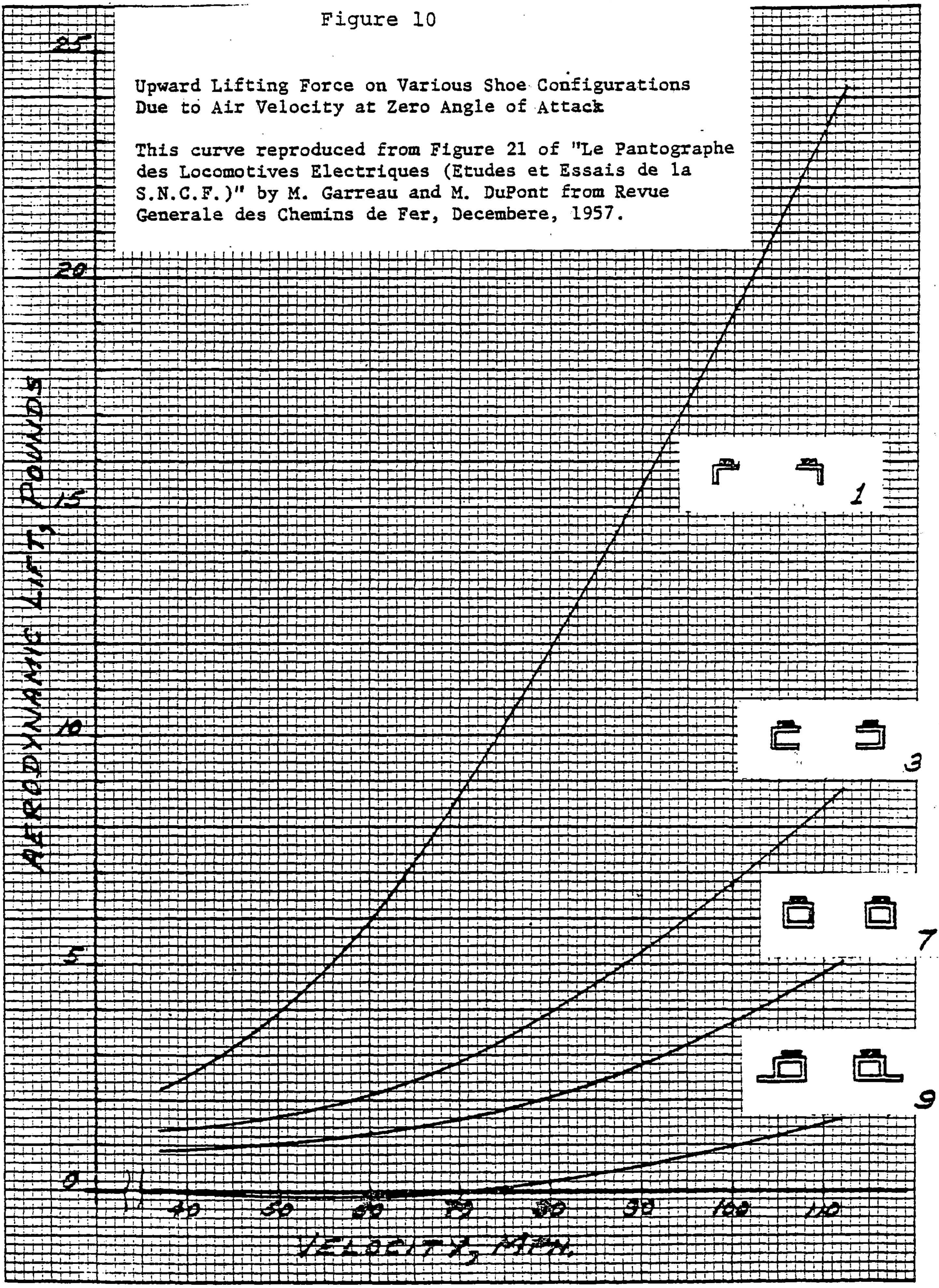


Figure 10



Upward Lifting Force on Various Shoe Configurations Due to Air Velocity at Zero Angle of Attack

This curve reproduced from Figure 21 of "Le Pantographe des Locomotives Electriques (Etudes et Essais de la S.N.C.F.)" by M. Garreau and M. DuPont from Revue Generale des Chemins de Fer, Decembere, 1957.

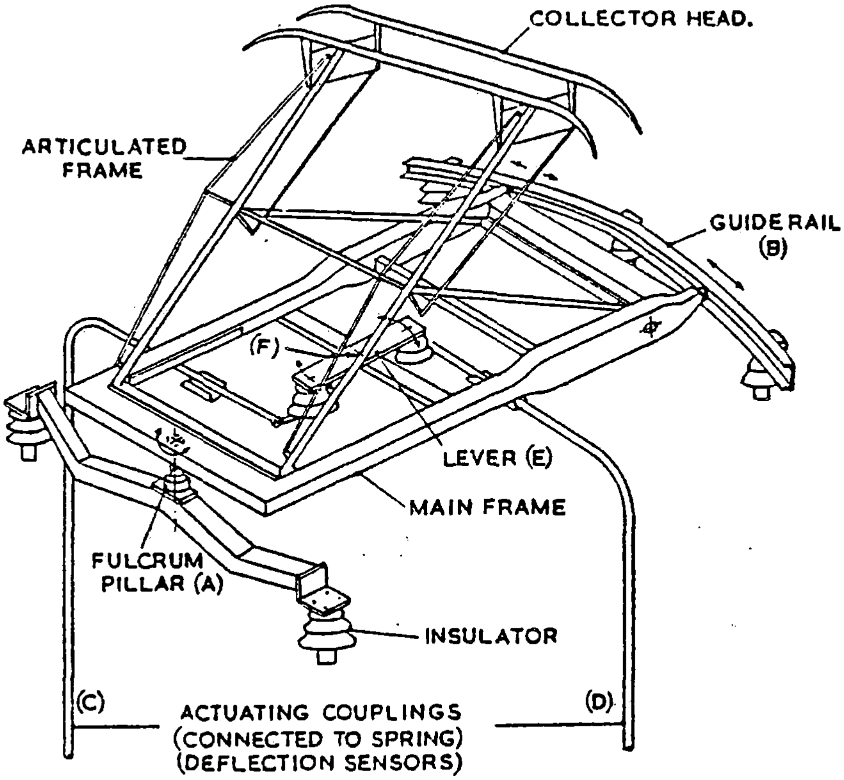


Figure 11

Pantograph Slewing Mechanism for Tilt-Body Vehicles

While not actually a design consideration, the importance of adequate service testing cannot be overemphasized. After the pantograph is designed and prototypes are constructed, there must follow a service testing period during which the design is perfected and its performance fine-tuned. This testing must be done under service conditions and under the catenary where the pantograph will ultimately operate. Furthermore, both pantographs and catenary must be thoroughly broken in before uniform and stable test results will obtain. Collector shoe wear rate tests can be particularly deceiving in this regard. A good performance record under one set of conditions and one catenary system does not insure that a pantograph will operate under another set of conditions and another catenary.

V - SUMMARY

RECOMMENDATIONS CONCERNING PANTOGRAPHS

1. Mass of the moving part of the pantograph

   a. The mass of the collector shoe and of the articulated system (moving parts) of the pantograph should be as small as possible.

   b. Weight reduction in the articulated system implies a small operating range of the pantograph, which is feasible on new lines through the installation of overhead catenary equipment of reduced and practically constant height.

   c. If constant catenary height cannot be realized, the influence of the mass can, if necessary, be reduced by adopting a two-stage current collecting device separating the compensation function for contact wire distortion from that for contact wire height variation.

   d. The first function could be accomplished by a pantograph with small operating range (12" to 16") mounted on the upper part of an articulated system having a sufficient operating range to handle the second function. In the case of the Northeast Corridor, this second function will require a travel of 11 ft.

   e. The movements of the two stages may be independent. The respective characteristics of the upper and lower pantograph assemblies should be studied so as to clearly separate the functions by taking into account the masses and inertia inherent in the constituent parts. Lower and upper stage damping does not appear to have any effect on dynamic performance.

2. Collector shoe springing

   a. This should be studied so as to correctly "uncouple", <u>for movements of small amplitude</u>, the mass of the collector shoe from that of the articulated system.

3. Upward contact force

   a. There is occasion to experimentally determine the optimum value of the static and aerodynamic upward force which ensures correct current collection and minimum contact wire lift. The coefficient of lift should be as nearly neutral as possible, in order to minimize the effects of very strong head-winds or cross-winds.

4. Position of pantographs on vehicle

    a. The position should be chosen so as to place the pantographs away from aerodynamic disturbances due to vehicle-body configuration. However, a location at or adjacent to a truck center must be retained to minimize lateral displacement of the pantograph on curves.

5. Number of pantographs in use

    a. When several pantographs are simultaneously working, the quality of the contact deteriorates increasingly from first to last pantograph. Moreover, the mechanical wear of the contact wire is directly proportional to the number of pantograph passages.

    b. Consequently, it is recommended to limit the number of pantographs working on a same trainset to 1 or 2, avoiding in the latter case close spacing. Bus coupling through the train is necessary when the number of working pantographs is limited.

6. Additional recommendation

    a. For the purpose of reducing energy consumption at high speed, the aerodynamic drag of the pantograph should be as low as possible. Pantograph structure should be streamlined and reduced in cross section insofar as is possible without detriment to other pantograph functions.

APPENDIX

DETAILS - PANTOGRAPH TYPES

Diamond Frame Pantograph

This is the oldest form of pantograph in use, and until twenty years ago it dominated the field of heavy electric traction. A typical pantograph of this type is pictured in Figure 2. Usage of this type of pantograph on Northeast Corridor equipment is as shown on lines 1-7 and 15 and 16 of Figure 3, which also gives working height dimensions.

Arrangement and operation of this type of pantograph is shown schematically in Figure 12.

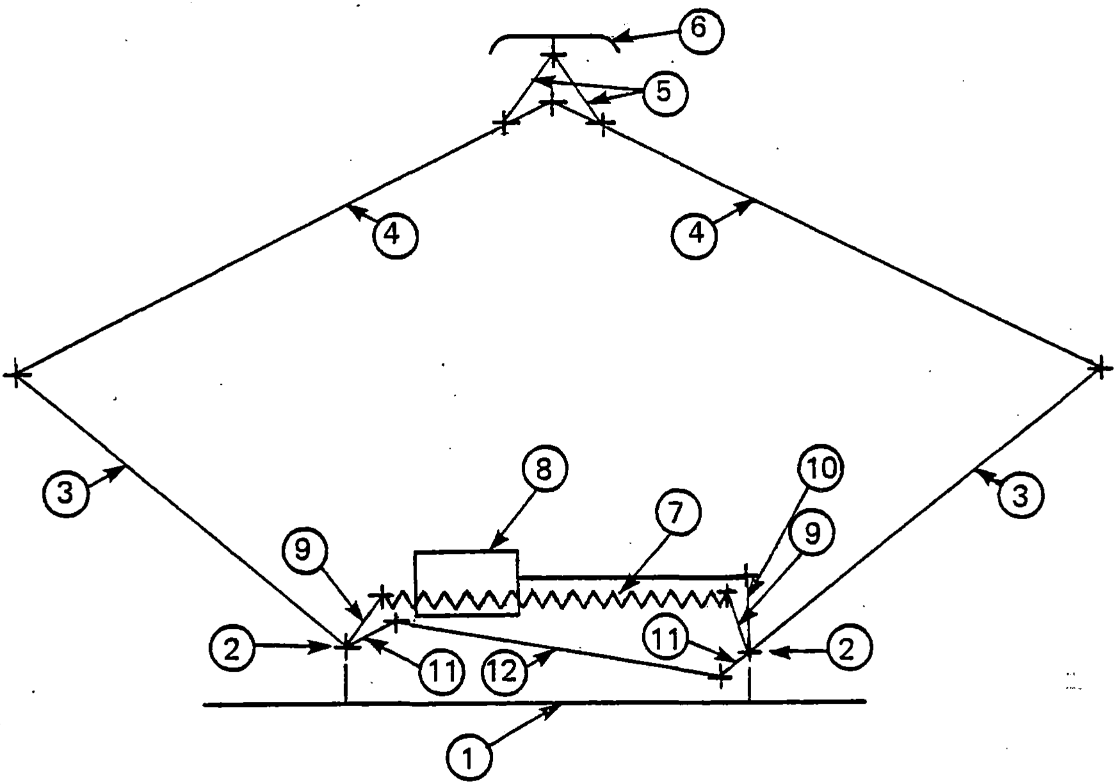
Lower and upper pantograph frames 3 and 4 support the collector shoe 6 through links 5 and are supported on the bottom frame 1, which is electrically isolated from the vehicle structure. Lower frames 3 are pivoted about shafts 2, these shafts being acted upon by springs 7 through cranks 9, causing pantograph to rise, and collector shoe 6 to touch trolley wire. A link 12 working through cranks 11 equalizes rotation of shafts 2 and causes pantograph to rise symmetrically. An air cylinder 8 working on crank 10 affixed to one shaft 2 and against springs 7 allows pantograph to be lowered.

Metallic wearing strips, typically mild steel, were originally used on the collector heads of these pantographs, but carbon wear strips have generally been substituted in recent years. Carbon wear strips offer the advantages of longer service life, reduced wire wear, and reduced static interference with radio and telephone communications.

Other characteristics of these pantographs, as used in Corridor service are as follows:

Speed range	0-100 mph
Current capacity	1000 amps.
Total weight	1000 lbs.
Upper & lower frame weight	N.A.
Collector head weight	34# (3 lines of carbon)
Collector head weight	31# (2 lines of carbon)
Contact force	28#
Damping	Not used

While this type of pantograph has reasonable bi-directional characteristics because of its symmetrical construction, its aerodynamic characteristics are poor because of the large surface area of its frames. Likewise, the large inertia of its heavy frames cause it to have poor tracking characteristics at high speed. This type of pantograph is not a candidate for new installations.



① Bottom Frame
② Shafts
③ Lower Frame
④ Upper Frame
⑤ Links
⑥ Collector Shoe
⑦ Springs
⑧ Lowering Air Cylinder
⑨ Cranks
⑩ Cranks
⑪ Cranks
⑫ Link

SCHEMATIC – DIAMOND FRAME PANTOGRAPH
FIGURE 12

Modified Diamond Frame Pantograph

A contemporary modification of the diamond frame pantograph is manufactured by August Stemmann OHG of Germany, their type designations BS-134 and BS-167. This type of pantograph is illustrated in Figure 5, and schematically its operation is the same as that of the conventional diamond frame type shown in Figure 12. Usage of this type of pantograph on Northeast Corridor equipment is shown on lines 12-14 of Figure 3.

Because of its symmetrical construction, this pantograph has good directional and aerodynamic characteristics, and because of the reduction in number of frame members, its drag is reduced as compared to the conventional diamond frame type.

Other characteristics of this pantograph as used in Corridor service are as follows:

Speed range	0-150 mph
Current capacity	600 amps
Total weight	700 lbs.
Upper & lower frame weight	N.A.
Collector head weight	31# (2 lines of carbon)
Collector head weight	36# (3 lines of carbon-Metroliner)
Contact force	28#
Damping	Not used

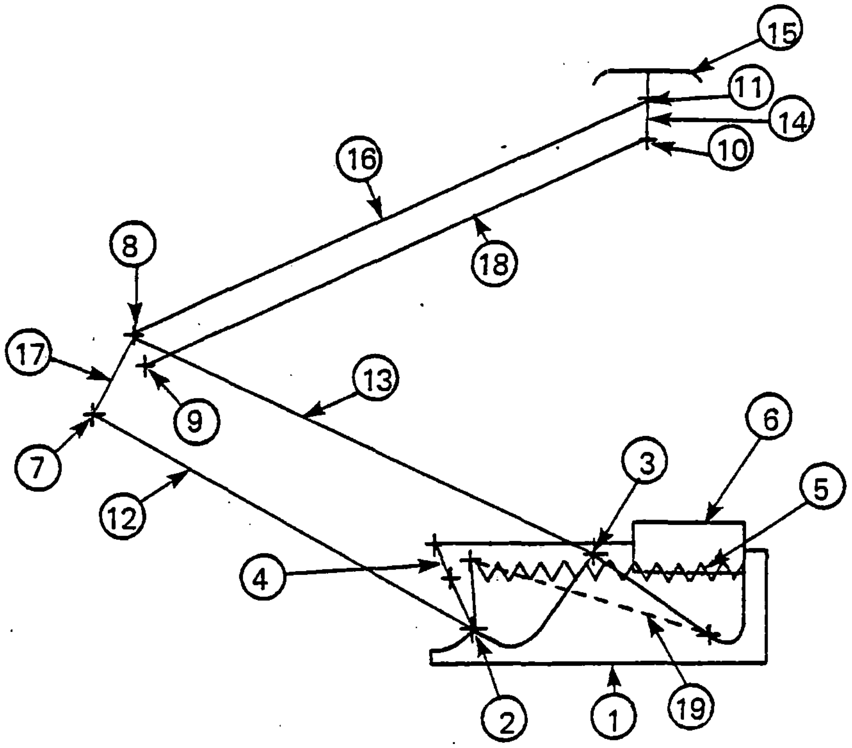
This pantograph is a candidate for use in high speed service.

Single Arm Pantographs

This type of pantograph has come into prominence in the last twenty years. Although not the only manufacturer of this type of pantograph, the name of L. Faiveley Co. of France has become synonymous with the type, and a typical Faiveley pantograph is illustrated in Figure 4. Usage of this type of pantograph on Northeast Corridor equipment is as shown on lines 8-11 and 17 and 18 of Figure 3, which also gives working height dimensions.

Arrangement and operation of this type of pantograph is shown schematically in Figure 13. The articulated system is composed of two arms 12 and 13. They form joints at points 2 and 3 of the frame and points 7 and 8 of the terminal bracket 17 and collector shoe frame 16. The points 2, 3, 7, 8, and 11 are located so that, when arms 12 and 13 rotate respectively in their joints, the curve of point 11 is a straight line almost perpendicular to the bottom frame 1.

Counterbalance springs 5 act on the rotating shaft 2 through cranks 4 to raise the pantograph. Pantograph is lowered by applying air pressure to lowering cylinder 6 which turns rotating shaft 2 through crank 4. If specified, a damper 19 may be installed to snub rotation of shaft 2.



① Bottom Frame
② Rotating Shaft
③ Fixed Rotating Point
④ Crank
⑤ Counterbalance Spring
⑥ Lowering Cylinder
⑦ Fixed Rotating Point
⑧ Fixed Rotating Point
⑨ Fixed Rotating Point
⑩ Fixed Rotating Point
⑪ Fixed Rotating Point
⑫ Lower Arm
⑲ Damper
⑬ Thrust Rod
⑭ Shoe Control Rod
⑮ Collector Shoe
⑯ Collector Shoe Frame
⑰ Terminal Bracket
⑱ Auxiliary Connecting Rod

SCHEMATIC – FAIVELEY PANTOGRAPH
FIGURE 13

The collector shoe is equipped with carbon wearing strips, the number of strips used being dependent on the current requirements of the particular vehicle.

Other characteristics of these pantographs as used in Corridor service are as follows:

Speed range	0-125 mph
Current capacity	1000 amps
Total weight	725 lbs.
Upper & lower frame weight	240 lbs.
Collector head weight	31# (2 lines of carbon)
Collector head weight	34# (3 lines of carbon)
Collector head weight	36# (3 lines of carbon-Metroliner)
Contact force	25# - 28#
Damping	Not presently used, optional

Damping, when used, is in the 2.5 to 4.0 lb. sec./ft. range, double acting.

Since the single arm pantograph is non-symmetrical, contact force during high speed operation may be greatly affected by direction of operation, with higher forces usually being associated with a leading knuckle. However, if close attention is given to collector shoe configuration, the directional effect can be compensated.

The Stemman BS-87 pantograph is similar in design and concept to the Faiveley single arm pantograph, the most noticeable difference being that the lower arm 12 and thrust arm 13 (see Figure 13) are transposed in position. Its characteristics are comparable to those of the Faiveley.

Both the Faiveley and Stemmenn BS-87 pantographs are candidates for use in high speed service.

Another design of single arm pantograph which may be a candidate for Northeast Corridor service is the Brecknell Willis & Co. (England) "Hugereach" design which is marketed in the United States by the Ringsdorff Corporation. A prototype of the "Hugereach" design has not yet been constructed, although similar pantographs of smaller size are in service overseas and on transit properties in this country.

The Brecknell Willis design is illustrated in Figure 14 and shown schematically in Figure 15.

The "Hugereach" pantograph consists principally of a bottom frame 1, a lower arm 7, upper arm 11, and collector shoe 12. The lower arm 7 is pin-jointed to the bottom frame at 3 and to the upper arm 11 at 8. Equalizer bar 6 (which physically is located inside lower arm 7) is pin-jointed to the bottom frame at

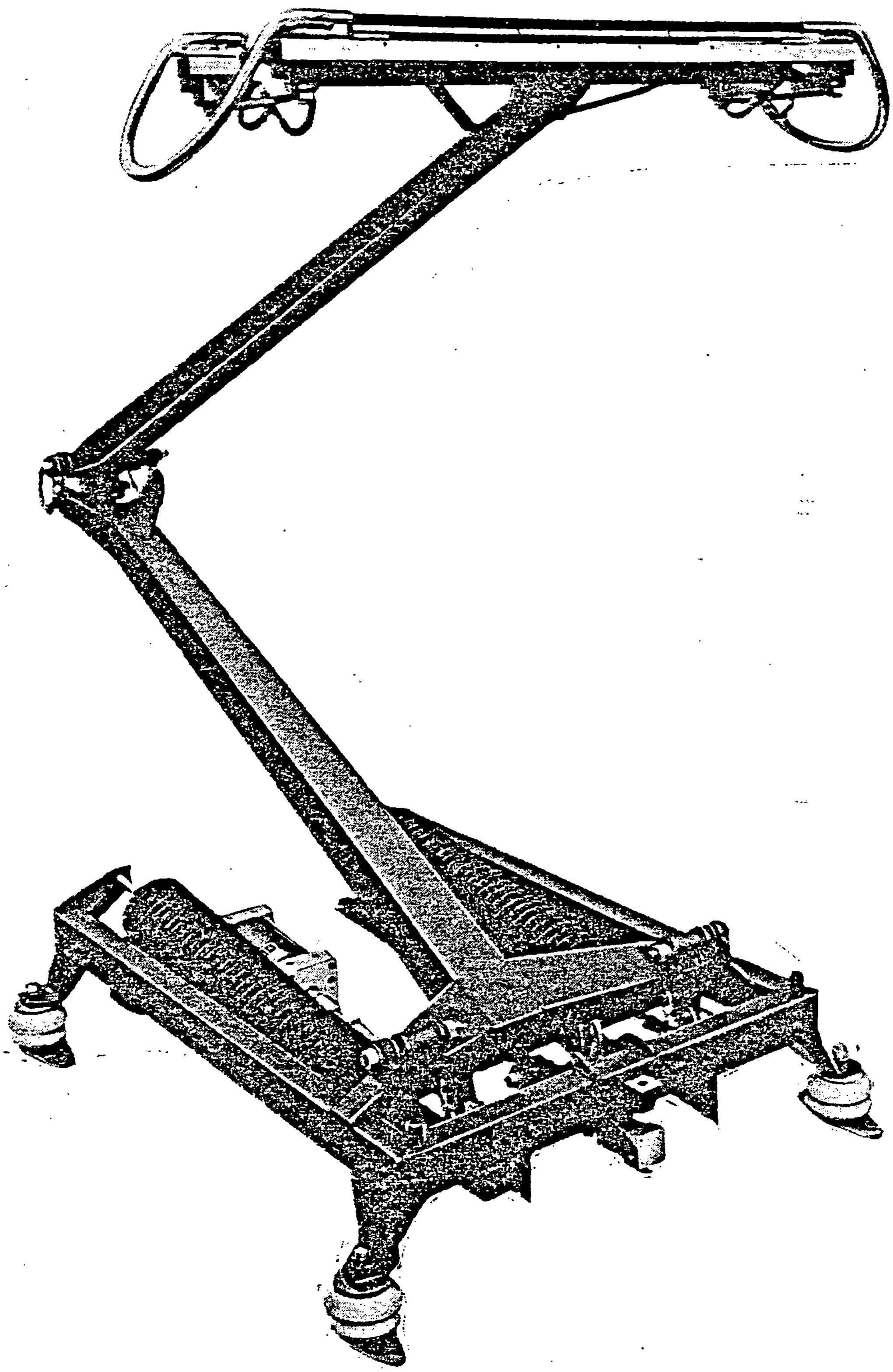
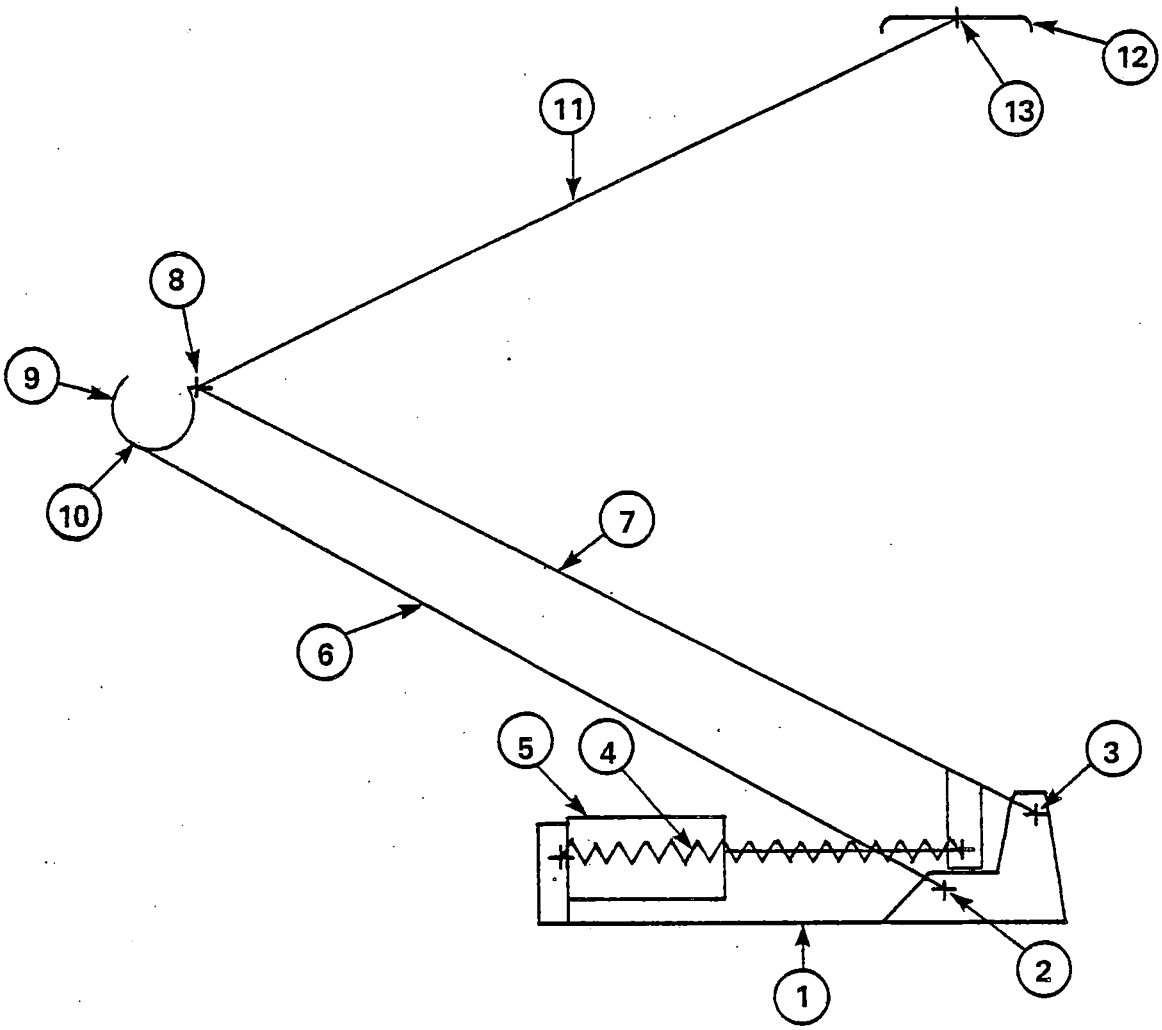


Fig. 14 Brecknell Willis Pantograph



①	Bottom Frame	⑦	Lower Arm
②	Fixed Rotating Point	⑧	Fixed Rotating Point
③	Fixed Rotating Point	⑨	Cam
④	Spring and Snubber	⑩	Roller Chain
⑤	Lowering Cylinder	⑪	Upper Arm
⑥	Equalizer Bar	⑫	Collector Shoe

⑬ Pivot

SCHEMATIC – BRECKNELL WILLIS
PANTOGRAPH

FIG. 15

2 and is connected to the upper arm 11 through roller chain 10 and cam 9 (which is part of upper arm 11). With clockwise rotation of lower arm 7, upper arm 11 is caused to rotate counterclockwise, causing collector shoe 12 to rise vertically on a line perpendicular to the bottom frame 1. Lower arm 7 is rotated clockwise by spring 4 to raise the pantograph, and counterclockwise by lowering cylinder 5 to lower the pantograph. Note that pivot 13 is so near to wire height that no virtual pivot or paralleling mechanism is required at the collector shoe. The collector shoe is equipped with two lines of carbon wearing strips.

Other characteristics of these pantographs are as follows:

Speed range	0-125 mph
Current capacity	700 amps
Total weight	350 lbs.
Upper & Lower frame weight	66 lbs.
Collector head weight	31 lbs. (2 lines of carbon)*
Contact force	15 lbs-25 lbs
Damping	Hydraulic

* Standard Northeast Corridor collector head

Two-Stage Pantographs

For very high speed service (over 125 mph) a two-stage pantograph becomes an attractive alternative. By separating the function of compensation for contact wire deformation from the function of compensation for contact wire height variation, better tracking characteristics are possible. The first function is assumed by an upper stage of short travel and low inertia, while the second function is assumed by a lower stage of conventional travel.

The two-stage pantograph of the L. Faiveley Co., their type AM DE, which is illustrated in Fig. 7, appears to have many desirable characteristics which make this pantograph a candidate for Northeast Corridor service, and one which will ameliorate many of the problems associated with high-speed power collection once it has been adequately developed. Service experience with this pantograph under American conditions does not presently exist.

This type of pantograph is illustrated in Figure 7, and schematically each of the two stages is arranged as shown in Figure 13.

Characteristics of this pantograph (as proposed for U.S. service) are as follows:

Speed range	0-175 mph
Current capacity	800 amps
Height range	10'-2"
Effective mass-collector head	26 lbs.
Effective mass-lower frame	75 lbs.
Effective mass-upper frame, at base	15 lbs.
Effective mass-upper frame, at apex	11 lbs.
Contact force	16 lbs.

Damping is provided on both upper and lower stages, with the "down" damping on the lower stage being higher than the "up" damping.

Aerodynamic characteristics of this pantograph should be favorable, although they have not been confirmed by service experience account a prototype pantograph of American configuration is still in the design stage.

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PART 6. ANALYSIS OF ENERGY CONSUMPTION OF FUTURE PASSENGER TRAINS

Richard A. Uher

1.0 EXECUTIVE SUMMARY

Energy consumption of future passenger trains (such as those in prototype and operational stages of development in North America, Europe and Japan, and which might be expected to be used with modification on the upgraded version of the Northeast Corridor (NEC), and other selected corridors) was reviewed using train performance simulation. In addition, a parametric analysis of both locomotive-hauled and Multiple-Unit (MU) passenger trains was conducted on the NEC. Variations of energy consumption and schedule time were estimated with train weight, maximum speed, speeds in curves and train resistance. The ranges of the parameters were selected to cover those types of trains which would be expected to operate in the corridor within the next 10 to 15 years.

Because of a lack of propulsion system data, estimates of energy consumption at the rail were made for several electric trains on the NEC. These include the British Advanced Passenger Train (APT), the German ET403, the Italian ET401, the Japanese 961, and the French TGVPSE. Estimates of energy consumption were made for the "as built" version of the trains and a version which was modified for North American operation. The trains were configured to be approximately equivalent in seating to an eight and six car upgraded Metroliner (MET), respectively. Figure 1.1 summarizes the results for the trains modified for North American operation and equivalent to eight car MET seating. The following conclusions refer to the figure.

1. The shortest schedule times in both corridor segments are exhibited by the ET401 and the APT, which have tilt capability and can negotiate curves at higher speeds (6 inch vs. 3 inch unbalance). The effect of tilt capability on schedule time is more significant in the New York-Boston segment because of the larger number of curves.

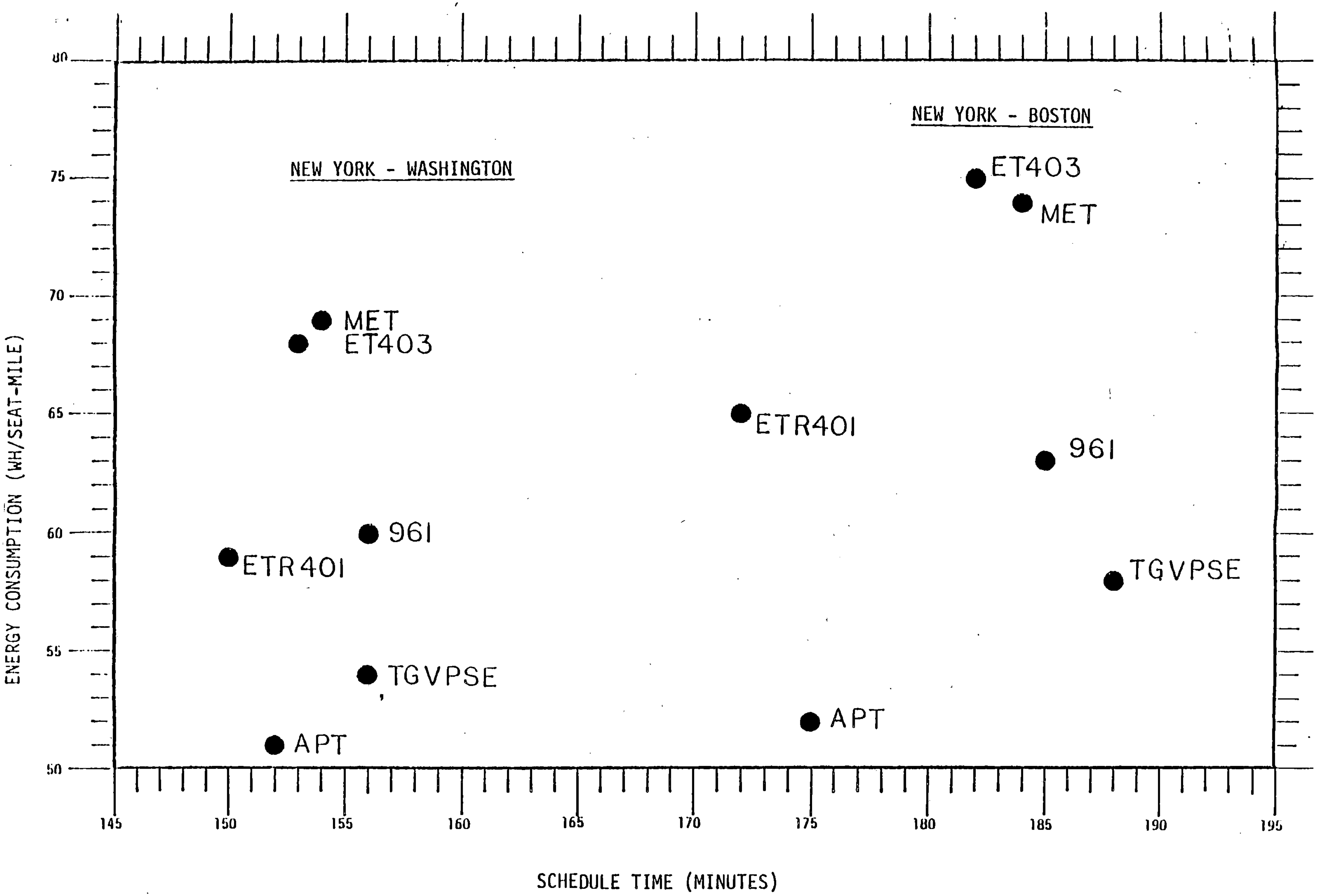


FIGURE 1.1 ENERGY CONSUMPTION VS. SCHEDULE TIME FOR POTENTIAL NEC TRAINS

2. Because of light weight construction techniques, reduction in cross section and articulation, the APT and TGVPSE have lower energy consumption than the remaining trains.

3. Energy consumption on a seat-mile basis is higher on the New York-Boston corridor segment because of the larger number of required slowdowns due to curves.

Estimates of fuel consumption were made for several non-electric passenger trains for selected corridors in the United States. Both present (existing conditions) and hypothetical upgraded versions of the New York-Buffalo, (NY-BU), Chicago-Detroit (CH-DE), Los Angeles-San Diego (LA-SD), and Vancouver-Portland (VA-PO) routes were used as the basis for energy consumption and schedule time estimate for the AMTRAK (F40PH-AMCOACH) train, the AMTRAK Turboliner (TURB), the SPV2000, the British High Speed Train (HST), and the Canadian LRC. A summary of the results is shown in Figure 1.2 for each train consist, which was equivalent in seating to the AMTRAK (F40PH-AMCOACH) train with four cars and one locomotive. The HST was modified for North American Operation. The following conclusions are valid:

1. The LRC, which has tilt capability, can improve schedule speed on the Los Angeles-San Diego and Vancouver-Portland corridors, but not significantly on the Chicago-Detroit and New York-Buffalo corridors.

2. The HST, which is also of lightweight construction, is penalized severely using AMTRAK seating policy and structure modifications to meet U.S. safety standards.

3. Although the Turboliner is a low-weight train, the use of the turbine engine, with its high idle fuel consumption, causes its energy consumption to be significantly higher than the other trains.

4. Both schedule speed and energy consumption are quite dependent on the characteristics of the route (profile, alignment and speed restrictions) as well as the characteristics of the trains.

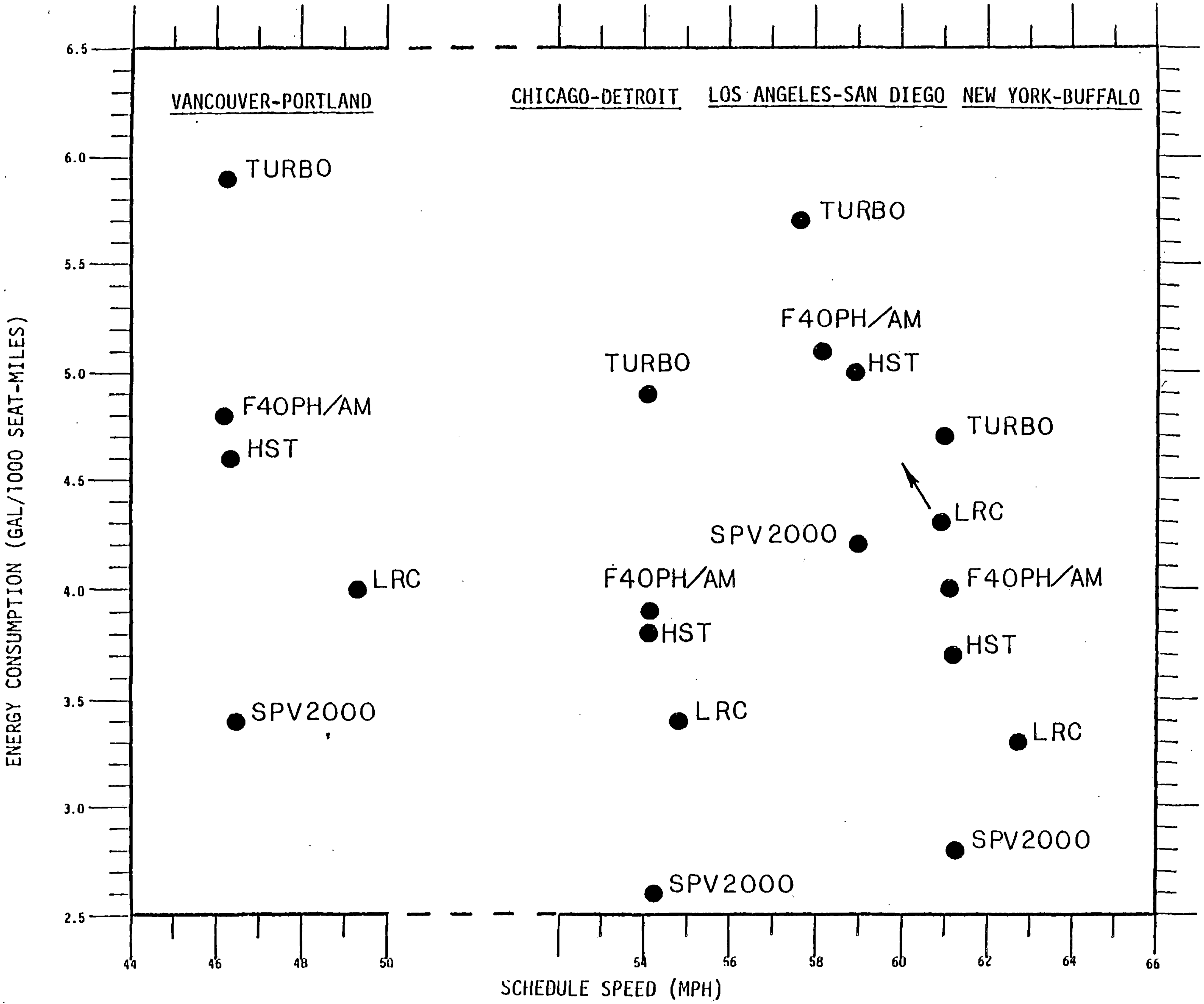


FIGURE 1.2 ENERGY CONSUMPTION VS. SCHEDULE SPEED
FOR NON-ELECTRIC TRAINS

A parametric analysis of the effect of train weight, maximum speed, train resistance and speed in curves on energy consumption for MU and locomotive-hauled trains, which could be expected to run in the future on the NEC, was completed. Speed restrictions for curve unbalance from 3 to 12 inches were developed, and maximum speeds were varied from 120 to 160 MPH for MU-trains and from 120 to 140 MPH for locomotive-hauled trains. The MU-train weight was varied between 410 and 610 tons for six cars, while the locomotive hauled train weight was varied between 310 and 570 tons for a locomotive with six coaches. This range of weights is reasonable for trains of the future, which may or may not have tilt in curving capability.

Energy consumption at the pantograph is plotted as a function of train weight in Figure 1.3 for various speeds for both type trains on the NEC. All trains have 400 seats. The propulsion system is a phase control rectifier DC drive.

The following conclusions can be drawn as a result of this parametric analysis:

1. As expected, energy consumption increases with train weight in the NEC. This increase ranges between 0.09-0.11 WH/seat-mile/ton.

2. The increase in energy consumption with maximum speed is different in the corridor segments. It ranges from 0.3-0.45 WH/seat-mile/MPH in the NY-BO segment to 0.7-1.05 WH/seat-mile/MPH in the NY-WA segment. The reason for the small increase in the NY-BO section is because of the many speed restrictions due to curves.

3. Energy consumption may increase or decrease with increase of speed in curves in the range from 3 to 12 inches of unbalance depending on the perturbation of kinetic energy supplied compared to increased train resistance because of higher curve speeds. The energy variation seems to be less than 7 WH/seat-mile over all ranges of unbalance and for all weights and maximum speed.

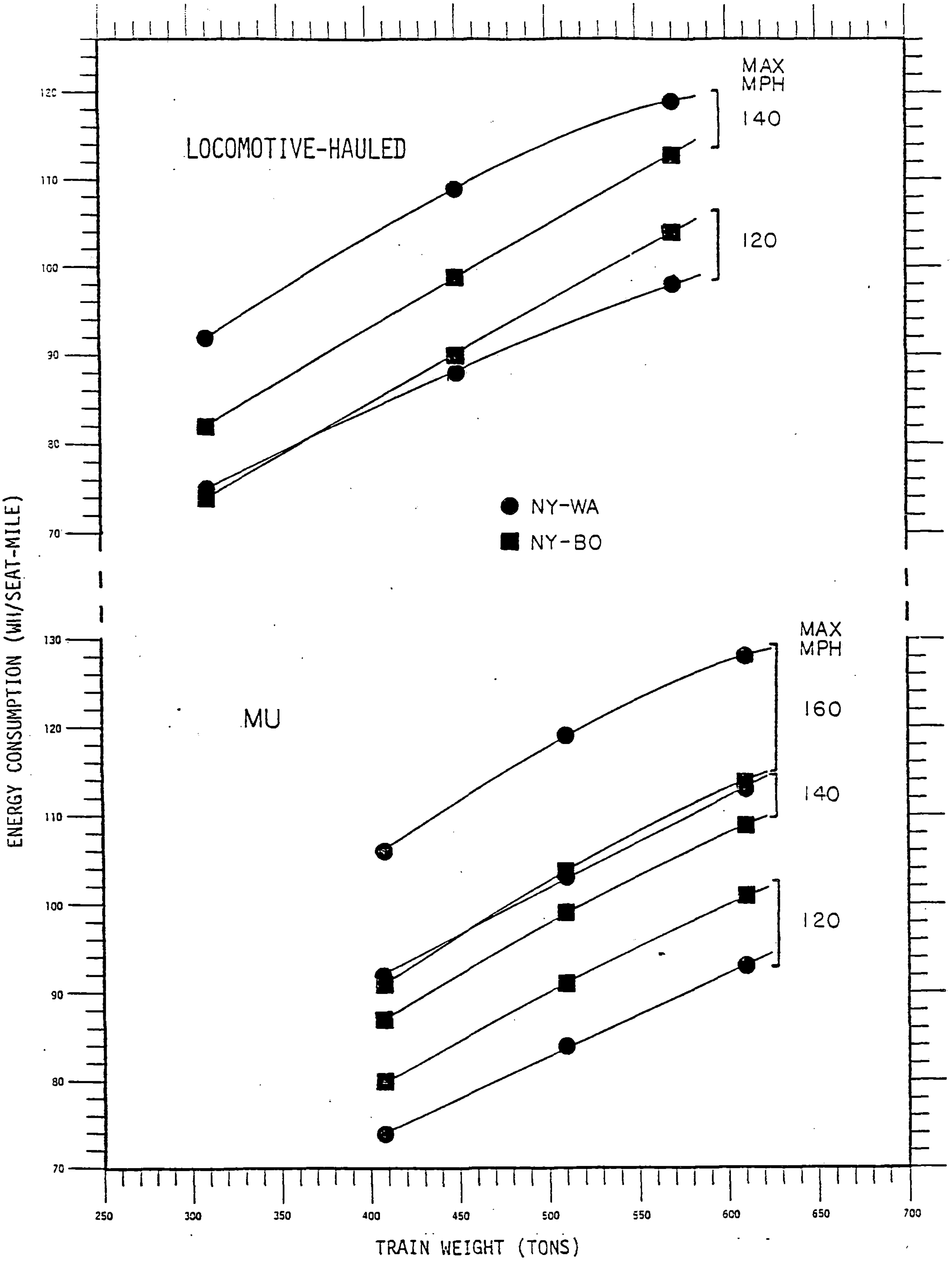


FIGURE 1.3 RESULTS OF ENERGY CONSUMPTION ANALYSIS OF MULTIPLE UNIT AND LOCOMOTIVE-HAULED TRAINS ON NEC

4. The variation of energy consumption with changes in aerodynamic train resistance ranges from 0.3 to 0.4% change in energy consumption per percent change in aerodynamic train resistance on the NY-BO corridor segment and from 0.4 to 0.5% change in energy consumption per percent change in aerodynamic train resistance on the NY-WA corridor segment. This value is independent of maximum speed within these limits, and independent of the manner in which aerodynamic train resistance is changed (i.e., streamlining, cross section changes, consist size changes). The values are good over a range of ± 30% in train resistance change.

2.0 INTRODUCTION

The purpose of this report is a comprehensive review of energy consumptions of advanced passenger trains on selected routes in the United States. This review was accomplished by simulating particular trains on these selected routes and estimating both their performance and energy consumption.

Section 3.0 covers the basic methodology used for the energy consumption estimates. A basic review of the train equations of motion used in the simulator, sources of train resistance and resistance formulae, grade and curve forces, and power and energy use in both electric and non-electric trains is presented. This section also considers the energy end use in the propulsion system itself and discusses the source of the indices generally used for energy consumption efficiency measures.

Section 4.0 reviews energy consumption of future passenger trains, which are in prototype and operational stages of development in North America, Europe, and Japan, and which might be expected to be used with modification on the upgraded version of the Northeast Corridor (NEC) and other selected corridors. Although some of the energy estimates were completed as part of the Improved Passenger Equipment Evaluation Program (IPEEP) train systems review, more detailed information on energy is presented on "as built" as well as modified versions of the trains. Section 4.1 covers the energy consumption of advanced electric trains on the NEC, both the New York-Boston and New York-Washington segments. Section 4.2 covers the energy consumption of advanced non-electric trains on four promising corridors.

In Section 5.0, a parametric analysis of the effects of weight, maximum speed, train resistance and speeds in curves on energy consumption is discussed. Both MU-trains and locomotive-hauled trains are considered.

A summary of the principle results of this study appears in Section 1.0.

3.0 ENERGY COMPUTATION METHODOLOGY

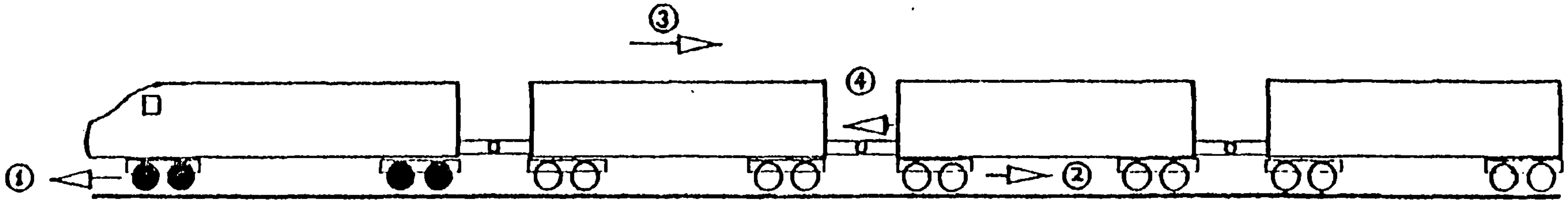
3.1 THE EQUATION OF MOTION OF A TRAIN

A simplified diagram of the longitudinal forces acting on a train in motion is shown in Figure 3.1. The forces are indicated by arrows and are labeled numerically.

Tractive effort is transmitted to the vehicle as the reactive force of the wheel against the rail. It can only be supplied from powered cars. The locomotive shown in the figure is a powered car. In passenger operations using rail, it is possible to have every car powered, in which case many more axles would be driven. This train configuration, referred to as multiple unit operation (MU), is generally capable of higher accelerating rates than locomotive hauled.

Braking effort is normally transmitted to the vehicle as the reactive force of the wheel against the rail, however, in a direction opposite from that of tractive effort. Generally all cars in the train have the capability of providing braking effort. Braking effort is usually divided into two categories, dynamic and friction. Friction braking is applied by rubbing two surfaces to create the force (tread on wheel/disc pad on disc), while dynamic is applied without surfaces in contact (electromagnetic, hydraulic or gas dynamic).

Those forces which oppose the motion of the train and act through the wheel other than braking effort are rolling train resistance, curve resistance and grade resistance. The aerodynamic portion of train resistance, which is an effective force generated because of the motion of the train through the air and the action of the wind on the train, acts on the total vehicle (rather than just through the wheels).



EQUATION OF MOTION: $F_A - T_{RR} - T_{RA} - G - C = M_E \frac{DV}{DT}$

FORCES (INDICATED BY NUMERALS AND ARROWS)

1 TRACTIVE EFFORT

2 ROLLING PORTION OF TRAIN RESISTANCE, CURVE RESISTANCE, GRADE RESISTANCE AND BRAKING EFFORT (FRICTION BRAKES)

3 AERODYNAMIC PORTION OF TRAIN RESISTANCE

4 COUPLER FORCE

F_A = T_E (TRACTIVE EFFORT)

= $-B_E$ (BRAKING EFFORT)

T_{RR} = ROLLING PORTION OF TRAIN RESISTANCE

T_{RA} = AERODYNAMIC PORTION OF TRAIN RESISTANCE

C = CURVE RESISTANCE

G = GRADE RESISTANCE

M_E = EQUIVALENT MASS

$\frac{DV}{DT}$ = ACCELERATION OR DECELERATION

● DRIVER WHEEL

○ NON-DRIVER WHEEL

FIGURE 3.1 DIAGRAM OF FORCES ACTING ON A TRAIN

Coupler forces are developed as the result of the motion of the train. They are very complicated forces and it is by means of the coupler that the forces of traction, braking, and train curve and grade resistance are transmitted from vehicle to vehicle. Because of variation of forces from vehicle to vehicle, coupler forces also include short time force oscillation induced by the dynamics of train motion.

The equivalent mass of the train includes the real mass plus the effects of rotating parts which include wheel and axles, gear units, motors etc. The reason that rotating parts must be included is that the torque to keep them rotating, and to change their speed of rotation is captured from the forces applied to train motion.

Unless it is desired to study the details of train motion for the purpose of train handling, the equation of motion in the figure may be applied to the train as a whole rather than to each vehicle independently. When this is done, as is the case in most train performance calculations, the following assumptions are made:

1. Dissipation of energy in the couplers (draft gear) is part of train resistance.

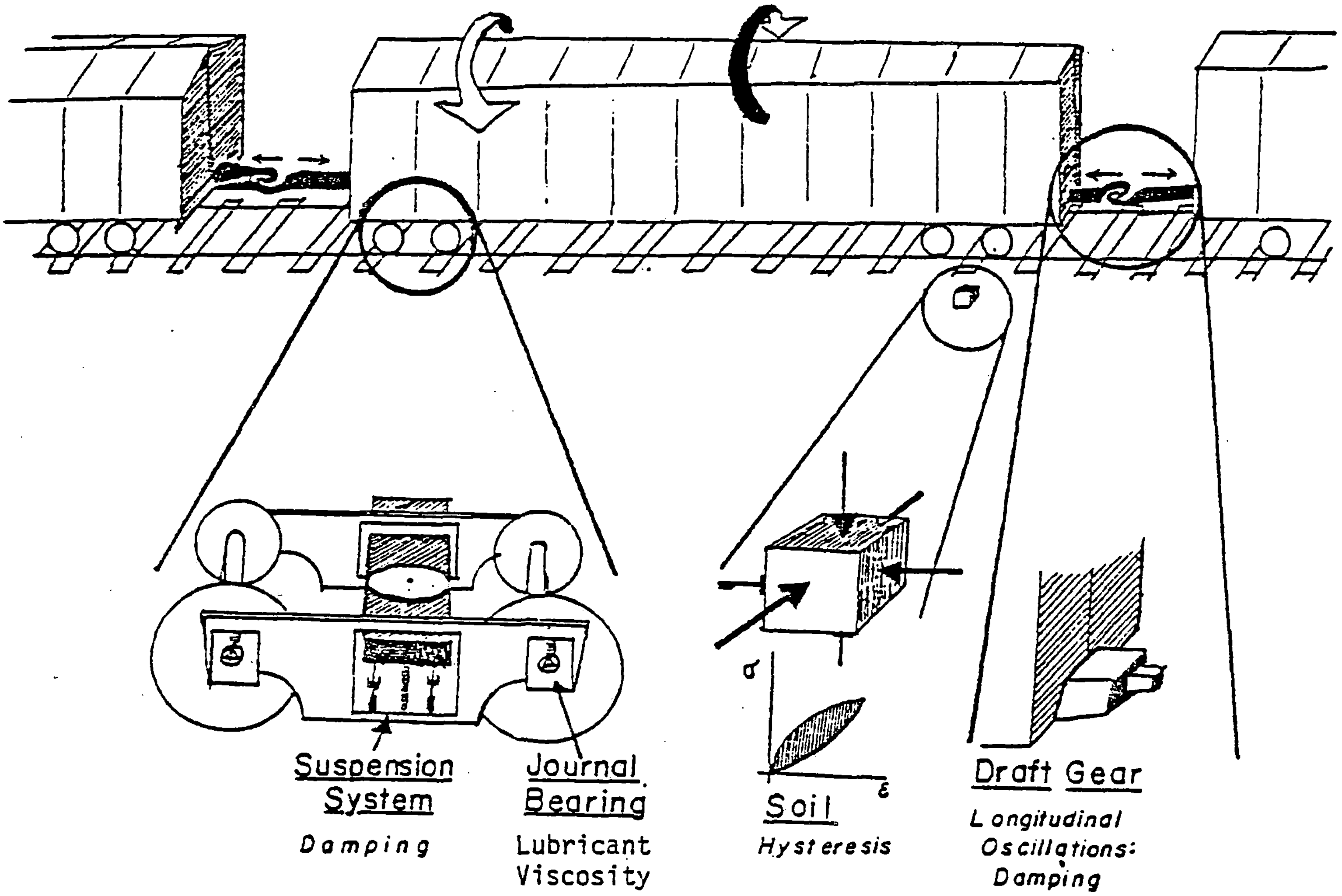
2. Curve and grade lengths are large compared to train length or that curve and grade magnitudes are small.

3.1.1 Train Resistance

Rolling resistance can be attributed to four principal causes. These sources are shown pictorially in Figure 3.2.

1. Ballast, subsoil, tie and track hysteresis, which is the alternate stressing and releasing of these components as the wheels, trucks, cars and train pass over them.

SOURCE OF ROLLING RESISTANCE:



Rolling Resistance Equation (Davis Formula):

$$T_{RR} = r_0 + r_1 v$$

Where: r_0 = speed independent coefficient, proportional to a term which varies linearly with the weight plus a term which depends on a number of axles.

r_1 = a term due to dynamic effects and proportional to the weight

FIGURE 3.2 ROLLING PORTION OF TRAIN RESISTANCE

2. Damping and hysteresis effects on the car itself, which are caused by suspension system damping, by flexing of car components or cargo movement (for example, the sloshing of oil in tank cars). Flat wheel spots and rail irregularities all produce the oscillatory motion of truck hunting and car pitching, rocking and rolling, which must be damped.

3. Journal bearing friction, which is another form of hysteresis as bearings and journals are alternately loaded and unloaded because of wheel-axle turning and dynamic loading.

4. Draft gear frictional damping which results from longitudinal oscillations between the cars which is caused by traversal of grades and curves, speed changes, wind load changes and variations in tractive effort caused by the operator or random effects in the prime mover.

Experimental measurements of train rolling resistance have tended to verify the Davis formula,(1) shown also in the figure.

Figure 3.3 presents the formula generally used for aerodynamic resistance. Again, this is part of the Davis formula.

Figure 3.4 lists the values of the coefficients r_0, r_1 of the rolling resistance and r_2 of the aerodynamic resistance usually used for North American locomotive-hauled and MU-passenger trains.

Detailed discussions of train resistance appear in reference 2. (Section 6.0) and are not reapeated here.

3.1.2 Grade and Curve Forces

On level ground with straight track, the only forces which oppose train motion are those due to train resistance. Two other forces which develop as a result of train motion are grade forces and curve forces. The sources of grade forces are shown in Figure 3.5.

BASIC FORMULA FOR AERODYNAMIC DRAG:

T_{RA} = $r_2 \, (V+V_W)^2$

r_2 = COEFFICIENT WHICH DEPENDS ON DETAILED CONSTRUCTION OF TRAIN AND ITS VEHICLES

V = SPEED OF THE TRAIN

V_W = COMPONENT OF WIND SPEED PARALLEL TO AND OPPOSING MOTION OF TRAIN

THE COEFFICIENT r_2 DEPENDS UPON MANY FACTORS INCLUDING

1. THE NUMBER OF CARS IN THE TRAIN
2. CROSS SECTIONAL AREA OF TRAIN
3. DEGREE OF STREAMLINING
4. DEGREE OF TUNNEL ENCLOSURE WHEN TRAIN MOVES THROUGH RESTRICTED SPACE.

FIGURE 3.3 AERODYNAMIC PORTION OF TRAIN RESISTANCE

MU-OPERATION

	LEAD CAR	TRAILING CARS
r_0	1.3W + 29n	
r_1	0.045W	
r_2	0.0024A	0.00034A

LOCOMOTIVE-HAULED OPERATION

	LOCOMOTIVE	TRAILING CARS
r_0	1.3W + 29n	
r_1	0.03W	
r_2	0.0024A	0.00034A

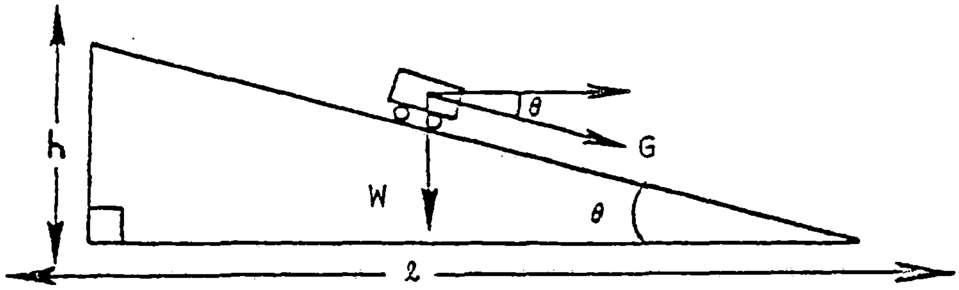
W = Vehicle Weight (tons)

n = Number of Axles per Vehicle

A = Vehicle Cross Sectional Area (sq. ft.)

FIGURE 3.4 VALUES OF TRAIN RESISTANCE FORMULA COEFFICIENTS

GRADE FORCE, (G)



$$G = W \sin\theta$$

$$\frac{h}{\ell} = \tan\theta$$

W = WEIGHT OF VEHICLE

FOR SMALL θ

$$\tan\theta \cong \sin\theta \cong \theta$$

$$\therefore \quad G = W\theta = (20 \text{ LBS/TON/\%GRADE}) \cdot W$$

CURVE RESISTANCE, (C)

$$C = 0.8 \text{ LBS/TON/}^{\circ}\text{CURVATURE} \cdot W$$

NOTE THAT GRADE FORCES CAN OPPOSE OR HELP THE MOTION WHEREAS CURVE FORCES ALWAYS OPPOSE THE MOTION.

FIGURE 3.5 CURVE AND GRADE FORCES

Grade forces can oppose or help the motion of the train, whereas curve forces always oppose the motion.

3.1.3 Specific Forces

If the equation of motion illustrated in Figure 3.1 is divided by the weight of the train, the terms on the left hand side of the equations are named specific forces (specific tractive effort, specific braking effort, specific train resistance, etc.). The right hand side of that equation is just proportional to the acceleration (or deceleration) of the train. Specific forces are sometimes used to characterize train motion.

3.2 POWER AND ENERGY USE

The calculation of energy consumption in rail passenger systems depends on a detailed knowledge of how the traction system utilizes the input power to provide work to move trains and provide a clean, comfortable environment for the passengers.

3.2.1 Mechanical Power at Wheels

$$P_M = F_A \cdot V$$

This power may be positive or negative depending on whether tractive or braking effort is being applied.

3.2.2 Auxiliary Power

The auxiliary power may be divided into two parts:

1. P_{AM} = required power for the equipment necessary to provide tractive and braking effort.
2. P_{AC} = required power for durability of cargo or comfort of passengers.

The total auxiliary power is the sum of the two parts.

$$P_A = P_{AM} + P_{AC}$$

3.2.3 Total Power Required for Diesel Propulsion

$$P_D = P_M/\eta_D(F_A,V)^* + P_A/\eta_{AD}$$

The power consumption P_D can be directly converted to a fuel consumption rate if the BTU content of the fuel is known. The quantities η_D and η_{AD} are efficiencies for conversion of mechanical and auxiliary power to prime mover chemical power, respectively. These can either be measured or calculated.

3.2.4 Total Power Required for Electric Propulsion

At the vehicle power collector:

$$P_E = P_M/\eta_E(F_A,V) + P_A/\eta_{AE}$$

This represents power consumption at the line. The railroad operation is interested in power consumption at the metering point or the point at which it is billed for the energy. Thus at the metering point:

$$P_{EM} = P_E/\eta_T(X)$$

where $\eta_T(X)$ represents the efficiency of transmission from the metering point through the electric network and catenary to the position of the train drawing power, P_E.

Unless a comparison is being made between diesel and electric propulsion in terms of energy consumption, there is no need to determine fuel consumption at the power plant.

3.2.5 Energy Calculation

For AC traction systems, there is reactive power which is generated by the traction vehicles, which contributes to the losses in the power transmission and distribution system, and which produces a power factor which is less than one. Computation of energy charges may include both factors.

$$(KVA)_E = KW \cdot PF = P_E \cdot PF$$

* $\eta_D(F_A,V)$ means that η_D depends on F_A and V (is a function of F_A and V).

Energy is just power summed (or, more properly integrated) over time since the mechnical power (P_M), the auxiliary power (P_A) and total power (P_D, for diesel propulsion or P_{EM}, for electric propulsion) are really functions of time as the train moves along the rail. Thus the energy consumed between time t_o and t_F is

$$E_i = \int_{t_o}^{t_F} P_i dt \qquad \text{for } P_i>0$$
$$i = M \text{ or } A \text{ or } D \text{ or } EM$$

Only positive values of P_i are included in the summation because we are interested in energy consumed.

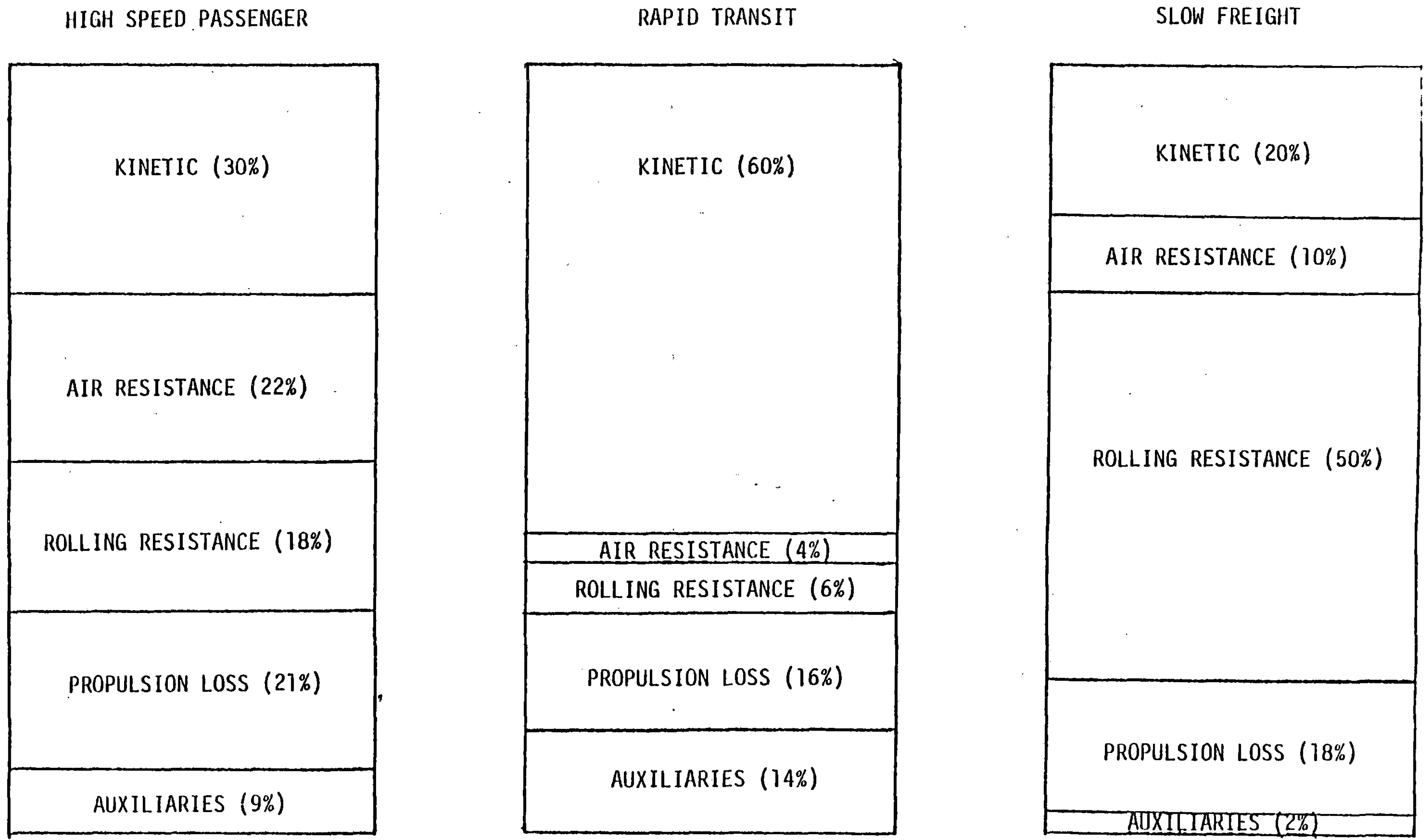
3.3 ENERGY END USE

The energy used to transport passengers and freight by rail can be divided into several parts depending on its end use. These parts are:

1. Kinetic
2. Aerodynamic Train Resistance
3. Rolling Train Resistance
4. Propulsion Losses
5. Auxiliaries
6. Power Distribution System Losses.

Figure 3.6 shows typical energy budgets for three modes of rail transportation.

The kinetic energy developed during train motion is usually dissipated in braking. It is the only energy "pool" which can be tapped for regeneration. Thus, it is easily seen from the diagram why rapid transit systems are excellent candidates for applying regeneration, while high speed passenger and slow freight are not.



NOTE: Regeneration of Energy Must Come from Kinetic Energy

FIGURE 3.6 ENERGY BUDGET FOR TYPICAL RAIL MODES

3.4 ENERGY CONSUMPTION PERFORMANCE INDICES

Energy consumption performance indices are measures used by the rail operator to gauge the energy productivity of the service provided. These indices can be energy-based power, demand-based or energy-cost-based. Requirements for such indices are that they:

1. Are easily measured and accumulated,
2. Have some meaning in terms of energy productivity,
3. Remain fairly constant gauges of energy productivity even with varying schedules and passenger loading,
4. Be predictable.

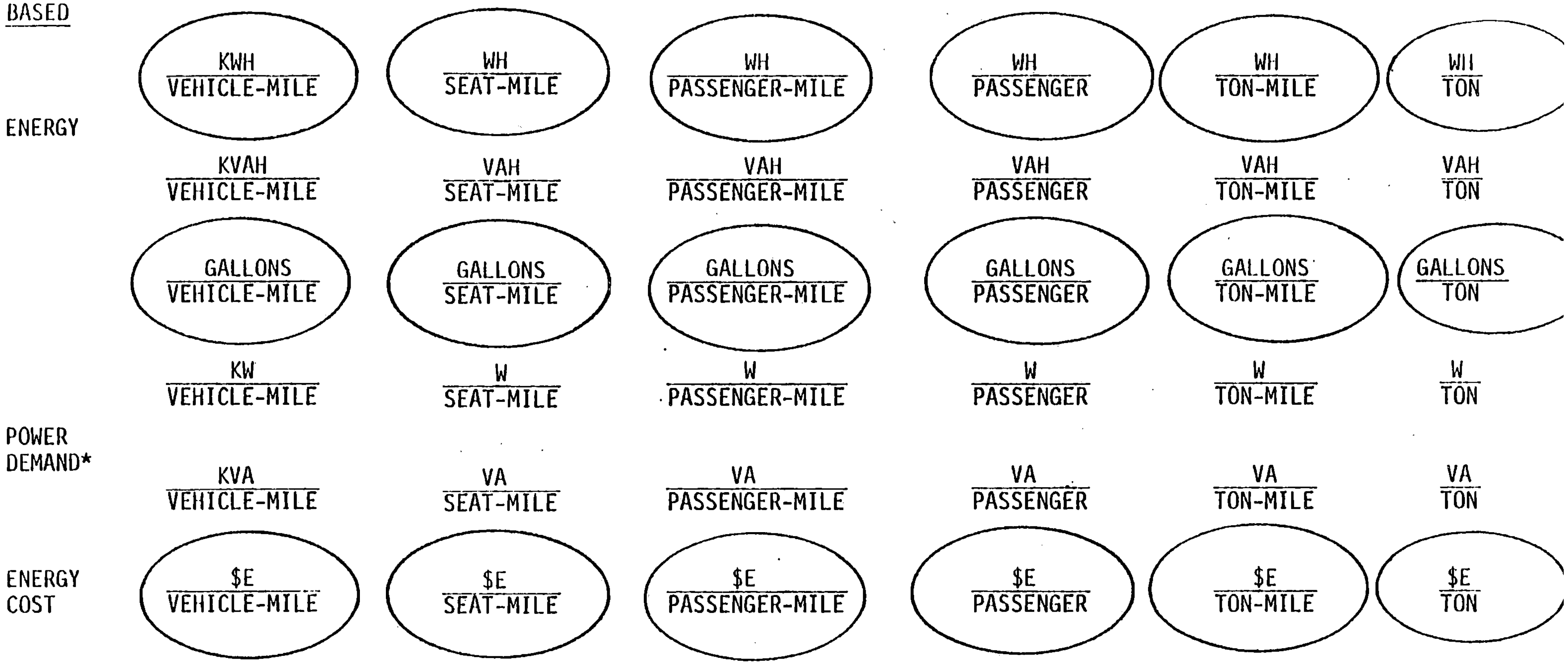
Indices which have generally been used are quotients obtained by dividing total energy consumption, average power demand or total energy cost by vehicle-miles, passenger-miles, passengers, ton-miles or tons.

$$\text{INDEX} = \frac{\text{NUMERATOR (Energy, Demand, Cost Based)}}{\text{DENOMINATOR (Passenger, Vehicle, Cargo Weight)}}$$

Figure 3.7 lists the indices which can be constructed. Those which are circled are most commonly used. Energy cost indices may depend on both energy consumption and power demand.

Indices which contain vehicle-miles or seat-miles in the denominator are generally referred to as technical or structural indices because they refer to the equipment used, while indices which contain passenger-miles, passengers, ton-miles or tons in the denominator are referred to as operational indices. This latter type of index is a measure of system utilization from the energy viewpoint.

Certain energy consumption performance indices are referred to as energy efficiency. It is defined as BTU/ton-mile for freight and BTU/passenger-mile for passenger traffic. The reciprocal of these two quantities is sometimes referred to as energy intensiveness.



BASED						
ENERGY	$\frac{\text{KWH}}{\text{VEHICLE-MILE}}$	$\frac{\text{WH}}{\text{SEAT-MILE}}$	$\frac{\text{WH}}{\text{PASSENGER-MILE}}$	$\frac{\text{WH}}{\text{PASSENGER}}$	$\frac{\text{WH}}{\text{TON-MILE}}$	$\frac{\text{WH}}{\text{TON}}$
	$\frac{\text{KVAH}}{\text{VEHICLE-MILE}}$	$\frac{\text{VAH}}{\text{SEAT-MILE}}$	$\frac{\text{VAH}}{\text{PASSENGER-MILE}}$	$\frac{\text{VAH}}{\text{PASSENGER}}$	$\frac{\text{VAH}}{\text{TON-MILE}}$	$\frac{\text{VAH}}{\text{TON}}$
	$\frac{\text{GALLONS}}{\text{VEHICLE-MILE}}$	$\frac{\text{GALLONS}}{\text{SEAT-MILE}}$	$\frac{\text{GALLONS}}{\text{PASSENGER-MILE}}$	$\frac{\text{GALLONS}}{\text{PASSENGER}}$	$\frac{\text{GALLONS}}{\text{TON-MILE}}$	$\frac{\text{GALLONS}}{\text{TON}}$
POWER DEMAND*	$\frac{\text{KW}}{\text{VEHICLE-MILE}}$	$\frac{\text{W}}{\text{SEAT-MILE}}$	$\frac{\text{W}}{\text{PASSENGER-MILE}}$	$\frac{\text{W}}{\text{PASSENGER}}$	$\frac{\text{W}}{\text{TON-MILE}}$	$\frac{\text{W}}{\text{TON}}$
	$\frac{\text{KVA}}{\text{VEHICLE-MILE}}$	$\frac{\text{VA}}{\text{SEAT-MILE}}$	$\frac{\text{VA}}{\text{PASSENGER-MILE}}$	$\frac{\text{VA}}{\text{PASSENGER}}$	$\frac{\text{VA}}{\text{TON-MILE}}$	$\frac{\text{VA}}{\text{TON}}$
ENERGY COST	$\frac{\text{\$E}}{\text{VEHICLE-MILE}}$	$\frac{\text{\$E}}{\text{SEAT-MILE}}$	$\frac{\text{\$E}}{\text{PASSENGER-MILE}}$	$\frac{\text{\$E}}{\text{PASSENGER}}$	$\frac{\text{\$E}}{\text{TON-MILE}}$	$\frac{\text{\$E}}{\text{TON}}$

*Where demand is taken over some time interval

KWH - Kilowatt Hours

WH - Watt Hours

KVAH - Kilovolt Ampere Hours

VAH - Volt Ampere Hours

$E - Energy Cost in Dollars

FIGURE 3.7 ENERGY CONSUMPTION INDICES

4.0 ENERGY PERFORMANCE RESULTS OF IPEEP TRAIN REVIEW

As part of the IPEEP train review program, the energy performance of modern foreign and domestic passenger trains was estimated using a train performance simulator.(3-4) The electric trains were simulated on the upgraded version of the Northeast Corridor from Boston-Washington. Non-electric trains were simulated on both the present and hypothetically upgraded versions of the New York-Buffalo, Chicago-Detroit, Los Angeles-San Diego and Vancouver-Portland corridors. Descriptions of the right of way along all corridors are contained in Reference 3.

4.1 ELECTRIC TRAINS - NORTHEAST CORRIDOR

4.1.1 Corridor Information

The profile, alignment and speed restrictions used for the upgraded version of the Northeast Corridor (NEC) were those established by the NEC Office of FRA. The elevation and speed restrictions for the New York-Washington (NY-WA) and New York-Boston (NY-BO) sections of the NEC are shown in Figures 4.1 and 4.2, respectively. Speed restrictions for both three and six inches of unbalance on curves are shown. Trains with tilt body equipment were simulated using the six inch unbalance speed limits, while the other trains were simulated using the three inch unbalance limits. In all cases, the six inch unbalance speeds met the one-third rule against vehicle overturning. The maximum speed for both cases is 120 MPH.

Station stops are also shown on the elevation diagrams. In all simulations, dwell time at station stops was 75 seconds. Rail travel time specified by law is 2 hours, 40 minutes between NY-WA and 3 hours, 40 minutes between NY-BO. Other important NEC data are shown in Figure 4.3.

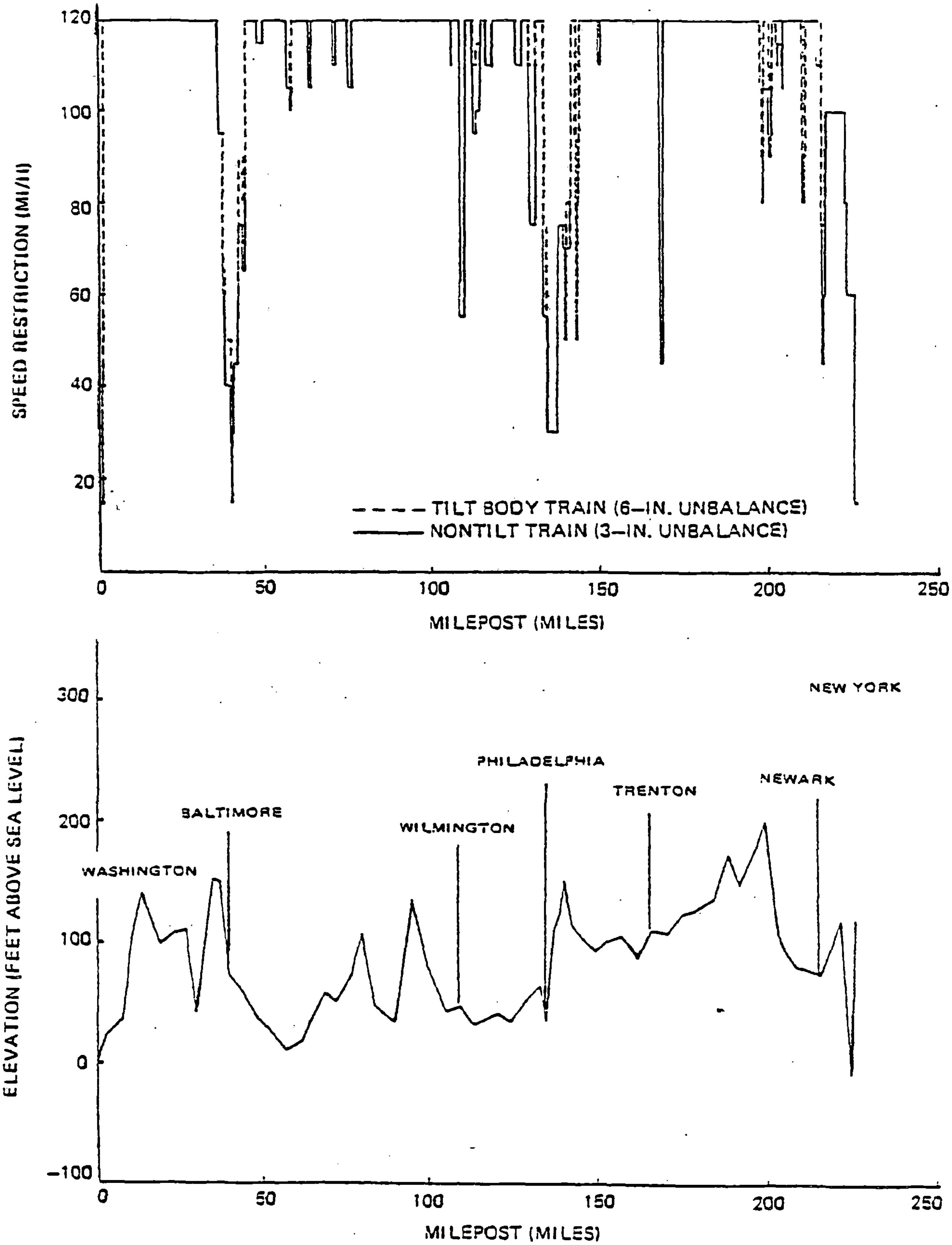


FIGURE 4.1 SPEED RESTRICTIONS AND ELEVATIONS
NEW YORK-WASHINGTON SEGMENT (1981)

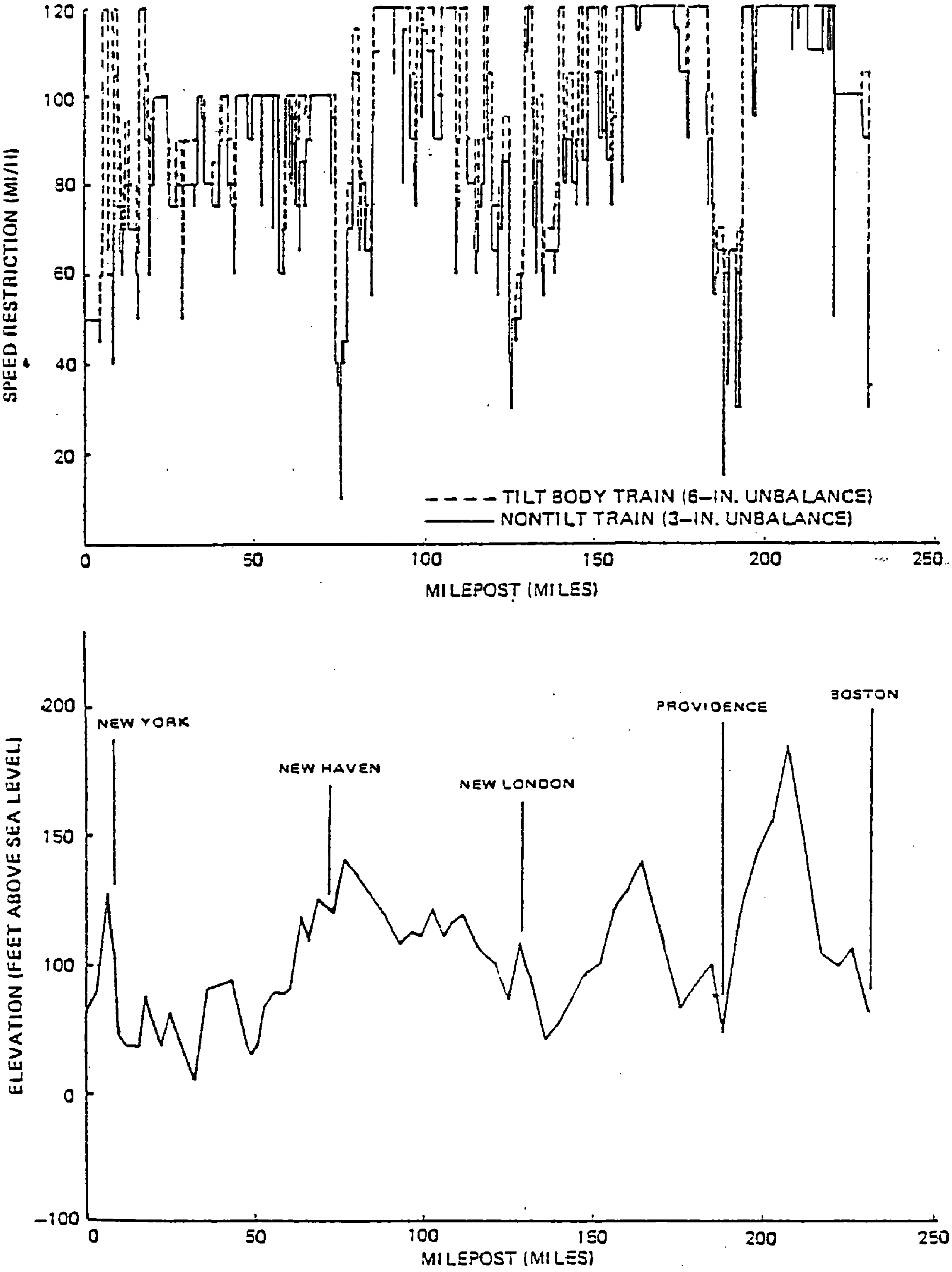
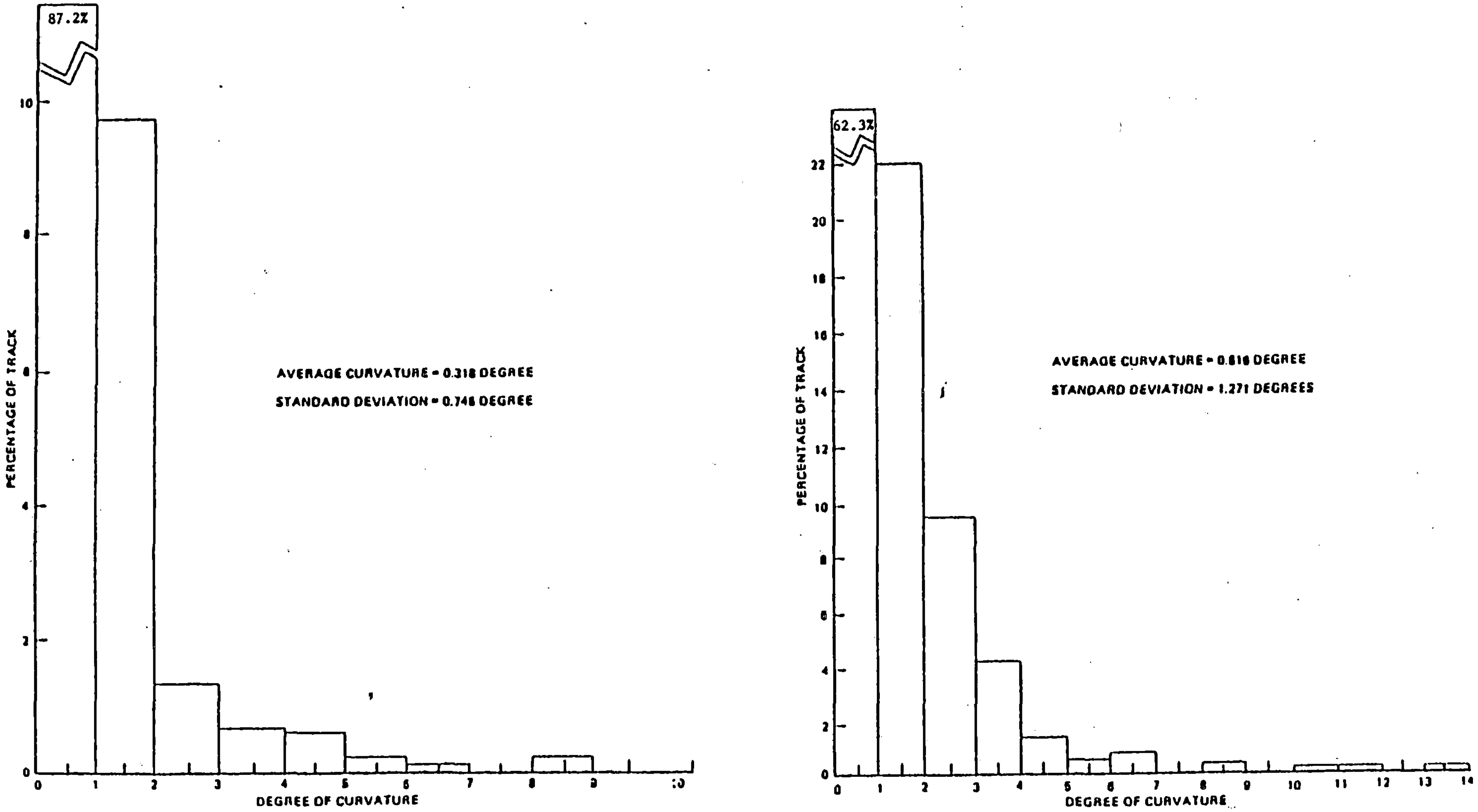


FIGURE 4.2 SPEED RESTRICTIONS AND ELEVATIONS
NEW YORK-BOSTON SEGMENT (1981)



NEW YORK-WASHINGTON
ROUTE LENGTH - 224 MILES
MAXIMUM SPEED - 120 MPH

NEW YORK-BOSTON
ROUTE LENGTH - 232 MILES
MAXIMUM SPEED - 120 MPH

FIGURE 4.3 NEC PHYSICAL DATA

4.1.2 Train Information

Six train types were simulated on the NEC:

1. The Upgraded Metroliner, an Multiple unit train with all axles powered.
2. The German ET403, an Multiple unit train with all axles powered.
3. The Italian ETR401, an Multiple unit train with half axles powered. The train has tilt body equipment.
4. The Japanese 961, an Multiple unit train with all axles powered.
5. The French TGV-PSE, a high speed, articulated train with twelve axles powered.
6. The British APT, a high speed, articulated, tilt body train with one or two power cars. All axles (four) on the power cars are powered.

More detailed descriptions of the trains (1-6, above) can be obtained from Reference 5.

The specific tractive efforts for all trains which were configured to be equivalent in seating to an eight car upgraded Metroliner and modified for North American Operation are shown in Figure 4.4. Modification for North American Operation consisted of structural and interior work necessary to comply with FRA safety standards, AMTRAK comfort criteria and compatibility with NEC operation.

The specific train resistance information for the trains are shown in Table 4.1. The total train resistance for all the trains at 120 MPH, the maximum NEC speed, varies from a low value of 10,000 lbs. for the APT to a high value of 13,650 lbs. for the upgraded Metroliner.

The auxiliary power requirements for the trains are listed in Table 4.2. These range from a low of 1.01 KW/seat for the ET403 to a high of 1.78 KW/seat for the ETR401. Braking rates for all trains were arbitrarily set at 1.4 MPHPS.

4.1.3 Energy Performance Summary

Both the schedule time and the energy consumption of the eight car Metroliner equivalent consists of the trains modified for North American Operation are summarized in Figure 4.5.

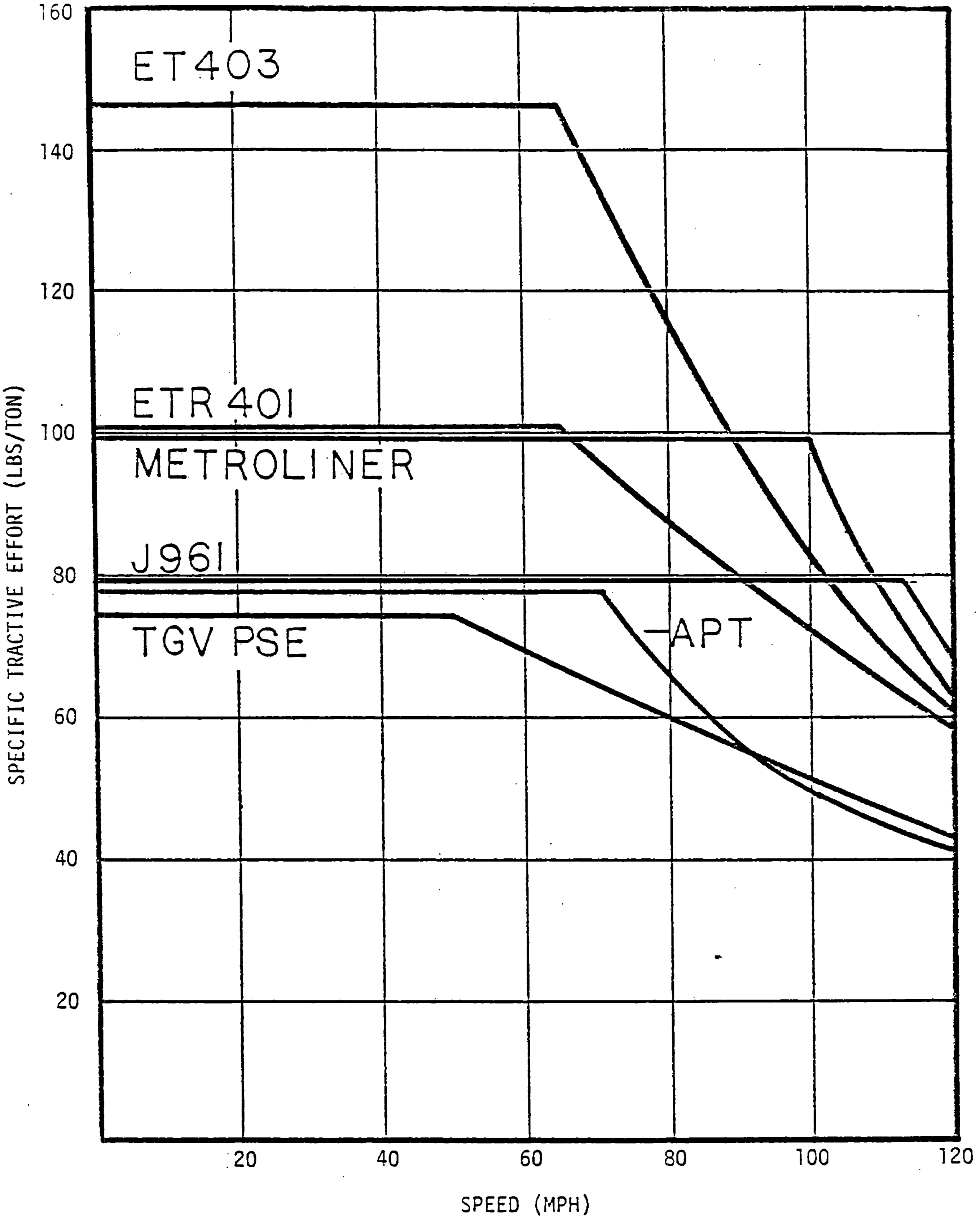


FIGURE 4.4 SPECIFIC TRACTIVE EFFORT VS. SPEED FOR ELECTRIC TRAINS EQUIVALENT TO EIGHT CAR METROLINER SEATING. MODIFIED FOR NORTH AMERICAN OPERATION

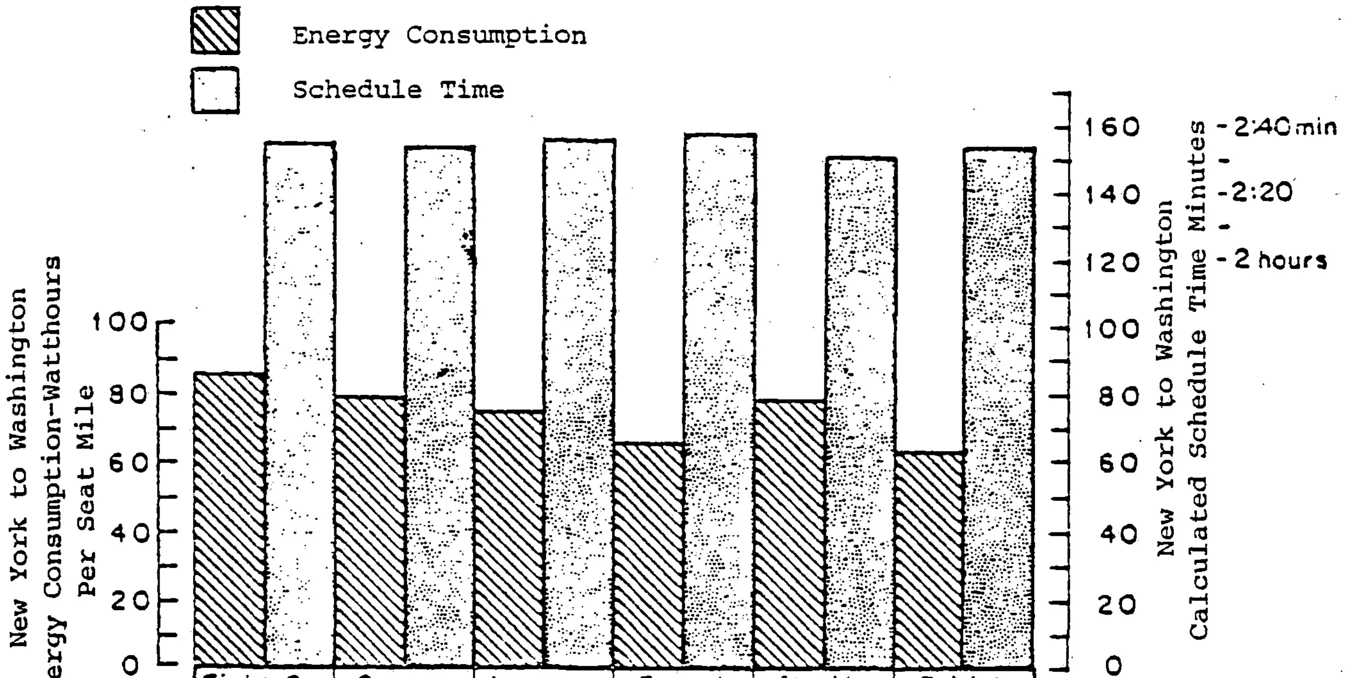
TABLE 4.1 SPECIFIC TRAIN RESISTANCE FOR ELECTRIC TRAINS WITH EIGHT CAR METROLINER EQUIVALENT SEATING AND MODIFIED FOR NORTH AMERICAN OPERATION

			COEFFICIENT			
TRAIN	LOADED WEIGHT (TONS)	FRONTAL CROSS SECTION (SQ. FT.)	r_0 LBS/TON	r_1 LBS/TON/MPH	r_2 LBS/TON/MPH^2	t_R @ 120 MPH LBS/TON
METROLINER	742	120	2.55	.045	.00073	18.4
APT	592	90	2.96	.030	.00072	16.9
ET403	760	118	2.83	.045	.00059	16.7
ETR401	710	86	3.26	.045	.00059	17.2
J961	606	145	2.83	.045	.00076	19.2
TGVPSE	643	88	2.74	.030	.00069	16.3

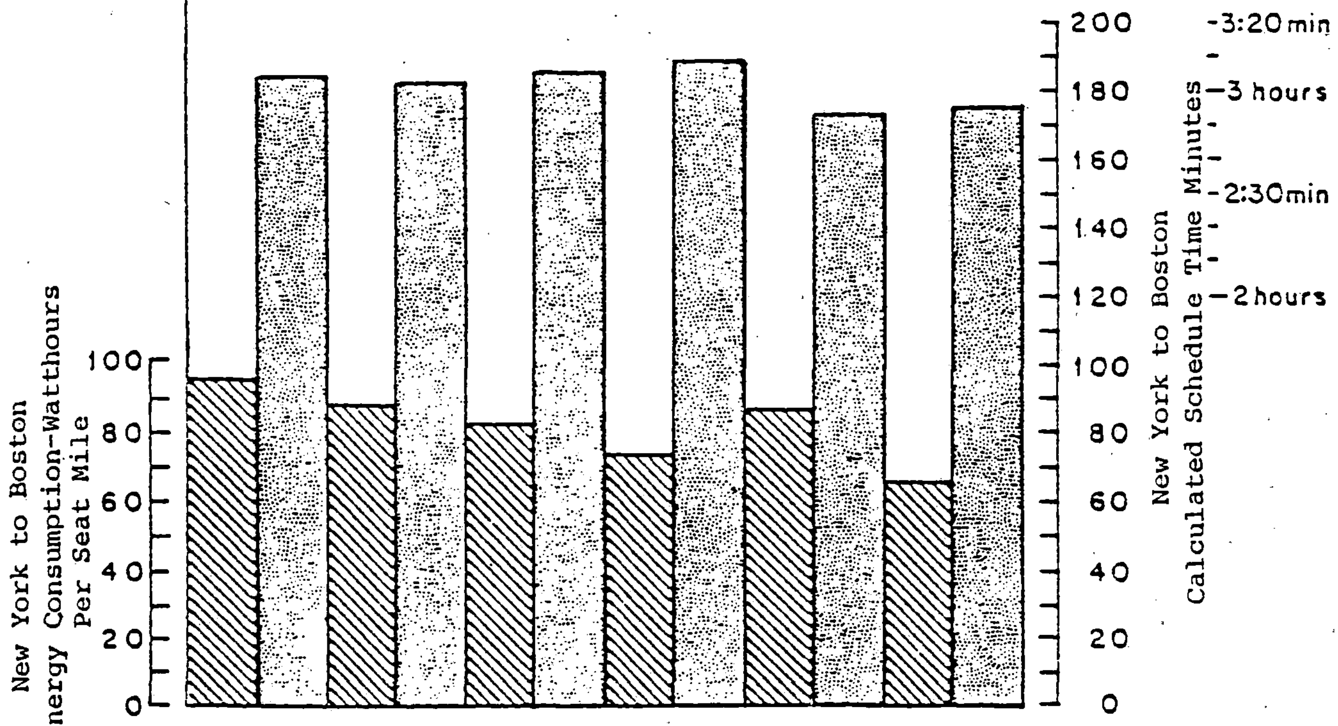
$$\boxed{t_R = r_0 + r_1 v + r_2 v^2}$$

TABLE 4.2 AUXILIARY POWER REQUIREMENTS FOR ELECTRIC TRAINS
WITH EIGHT CAR METROLINER EQUIVALENT SEATING
AND MODIFIED FOR NORTH AMERICAN OPERATION

TRAIN	NUMBER OF SEATS	AUXILIARY POWER (KW)	$\frac{\text{POWER}}{\text{SEAT}} \left(\frac{\text{KW}}{\text{SEAT}}\right)$
METROLINER	544	860	1.58
APT	528	608	1.15
ET403	540	535	1.01
ETR401	554	984	1.78
961	520	740	1.42
TGVPSE	524	560	1.07



	Eight Car Metroliner	German ET403	Japanese 961	French TGV-PSE	Italian ETR401	British APTP
Light Weight Construction	No	Yes	Yes	Yes	Yes	Yes
Aerodynamic Contour	No	Yes	Yes	Yes	Yes	Yes
Articulated	No	No	No	Yes	No	Yes
Tilt Body Capability	No	No	No	No	Yes	Yes



All Trains Equivalent to 8-Car Metroliner
and Modified for North American Operation

FIGURE 4.5 ENERGY CONSUMPTION AND SCHEDULE TIME
NORTHEAST CORRIDOR

It is interesting to note that the schedule time in the NY-WA section of the corridor varies by only eight minutes among all of the trains (2 hours, 30 minutes, to 2 hours, 38 minutes). This appears to indicate that any appreciable reduction in schedule time will require higher maximum speed limits.

In the NY-BO section of the corridor, schedule time among the trains vary by 17 minutes (2 hours, 52 minutes to 3 hours, 9 minutes). The best time performance is provided by the APT and ETR401 which have tilt capability.

No consistent data were available on propulsion system efficiency among all of the trains. Therefore, the energy consumption quoted in Figure 4.5 is the sum of mechanical energy at the rail plus auxiliary energy.

Table 4.3 lists the parameters which are most crucial for energy consumption determination along with mechanical energy at the rail displayed as WH/seat-mile and WH/ton-mile for both sections of the NEC. A plot of WH/ton-mile vs. specific train resistance at 120 MPH is also shown in Figure 4.6 associated with the table. The reasons the energy consumption does not increase smoothly with increasing specific train resistance are:

1. The schedule speeds of all trains are different. All other things being equal, a schedule speed increase of 1% results in an increase in traction energy consumption of from 2 percent to 3 percent.
2. Tilt trains have less slowdowns and these are of smaller magnitude than non-tilt trains.

In the NY-WA section of the NEC, the TGVPSE has the smallest per ton-mile energy consumption and specific train resistance but, it also has the lowest schedule speed. Both the APT and ETR401, which have high schedule speeds and nearly the same specific train resistance, show low energy consumption on a ton-mile base.

The effect of tilt train performance is enhanced in the NY-BO section of the NEC, which has many more curves. Schedule speeds of both tilt trains are the highest, yet the APT has the lowest energy consumption on a ton-mile basis. Again,

TABLE 4.3 ENERGY CONSUMPTION ANALYSIS FOR ELECTRIC TRAINS WITH EIGHT CAR METROLINER EQUIVALENT SEATING AND MODIFIED FOR NORTH AMERICAN OPERATIONS

TRAIN	NUMBER OF SEATS	WEIGHT (TONS)	SPECIFIC TRAIN RESISTANCE	NEW YORK - WASHINGTON						NEW YORK - BOSTON			
				SCHEDULE SPEED (MPH)	ENERGY CONSUMPTION ($\frac{WH}{SEAT\text{-}MILE}$)			ENERGY CONSUMPTION TRACTION (WH/TON-MILE)	SCHEDULE SPEED (MPH)	ENERGY CONSUMPTION ($\frac{WH}{SEAT\text{-}MILE}$)			ENERGY CONSUMPTION TRACTION (WH/TON-MILE)
					TOTAL	AUXILIARY	TRACTION			TOTAL	AUXILIARY	TRACTION	
MET	544	742	18.43	87.3	87	18	69	51	75.7	95	21	74	54
APT	528	592	16.92	87.3	64	13	51	46	79.1	67	15	52	46
ET403	540	760	16.72	87.8	79	11	68	48	76.5	88	13	75	53
ETR401	554	710	17.16	89.0	79	20	59	46	80.5	87	22	65	51
961	520	606	19.18	86.2	76	16	60	51	74.8	82	19	63	54
TGVPSE	524	643	16.25	85.1	67	13	54	44	73.7	73	15	58	47

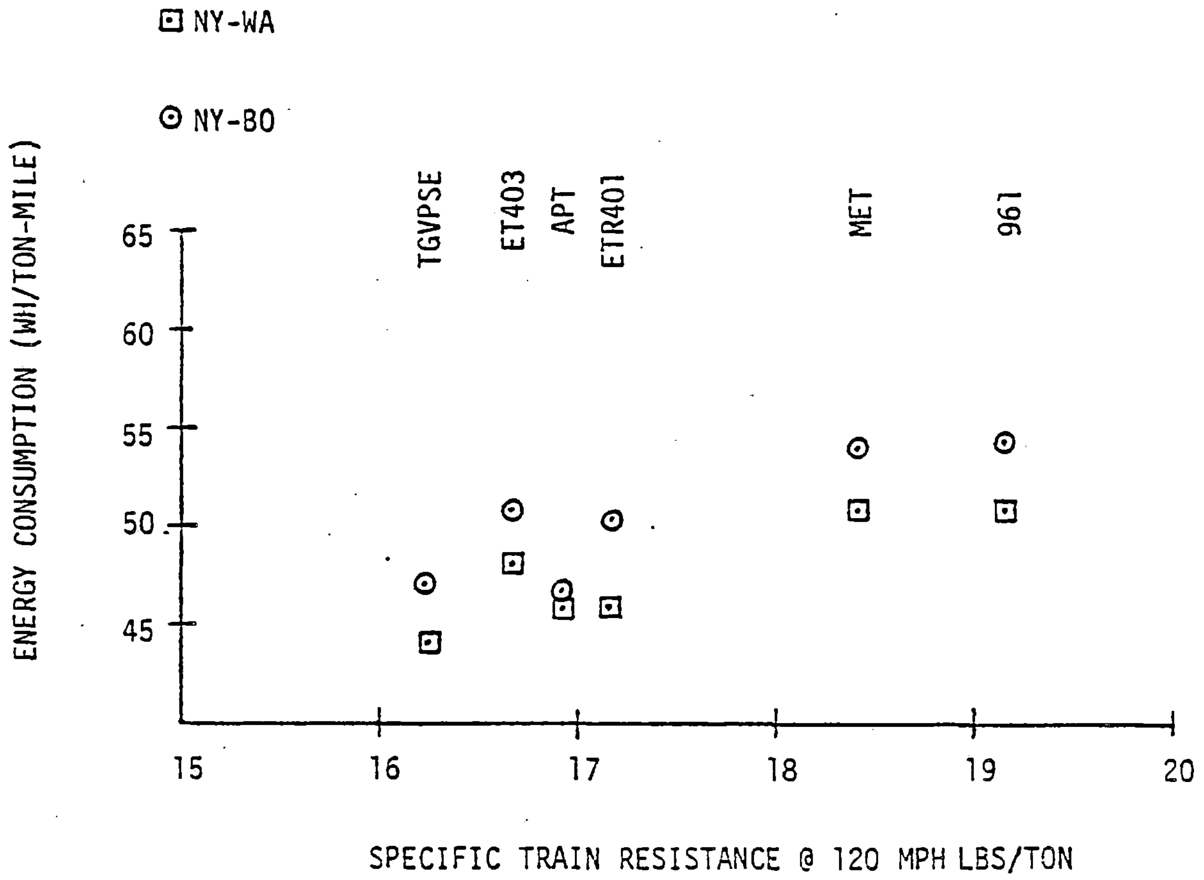


FIGURE 4.6 ENERGY CONSUMPTION AS A FUNCTION OF SPECIFIC TRAIN RESISTANCE

the TGVPSE with the lowest schedule speed has low energy consumption on a ton-mile basis.

On a performance basis and seat-mile energy consumption basis, the APT performs as well as any train in both sections of the NEC.

A discussion on the relation of schedule speed and tilt speed restrictions to energy consumption is contained in Section 5.0.

Table 4.4 shows an expansion of the information on energy consumption for the six trains reviewed to six and eight car Metroliner seating equivalent for both, as built in country of origin and as modified for North American Operation. Both schedule time and energy consumption are shown for both sections of the corridor.

4.2 NON-ELECTRIFIED CORRIDOR TRAINS

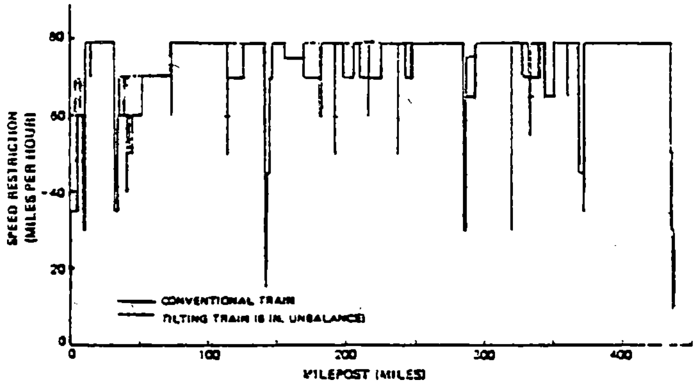
4.2.1 Corridor Information

The non-electrified trains were simulated on the New York-Buffalo (NY-BU), Chicago-Detroit (CH-DE), Los Angeles-San Diego (LA-SD), and Portland-Vancouver (PO-VA) corridors. Two versions of the rail right of way on each corridor were considered. The first version was the corridor rail in its present condition, and the second version was a hypothetical upgraded corridor where the track, interlocking, etcetera, were improved to a condition such that no speed restrictions, except those for curves, were required.

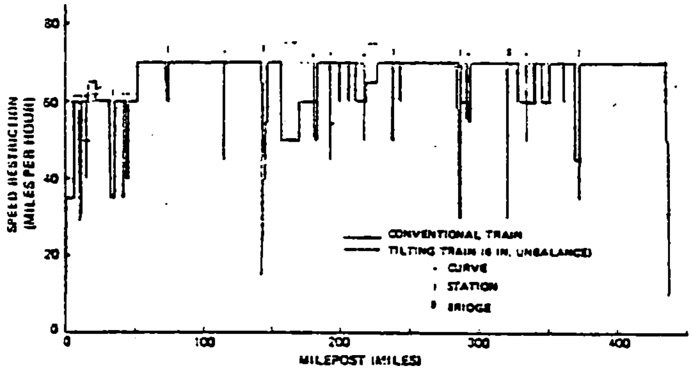
Figures 4.7-4.10 show plots of speed restrictions and elevations on the present and hypothetical upgraded routes for each of the corridors. Speed restrictions for three and six inches of unbalance on curves are shown. Trains with tilt body equipment were simulated using the six inch unbalance speed limits, while the other trains were simulated using the three inch unbalance limits. In all cases, the six inch unbalance speeds met the one-third rule against vehicle overturning. The station stops, which have a train dwell time of two minutes, are also shown on the elevation diagram.

TABLE 4.4 NORTHEAST CORRIDOR ELECTRIFIED TRAINS

	TRAIN CONSIST	TRAIN WEIGHT TONS	ARTICULATED	TILT	NUMBER OF PASSENGERS	SCHEDULE TIME HRS:MIN NY-WASH	SCHEDULE TIME HRS:MIN NY-BOSTON	WATT HOURS PER SEAT MILE NY-WASH	WATT HOURS PER SEAT MILE NY-BOSTON
BASE CASE TRAINS									
Six (6) Car Metroliner	6 MU	557	No	No	400	2:34	3:04	92	99
Eight (8) Car Metroliner	8 MU	742	No	No	544	2:34	3:04	87	95
ET403 (GERMAN)									
Six (6) Car Equivalent as Built	8 MU	557	No	No	420	2:33	3:02	78	87
Eight (8) Car Equivalent as Built	10 MU	698	No	No	540	2:33	3:01	75	84
Train as Operated in Origin Country	4 MU	277	No	No	198	2:33	3:02	88	95
Six (6) Car Equivalent for North American Operation	8 MU	606	No	No	420	2:33	3:03	82	91
Eight (8) Car Equivalent for North American Operation	10 MU	760	No	No	540	2:33	3:02	79	88
TGV-PSE (FRENCH)									
Six (6) Car Equivalent as Built	2-9	527	Yes	No	420	2:36	3:06	73	80
Eight (8) Car Equivalent as Built	2-11	604	Yes	No	524	2:38	3:08	66	71
Train as Operated in Origin Country	2-8	488	Yes	No	368	2:35	3:06	79	86
Six (6) Car Equivalent for North American Operation	2-9	559	Yes	No	420	2:37	3:07	76	82
Eight (8) Car Equivalent for North American Operation	2-11	643	Yes	No	524	2:38	3:09	67	73
APT (ENGLAND)									
Six (6) Car Equivalent as Built	5-2-4	473	Yes	Yes	420	2:32	2:53	68	72
Eight (8) Car Equivalent as Built	6-2-5	535	Yes	Yes	528	2:33	2:55	61	64
Train as Operated in Origin Country	Not Determined	Not determined	Yes	Yes	Not determined	-	-	-	-
Six (6) Car Equivalent for North American Operation	5-2-4	521	Yes	Yes	420	2:32	2:54	71	75
Eight (8) Car Equivalent for North American Operation	6-2-5	592	Yes	Yes	528	2:34	2:56	64	67
ETR401 (ITALY)									
Six (6) Car Equivalent as Built	10 MU	488	No	Yes	456	2:30	2:52	74	81
Eight (8) Car Equivalent as Built	12 MU	585	No	Yes	554	2:30	2:52	72	80
Train as Operated in Origin Country	4 MU	196	No	Yes	179	2:30	2:52	84	89
Six (6) Car Equivalent for North American Operation	10 MU	592	No	Yes	456	2:31	2:52	81	89
Eight (8) Car Equivalent for North American Operation	12 MU	710	No	Yes	554	2:31	2:53	79	87
961 (JAPAN)									
Six (6) Car Equivalent as Built	6 MU	427	No	No	368	2:36	3:05	80	86
Eight (8) Car Equivalent as Built	8 MU	568	No	No	520	2:36	3:05	74	80
Train as Operated in Origin Country	Not Determined	Not determined	No	No	Not determined	-	-	-	-
Six (6) Car Equivalent for North American Operation	6 MU	455	No	No	368	2:36	3:03	82	88
Eight (8) Car Equivalent for North American Operation	8 MU	606	No	No	520	2:36	3:06	76	82



UPGRADED HYPOTHETICAL



PRESENT

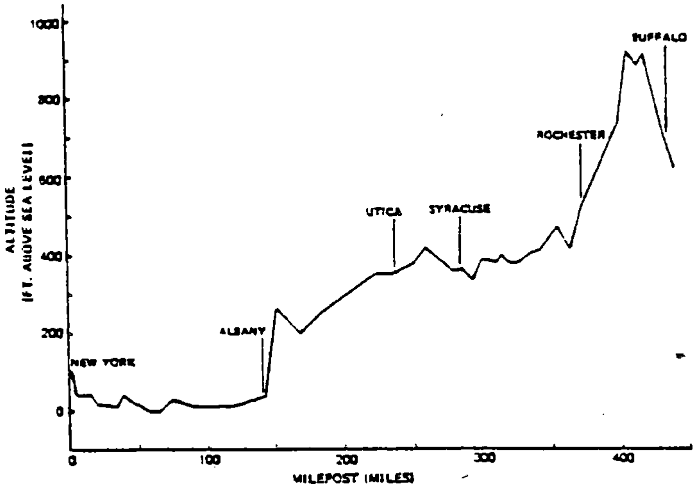
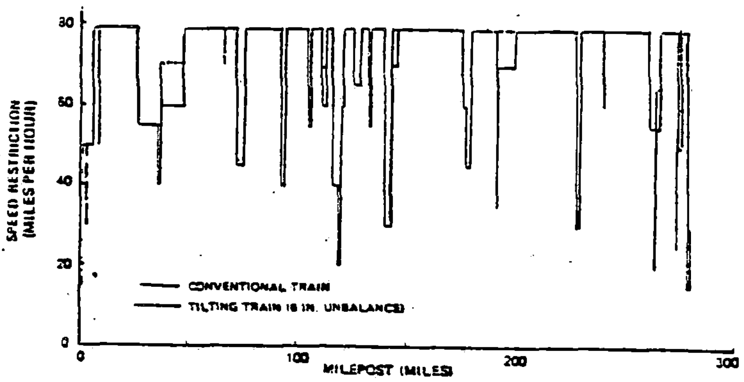
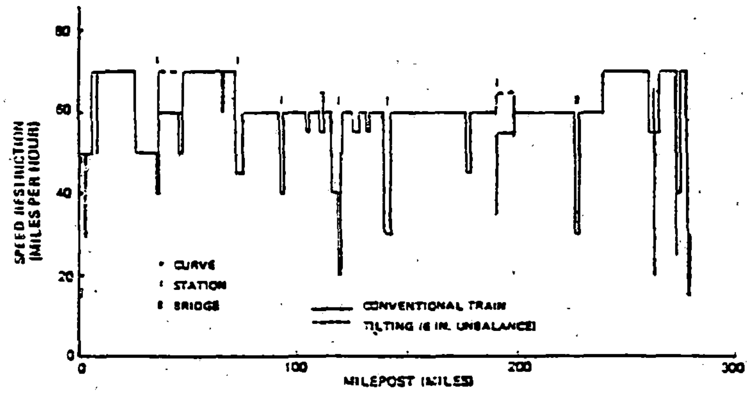


FIGURE 4.7 SPEED RESTRICTIONS AND ELEVATIONS
BUFFALO-NEW YORK CORRIDOR



UPGRADED HYPOTHETICAL



PRESENT

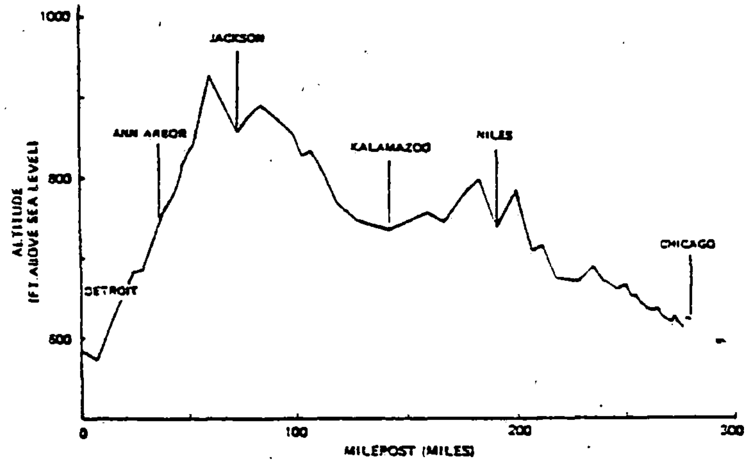
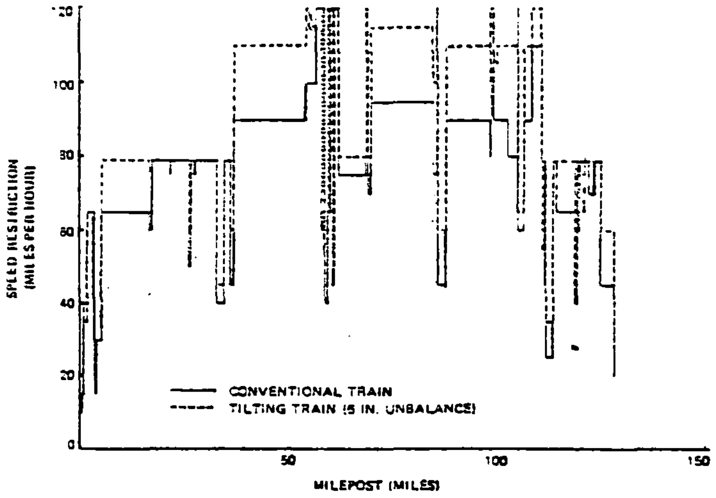
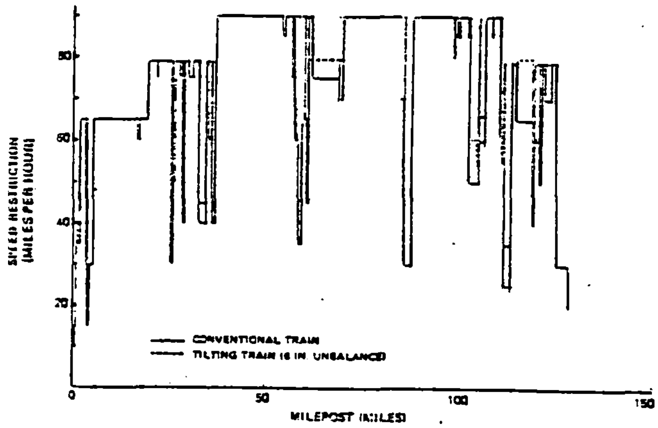


FIGURE 4.8 SPEED RESTRICTIONS AND ELEVATIONS CHICAGO-DETROIT CORRIDOR



UPGRADED HYPOTHETICAL



PRESENT

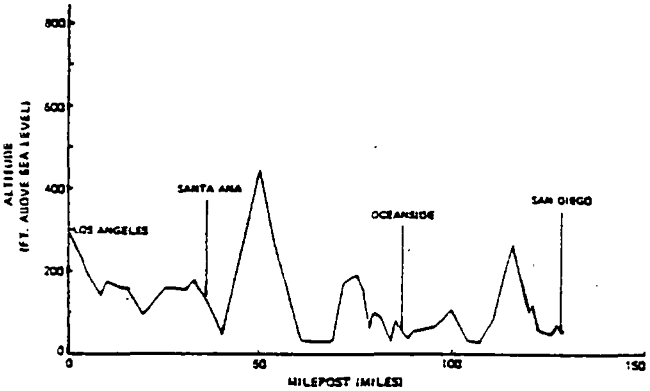
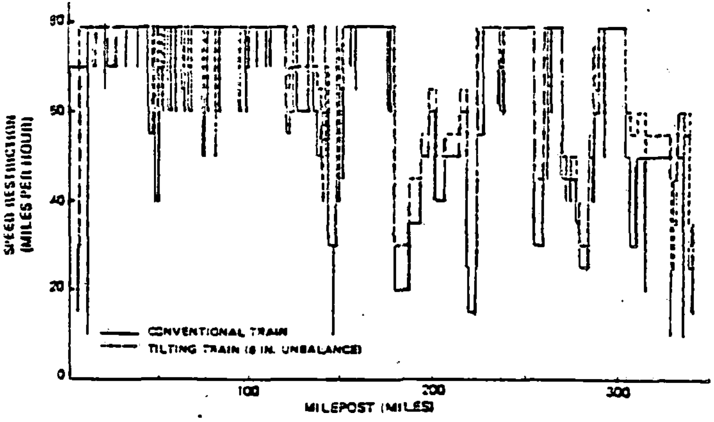
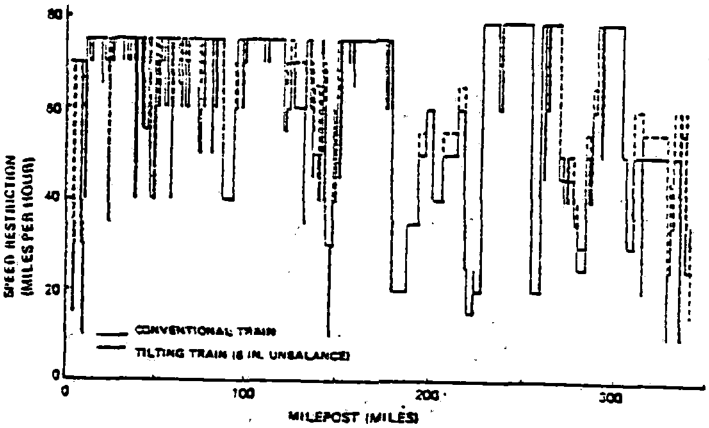


FIGURE 4.9 SPEED RESTRICTIONS AND ELEVATIONS
LOS ANGELES-SAN DIEGO CORRIDOR



UPGRADED HYPOTHETICAL



PRESENT

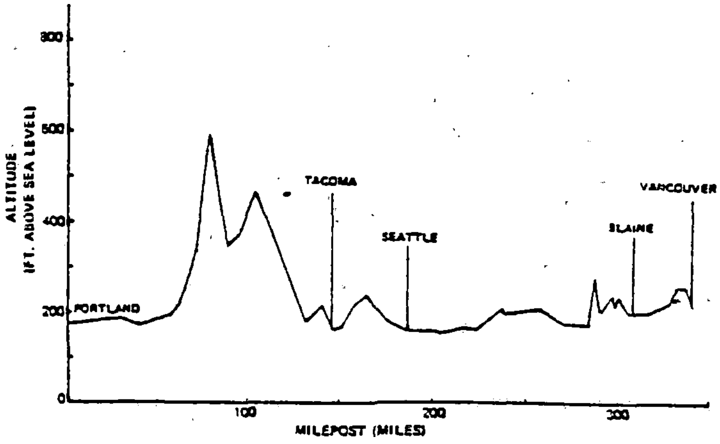


FIGURE 4.10 SPEED RESTRICTIONS AND ELEVATIONS VANCOUVER-PORTLAND CORRIDOR

Figure 4.11 shows curvature and other physical characteristics of the corridor. With the exception of the LA-SD route, all routes have maximum speed limits of 79 MPH because they lack cab-signalling or automatic train stop equipment.

4.2.2 Train Information

Five train types were simulated:

1. F40PH-AMFLEET - An F40PH diesel-electric locomotive hauling four Amfleet cars.
2. Turboliner Train - A five car unit train with a turbine power unit on each end.
3. The Canadian LRC - A locomotive-hauled, high-speed, tilt body train consisting of four coaches.
4. The British HST - Two diesel-electric locomotives and six cars operating in push-pull configuration.
5. The American SPV2000 - An MU-train utilizing diesel-mechanical propulsion systems.

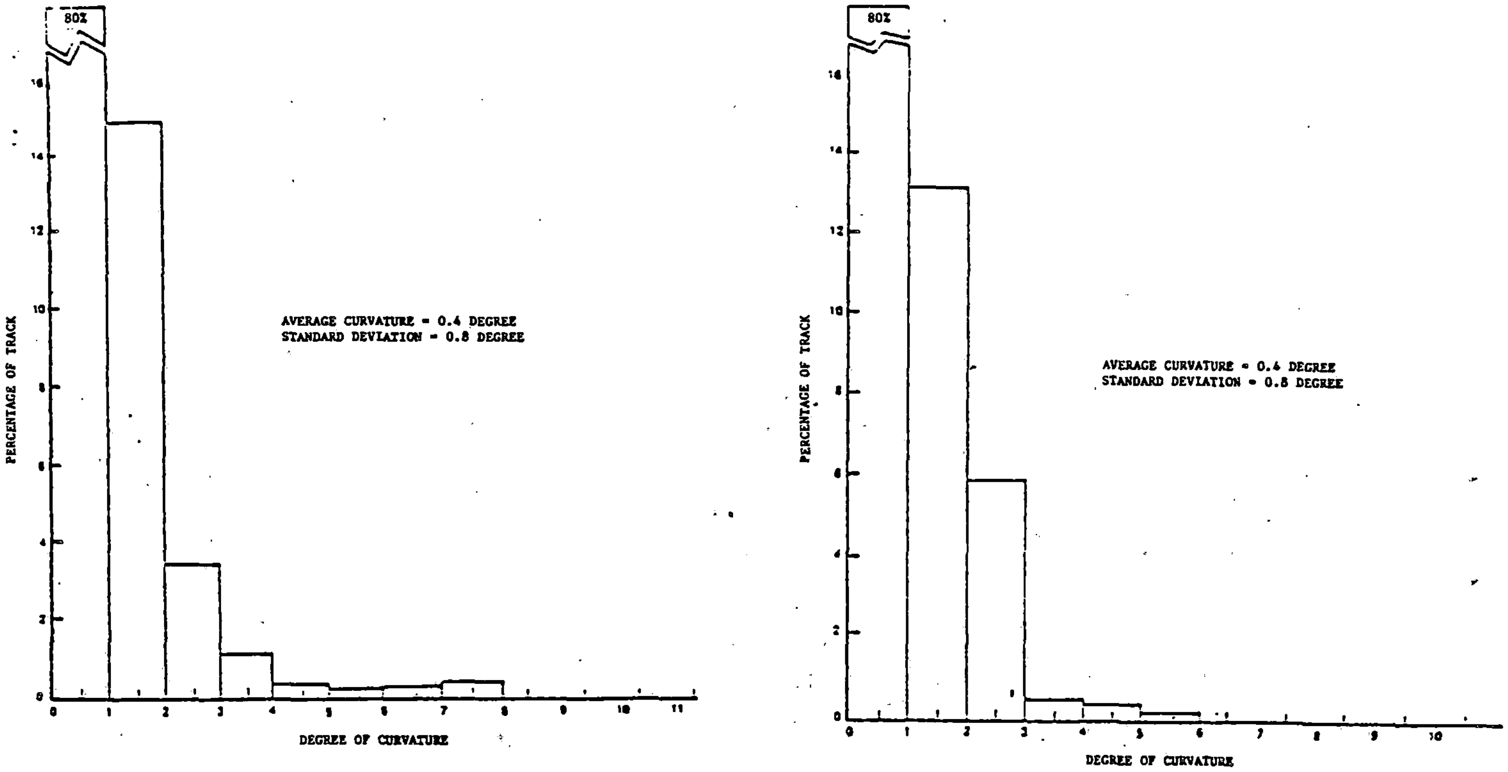
Four of these trains were simulated on each of the corridors (both present and updated versions).

More detailed descriptions of the trains (1-5 above) can be obtained from References 3 and 4.

The specific tractive efforts for all trains which configured to be equivalent in seating to the F40PH-AMFLEET and modified for North American operation are shown in Figure 4.12. Only the HST required modification for North American Operation.

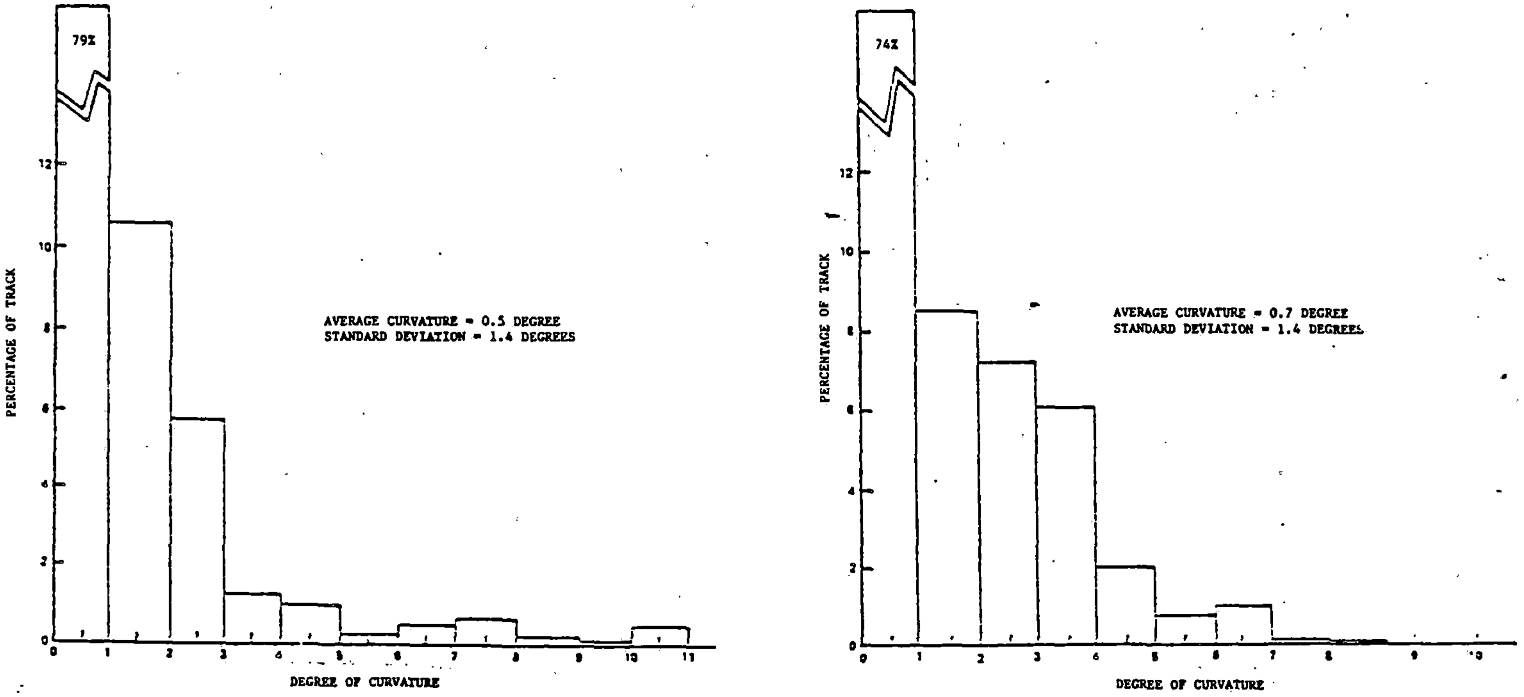
The specific train resistance information for these trains is listed in Table 4.5.

TRACK CURVATURE HISTOGRAMS



BUFFALO-NEW YORK
ROUTE LENGTH - 436 MILES
MAXIMUM SPEED-75 MPH(PRESENT)
79 MPH(UPGRADED)

CHICAGO-DETROIT
ROUTE LENGTH - 279 MILES
MAXIMUM SPEED-70 MPH(PRESENT)
79 MPH(UPGRADED)



LOS ANGELES-SAN DIEGO
ROUTE LENGTH - 128 MILES
MAXIMUM SPEED-90 MPH(PRESENT)
120 MPH(UPGRADED)

VANCOUVER-PORTLAND
ROUTE LENGTH - 342 MILES
MAXIMUM SPEED - 79 MPH (BOTH)

FIGURE 4.11 NON-ELECTRIFIED CORRIDOR CHARACTERISTICS

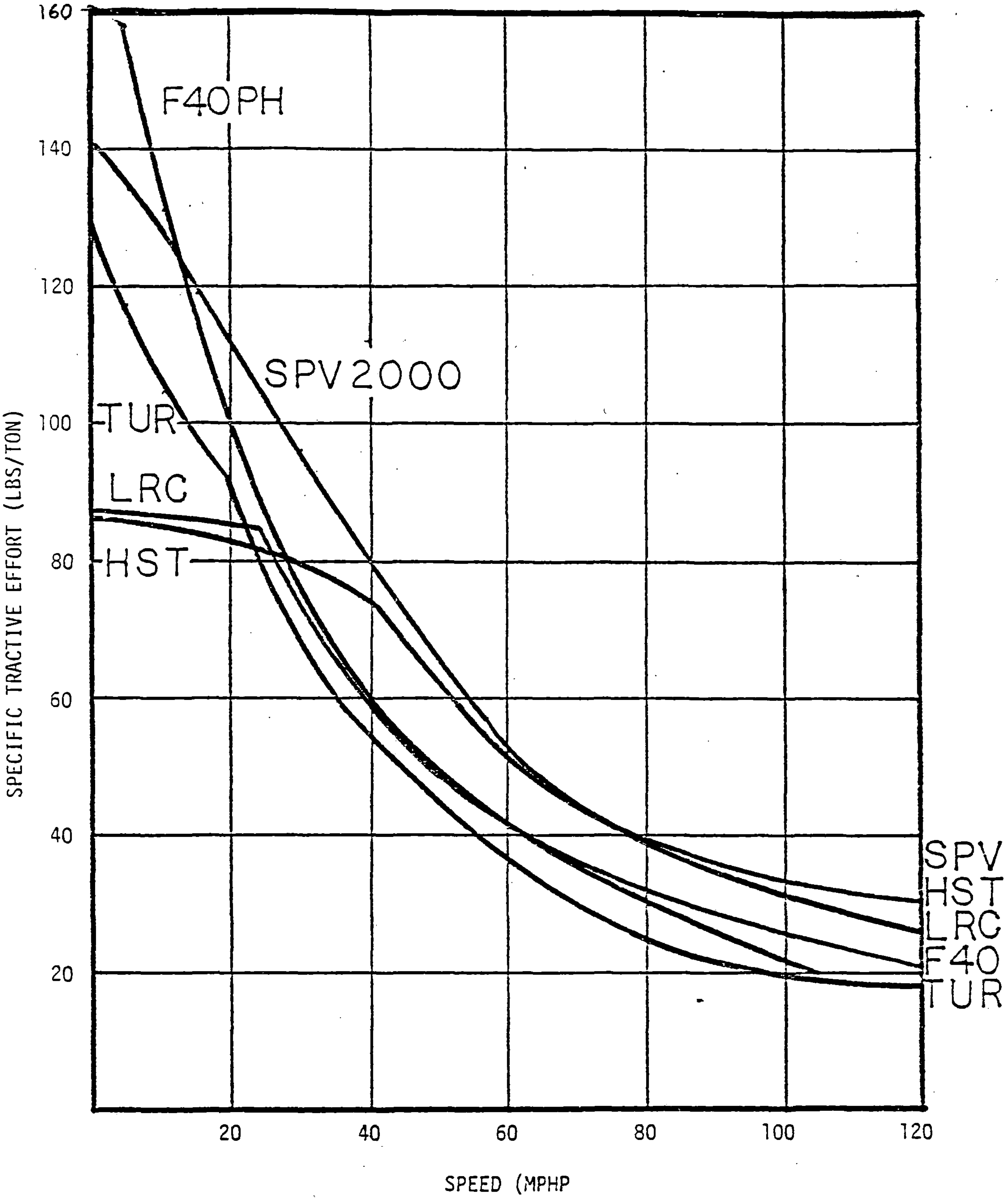


FIGURE 4.12 SPECIFIC TRACTIVE EFFORT VS. SPEED FOR NON-ELECTRIC TRAINS EQUIVALENT IN SEATING TO FOUR CAR AMFLEET HAULED BY F40PH LOCOMOTIVE

TABLE 4.5 SPECIFIC TRAIN RESISTANCE FOR NON-ELECTRIC TRAINS WITH FOUR AMFLEET CAR EQUIVALENT SEATING AND MODIFIED FOR NORTH AMERICAN OPERATION

			COEFFICIENT			
TRAIN	LOADED WEIGHT (TONS)	FRONTAL CROSS SECTION (SQ.FT.)	r_0 (LBS/TON)	r_1 (LBS/TON/MPH)	r_2 (LBS/TON/MPH^2)	t_R @ 80 MPH (LBS/TON)
F40PH-AMFLEET	374	154	2.85	.030	.00155	15.2
TURBOLINER	324	67	3.09	.030	.00077	10.4
LRC	336	103	3.03	.030	.00086	10.9
HST	444	61	3.39	.030	.00066	10.0
SPV2000	276	125	2.98	.045	.00096	12.7

$$\boxed{t_R = r_0 + r_1 v + r_2 v^2}$$

Auxiliary power requirements for all trains are listed in Table 4.6. It is interesting to note that on a per seat basis the electric trains auxiliary power (see Figure 4.2) is a factor of two higher than the non-electric trains.

Table 4.7 lists the fuel consumption data for all of the prime movers of the trains simulated. It is clear from this table that the Turboliner will consume significantly more fuel than the diesel engine power vehicles.

Braking rates for all trains were arbitrarily set at 1.4 MPHPS for all simulations.

4.2.3 Energy Performance Summary

Both schedule time and energy consumption of the four car Amfleet seating equivalent consist of the trains modified for North American operation on the present version of the corridors are summarized in Figure 4.13. The only significant betterment of schedule time is the LRC train on the VA-PO corridor. This is attributed to the higher speed capability in curves because of the tilt equipment.

On a per seat-mile basis, energy consumption is largest for the Turboliner and smallest for the SPV2000.

Table 4.8 presents energy consumption information for all of the non-electric trains on both updated hypothetical and present corridors. The energy consumption is divided into the auxiliary and the traction portions on a seat-mile base, as well as the traction portion on a per ton-mile base.

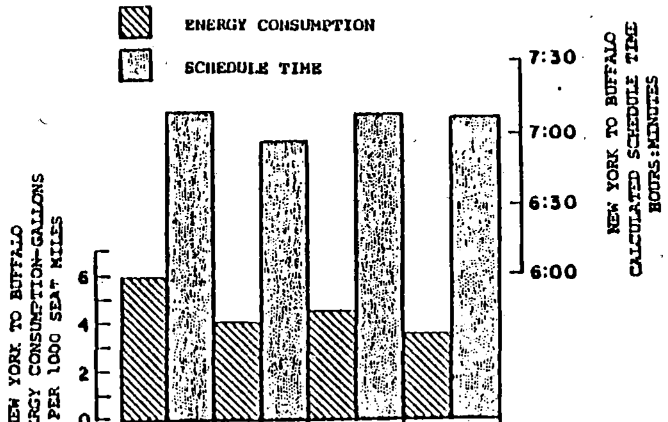
Figure 4.14 displays the energy consumption (on a per ton-mile basis) of the trains on all versions of the corridors. It should be noted that there is a wide variation in energy consumption of a particular train depending on the corridor considered. It is also apparent that because of the poor energy efficiency of the Turboliner, it has significantly higher fuel consumption than the other trains, even when noting its relatively low specific train resistance.

TABLE 4.6 AUXILIARY POWER REQUIREMENTS FOR NON-ELECTRIC TRAINS WITH FOUR AMFLEET CAR EQUIVALENT SEATING AND MODIFIED FOR NORTH AMERICAN OPERATION

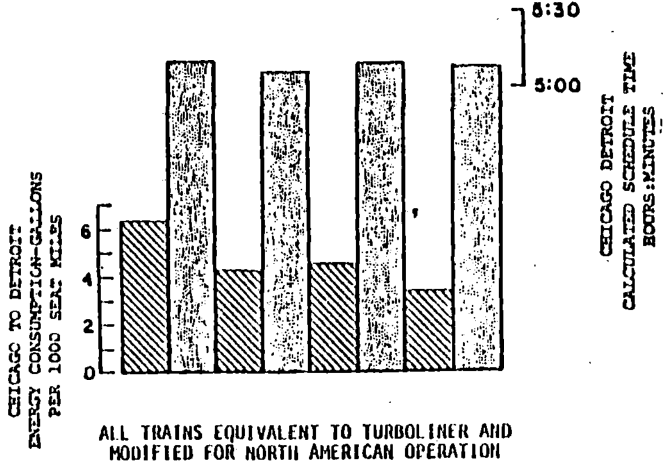
TRAIN	NUMBER OF SEATS	AUXILIARY POWER (KW)	$\frac{\text{POWER}}{\text{SEAT}}\left(\frac{\text{KW}}{\text{SEAT}}\right)$
F40PH-AMFLEET	312	138	0.44
TURBOLINER	300	214	0.71
HST	306	211	0.69
LRC	312	200	0.64
SPV2000	304	171	0.56

TABLE 4.7 FUEL CONSUMPTION INFORMATION FOR PRIME MOVERS OF NON-ELECTRIC TRAINS (GAL/HOUR)

TRAIN	IDLE AND BRAKING	POWER	AUXILIARY
F40PH (LOCOMOTIVE)	39.83	31.1 + 0.0503/HP	0.0675/KW
TURBOLINER	50.6	50.6 + 0.0555/HP	0.129 /KW
HST	13.65	13.65 + .0507/HP	.0680/KW
LRC (LOCOMOTIVE)	26.2	26.2 + .0559/HP	.0658/KW
SPV2000 (ONE CAR)	6.32	6.32 + .0843/HP	.0735/KW

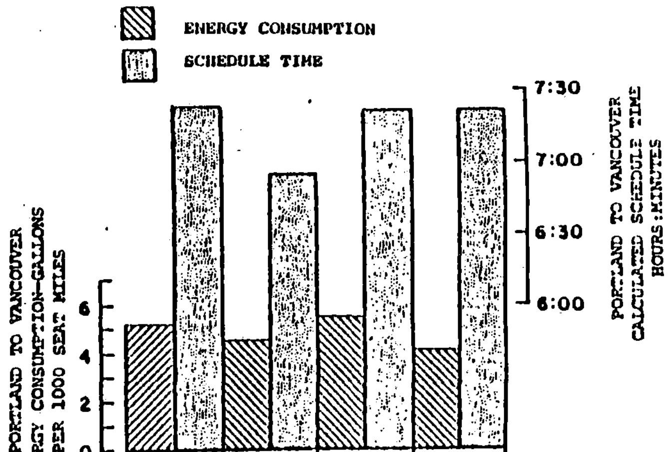


	Turbo-Liner	Canadian LRC	British HST	American SPV2000
Aerodynamic Contour	Yes	No	Yes	Yes
Articulated	No	No	No	No
Tilt Body Capability	No	Yes	No	No
Prime Mover	Gas Turbine	Diesel Electric	Diesel Electric	Diesel Torque Conv.

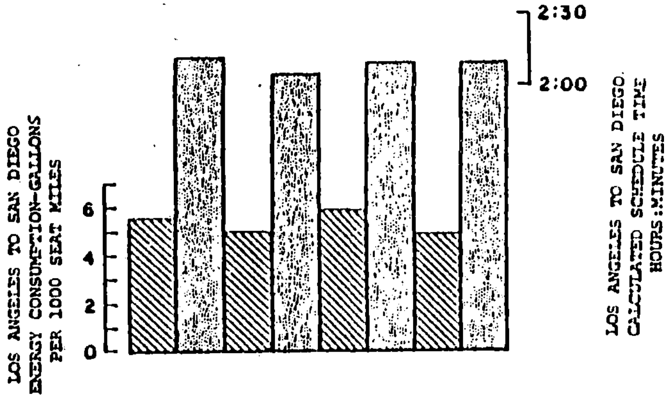


ALL TRAINS EQUIVALENT TO TURBOLINER AND MODIFIED FOR NORTH AMERICAN OPERATION

ENERGY CONSUMPTION & SCHEDULE TIME NEW YORK TO BUFFALO CORRIDOR (PRESENT) & CHICAGO TO DETROIT CORRIDOR (PRESENT)



	F40 PH Amcoach	Canadian LRC	British HST	American SPV2000
Aerodynamic Contour	No	No	Yes	Yes
Articulated	No	No	No	No
Tilt Body Capability	No	Yes	No	No
Prime Mover	Diesel Electric	Diesel Electric	Diesel Electric	Diesel Torque Conv.



ALL TRAINS EQUIVALENT TO F40PH-AMCOACH AND MODIFIED FOR NORTH AMERICAN OPERATION

ENERGY CONSUMPTION & SCHEDULE TIME PORTLAND TO VANCOUVER CORRIDOR (PRESENT) & LOS ANGELES TO SAN DIEGO CORRIDOR (PRESENT)

FIGURE 4.13 ENERGY CONSUMPTION AND SCHEDULE TIME FOR VARIOUS TRAINS ON FOUR CORRIDORS

TABLE 4.8

TABULATION OF ENERGY CONSUMPTION FOR NON-ELECTRIC TRAINS ON ALL CORRIDORS

Train	Seats #	Weight (tons)	Sp. Train Resistance @ 80 MPH (lbs/ton)	NEW YORK-BUFFALO (PRESENT)					NEW YORK-BUFFALO (UPGRADED-HYPOTHETICAL)				
				Sch.Speed (MPH)	Energy Consumption GAL/1000 Seat-Miles			GAL/1000 Ton-Miles Traction	Sch.Speed (MPH)	Energy Consumption GAL/1000 Seat-Miles			GAL/1000 Ton-Miles Traction
					Total	Aux.	Traction			Total	Aux.	Traction	
F40PH	312	374	15.16	61.06	4.5	0.5	4.0	3.3	66.97	4.6	0.4	4.2	3.5
TURBO	300	324	10.43	60.98	6.2	1.5	4.7	4.4	66.87	6.0	1.4	4.6	4.3
HST	306	444	10.02	61.15	4.5	0.8	3.7	2.6	67.08	4.5	0.7	3.8	2.6
LRC	312	336	10.94	62.73	4.0	0.7	3.3	3.1	69.10	4.0	0.6	3.4	3.2
SPV2000	304	276	12.73	61.24	3.5	0.7	2.8	3.1	67.28	3.7	0.6	3.1	3.4
				CHICAGO-DETROIT (PRESENT)					CHICAGO-DETROIT (UPGRADED-HYPOTHETICAL)				
F40PH				54.17	4.5	0.6	3.9	3.3	62.00	4.9	0.5	4.4	3.7
TURBO				54.07	6.6	1.7	4.9	4.5	61.86	6.4	1.5	4.9	4.5
HST				54.17	4.7	0.9	3.8	2.6	62.28	4.9	0.8	4.1	2.8
LRC				54.92	4.2	0.8	3.4	3.2	62.84	4.3	0.8	3.5	3.3
SPV2000				54.28	3.4	0.8	2.6	2.9	62.42	3.9	0.7	3.2	3.5
				LOS ANGELES-SAN DIEGO (PRESENT)					LOS ANGELES-SAN DIEGO (UPGRADED-HYPOTHETICAL)				
F40PH				58.18	5.6	0.5	5.1	4.3	61.84	5.5	0.5	5.0	4.2
TURBO				57.66	7.3	1.6	5.7	5.3	61.84	7.0	1.5	5.5	5.1
HST				58.99	5.9	0.8	5.1	3.5	62.75	5.7	0.7	5.0	3.4
LRC				60.95	5.0	0.7	4.3	4.0	69.19	5.0	0.6	4.4	4.1
SPV2000				58.99	4.9	0.7	4.2	4.6	63.05	4.8	0.7	4.1	4.5
				VANCOUVER-PORTLAND (PRESENT)					VANCOUVER-PORTLAND (UPGRADED-HYPOTHETICAL)				
F40PH				46.22	5.4	0.6	4.8	4.0	49.57	5.4	0.6	4.8	4.0
TURBO				46.22	7.9	2.0	5.9	5.5	49.49	7.6	1.9	5.7	5.3
HST				46.40	5.7	1.0	4.7	3.2	49.78	5.6	0.9	4.7	3.2
LRC				49.42	4.9	0.9	4.0	3.7	55.97	4.5	0.8	3.7	3.4
SPV2000				46.47	4.3	0.9	3.4	3.7	49.85	4.2	0.8	3.6	4.0

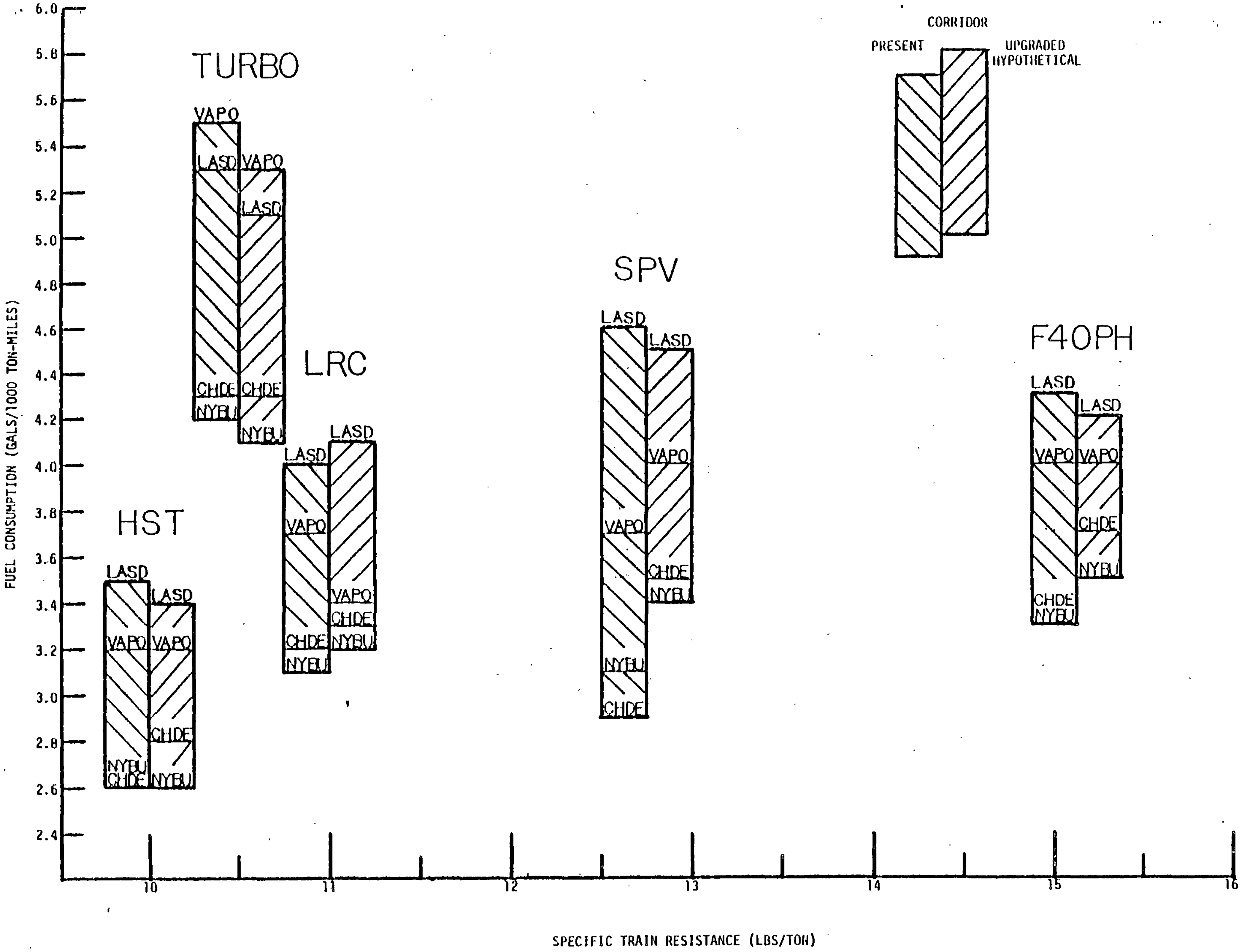


FIGURE 4.14 FUEL CONSUMPTION VS. SPECIFIC TRAIN RESISTANCE FOR NON-ELECTRIC TRAINS

5.0 PARAMETRIC ANALYSIS OF ENERGY CONSUMPTION AND PERFORMANCE ON THE NEC

The profile for the upgraded version of the NEC was selected for conducting a parametric analysis of the effect of weight, maximum speed, train resistance and speeds in curves on energy consumption and schedule performance.

Speed restrictions for 3" and 6" unbalance on curves for the NEC with a maximum speed of 120 MPH were shown in Figures 4.1 and 4.2 in the previous section. Speed restrictions were also developed for 3" and 6" of unbalance on curves with maximum speed limits of 140 and 160 MPH and, for 9" and 12" of unbalance on curves with maximum speed limits of 120, 140 and 160 MPH. The speed restrictions for the ten new profiles were developed using the following rules:

1. At no time could the speed limit exceed the unbalance speed on curves indicated (i.e., 3", 6", 9" or 12").
2. Speed limits could be raised (to 140 and 160 MPH) only if they were originally 120 MPH and the unbalance speed on curves was not exceeded.

Car weight, maximum speed and curve unbalance were selected to cover a range of foreseeable future trains and do not represent approved values for safe application. For example, the one third rule for safety against overturning would limit curve unbalance to approximately 7". However, by varying the unbalance condition, the effect of tilt-body equipment could be studied.

The parametric analysis was applied to both MU-car and locomotive-hauled equipment. Although no auxiliary power consumption was used for these runs, propulsion system effeciencies typical of phase-controlled rectifier-DC drive traction units, similar to the upgraded Metroliner or AEM7 locomotive, were used.

5.1 MULTIPLE UNIT TRAINS

The parametric analysis of MU-trains was accomplished using a six car train with single car weights of 68, 85 or 102 tons. This range of weights (68-102 tons/car) was selected to incorporate the lightest weight European and Japanese self-propelled cars and the largest weight cars to which a tilt capability has been added.

The self-propelled car, which is used as the basic unit, utilizes a Metroliner type propulsion system. This is certainly a good assumption, since a propulsion system with significantly more capability would not be expected to fit under the car.

The specific tractive effort vs. speed curves for the three MU-trains (of different weights) are shown in Figure 5.1. Train resistance was estimated using the Davis formula, and the information is shown in Table 5.1.

Train performance estimates for these three MU-trains were made with maximum speeds of 120, 140 and 160 MPH at 3", 6", 9" and 12" of unbalance on curves. Four intermediate stops were included in the New York-Washington (NY-WA) section of the NEC and three intermediate stops in the New York-Boston (NY-BO) section. Dwell time was 75 seconds/stop.

Figures 5.2 and 5.3 show schedule time and energy consumption plotted against curve unbalance for the three MU-trains considered on the NY-WA and NY-BO corridor sections, respectively. Variation with maximum speed is also shown. Note the difference in the slope of the curves for the two corridor sections. In the NY-WA section, there are fewer curves, so that increasing speed on curves by increasing permitted curve unbalance has little effect on schedule time, while the opposite is true in the NY-Bo section. However, increasing speed on the NY-BO corridor, because of much more pronounced effect on schedule time than on the NY-BO corridor, because of less slowdowns due to fewer curves.

Energy consumption, as expected, increases with both weight and maximum speed. Energy consumption may be higher or lower with increased curve unbalance permitted, depending upon the perturbations of kinetic energy supplied composed to the increased train resistance at higher speed.

Figure 5.4 presents a different aspect of the energy consumption analysis by energy consumption vs. schedule time for the various unbalance speeds, train weights and maximum speeds for both corridor sections.

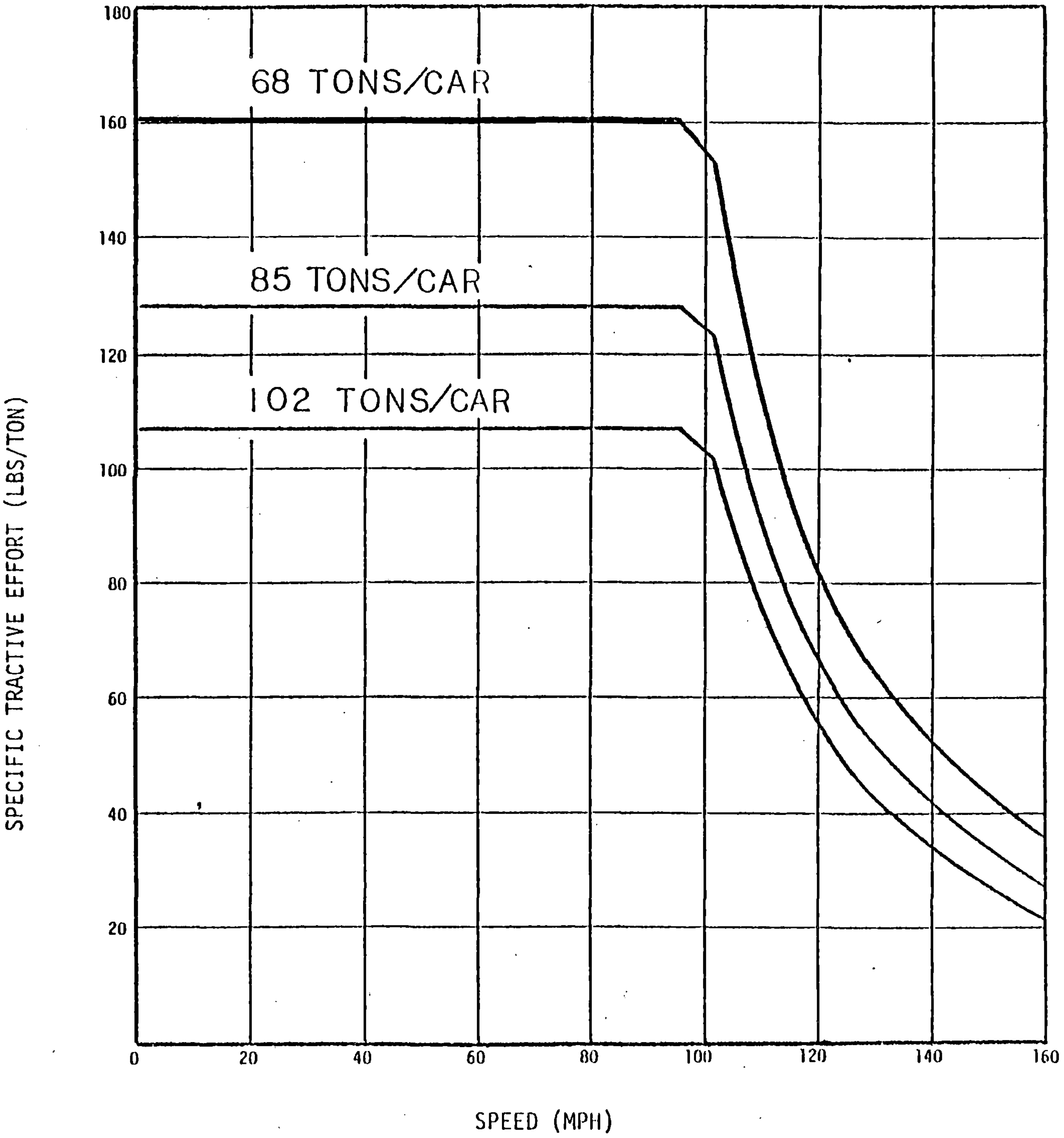
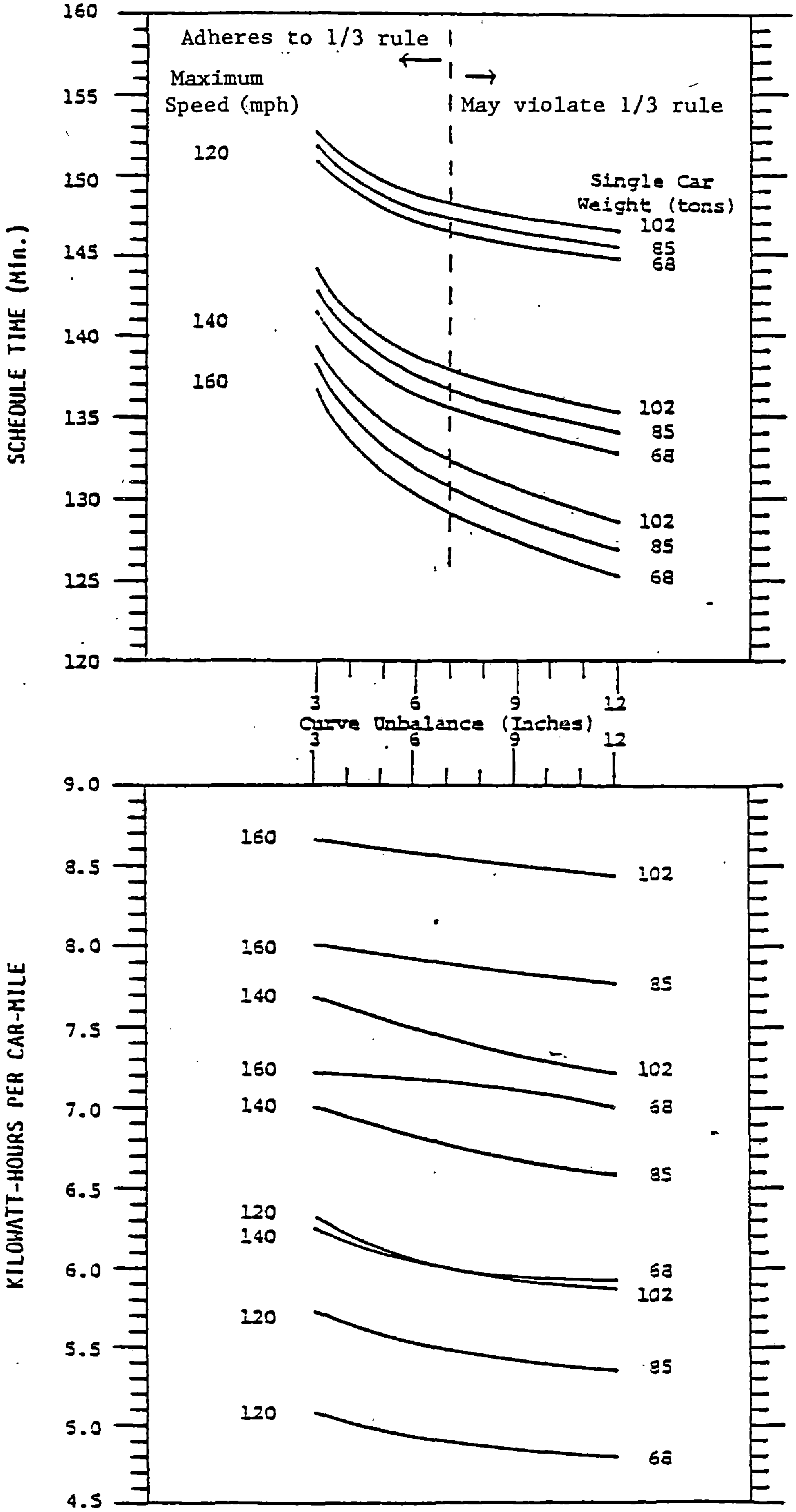


FIGURE 5.1 SPECIFIC TRACTIVE EFFORT CURVES FOR MU-TRAIN USED IN ANALYSIS

TABLE 5.1 SPECIFIC TRAIN RESISTANCE INFORMATION FOR THE MULTIPLE-UNIT TRAINS USED IN THE PARAMETRIC ANALYSIS

TRAIN WEIGHT/CAR (TONS)	FRONTAL CROSS SECTION (SQ. FT.)	COEFFICIENT			
		r_0 (LBS/TON)	r_1 (LBS/TON/MPH)	r_2 (LBS/TON/MPH^2)	t_R @ 120 MPH (LBS/TON)
68	110	3.00	.045	0.0066	24.44
85	110	3.00	.045	0.0053	20.92
102	110	3.00	.045	0.0044	18.57

$t_R = r_0 + r_1 v + r_2 v^2$



ENERGY CONSUMPTION
NO AUXILIARIES

FIGURE 5.2 SCHEDULE TIME AND ENERGY CONSUMPTION VS. CURVE UNBALANCE -- MU-TRAIN -- NEW YORK-WASHINGTON

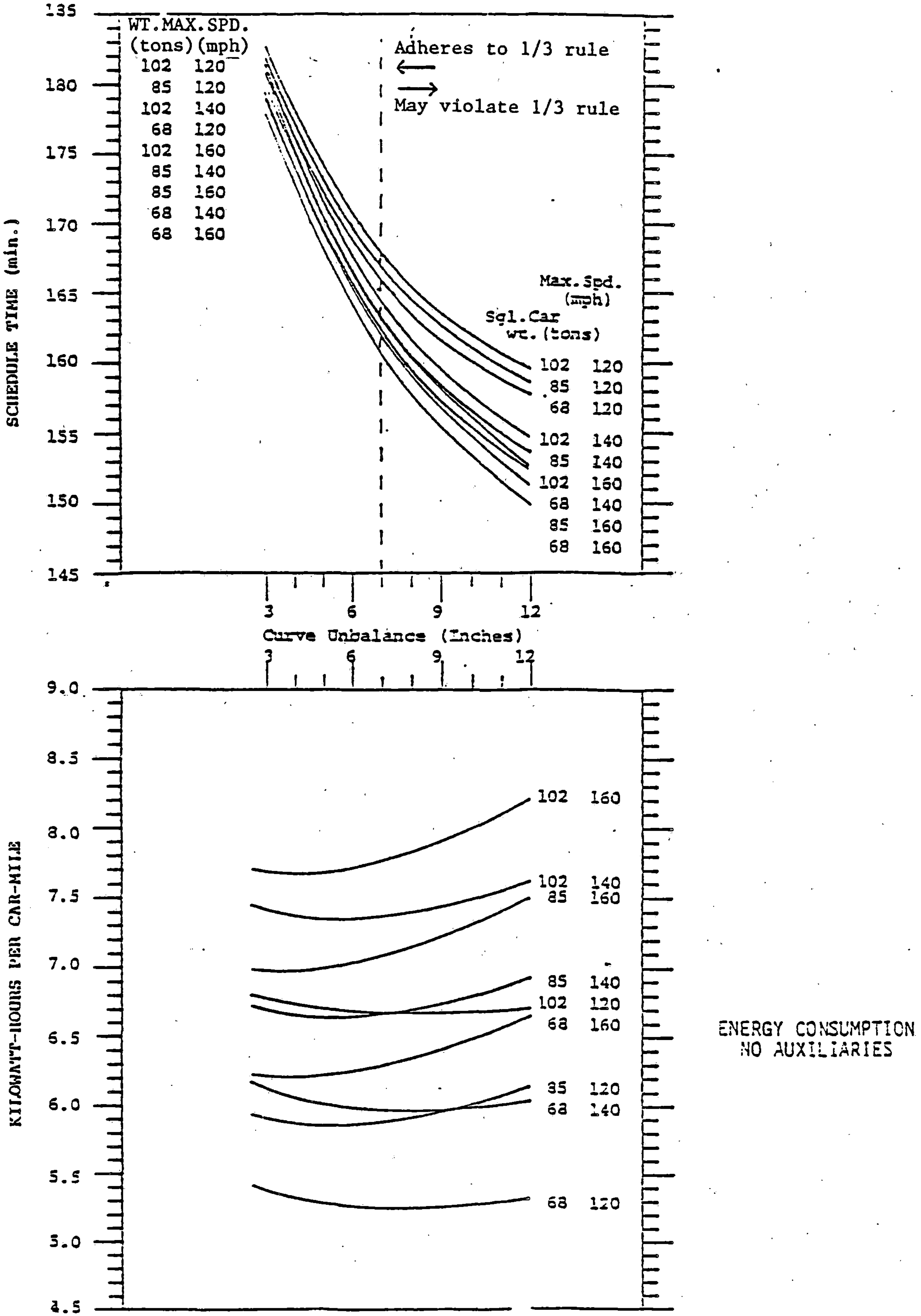
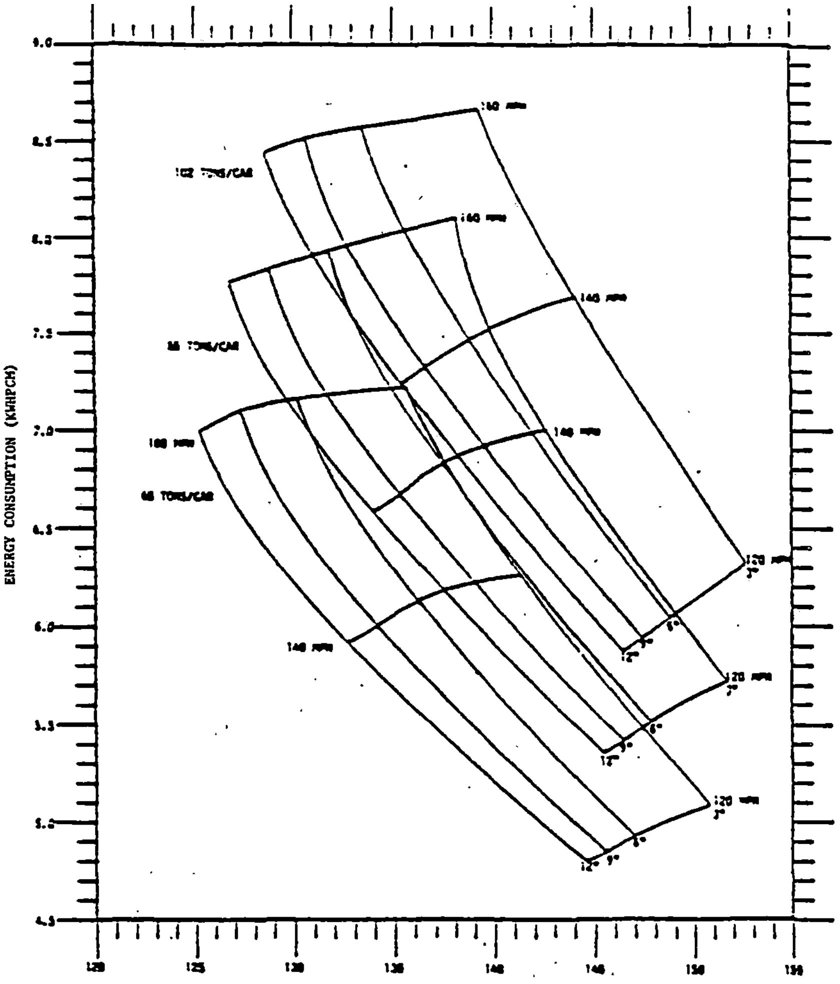


FIGURE 5.3 SCHEDULE TIME AND ENERGY CONSUMPTION VS. CURVE UNBALANCE -- MU-TRAIN -- NEW YORK-BOSTON

MU-TRAIN NEW YORK - WASHINGTON



MU-TRAIN NEW YORK - BOSTON

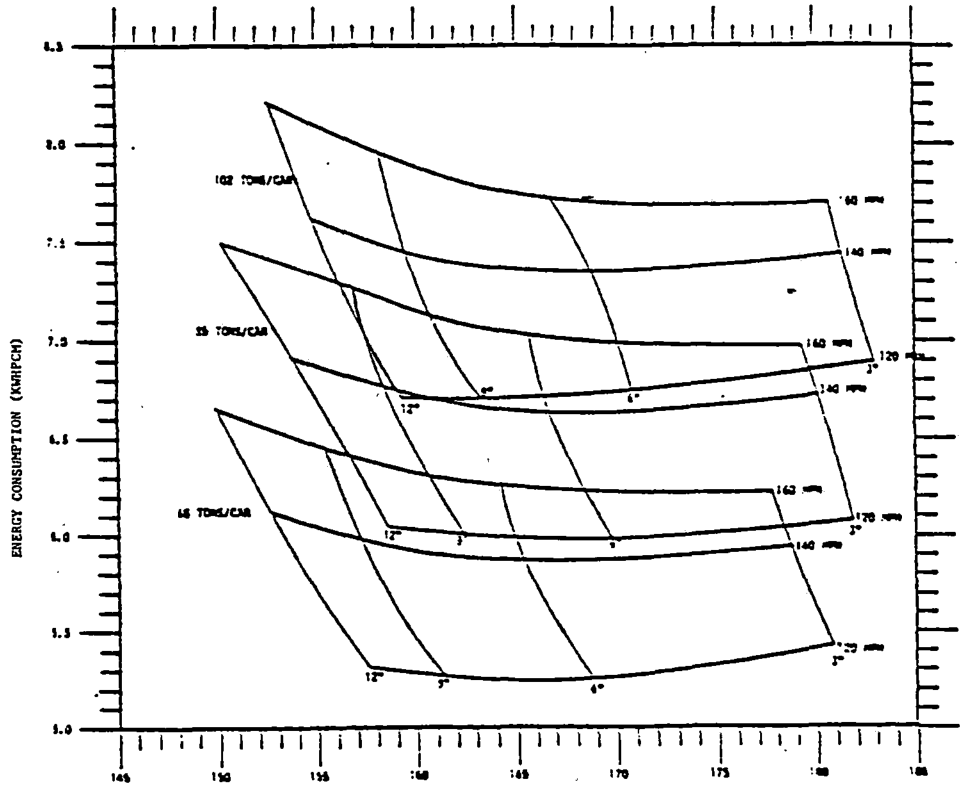


FIGURE 5.4 MU-TRAIN ENERGY CONSUMPTION VS. SCHEDULE TIME

To test the sensitivity of the results to the aerodynamic portion of the train resistance assumed, the train resistance was varied by ± 20% over the nominal case for the 85 ton train at a maximum speed of 120 MPH on the New York-Washington segment of the Northeast Corridor. The results are shown in Table 5.2.

This represents a ± 6% change in energy consumption per ± 20% change in the train resistance due to aerodynamic drag.

Another interesting comparison is the schedule time and energy consumption if there were no speed restrictions and the train ran on level-tangent track between Boston and Washington. This would represent some ideal lower limit schedule time. Table 5.3 shows these curves for top speeds of 120 and 160 MPH with the same number of intermediate stops as indicated.

It is interesting to note that adding or subtracting a stop of 75 seconds, or 1.25 minute dwell time, is worth 1.5-2.6 minutes on the New York-Washington segment and 1.5-2.7 minutes on the New York-Boston segment, therefore, adding or subtracting a stop could mean an increase or decrease in the schedule time of 1.5-2.7 minutes. The lower value is the result of speed restrictions in station areas, which can be as low as 15 MPH.

5.2 LOCO-HAULED TRAINS

The parametric analysis of locomotive-hauled trains was accomplished using a locomotive hauling six passenger cars. Three total train weights were used: 310 450 and 570 tons. This range of weights was selected to incorporate a range of locomotive weights from 100-150 tons and passenger car weights in the range from 35-70 tons. Table 5.4 shows the make-up of the three consists used in the analysis. The range of weight of the passenger cars cover the range of weights of domestic and foreign vehicles available for the future.

The locomotive, which is similar to the AMTRAK AEM7, has the same tractive effort-speed curve for all three consists. Specific tractive effort curves are shown in Figure 5.5.

TABLE 5.2 EFFECT OF SCHEDULE TIME AND ENERGY CONSUMPTION ON TRAIN RESISTANCE

	New York - Washington	
Aerodynamic Portion of Train Resistance	Schedule Time (min)	Energy Consumption (KWHPCM)
Nominal + 20%	151.7	6.07
Nominal	151.7	5.72
Nominal - 20%	151.6	5.39

TABLE 5.3 LEVEL TANGENT TRACK RUN COMPARISON WITH NO SPEED RESTRICTIONS

	MAXIMUM SPEED			
	120 MPH		160 MPH	
Corridor Segment	Schedule Time (min)	KWHPCM	Schedule Time (min)	KWHPCM
New York-Washington	124.9	5.06	100.0	7.45
New York-Boston	125.2	4.87	98.9	7.20

TABLE 5.4 WEIGHTS OF THREE LOCOMOTIVE HAULED CONSISTS USED IN ANALYSIS

TRAIN TYPE	LOCOMOTIVE WEIGHT (TONS)	PASSENGER CAR (TONS)	CONSIST WEIGHT (TONS)
Light	100	35	310
Intermediate	150	50	450
Heavy	150	70	570

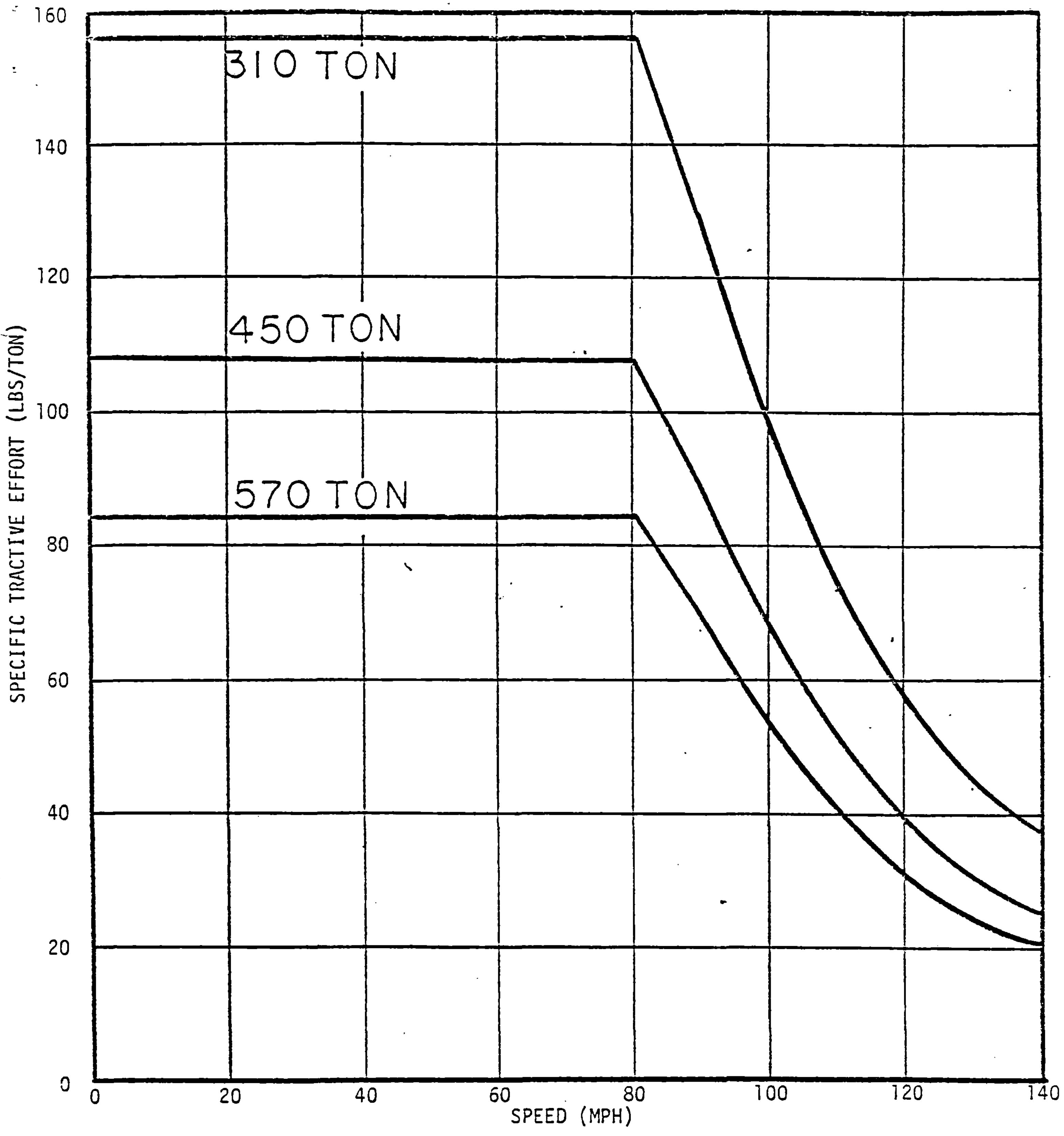


FIGURE 5.5 SPECIFIC TRACTIVE EFFORT CURVES FOR LOCOMOTIVE HAULED TRAINS IN PARAMETRIC ANALYSIS

Train resistance was estimated using the Davis formula and this information is shown in Table 5.5.

Train performance estimates were run for the three locomotive-hauled trains with maximum speeds of 120 and 140 MPH at 3", 6", 9" and 12" unbalance on curves. Four intermediate stops were included in the NY-WA corridor section and three intermediate stops in the NY-BO section. Dwell time was set at 75 seconds/stop.

Figure 5.6 and 5.7 summarize the schedule time and energy consumption plotted as a function of curve unbalance for the NY-WA and NY-BO sections of the corridor. The results are vary similar to the MU-train analyzed in the previous section, since the locomotive has high performance capability. Again, because of the large number of curves in the NY-BO segment, the curves of schedule time have much steeper slopes than in the case of the NY-WA segment.

Figure 5.8 shows energy consumption vs. schedule time for the various unbalance speeds permitted, train weights and maximum speeds for both corridor segments. Energy consumption increases with maximum speed and weight, and may increase or decrease with curve unbalance permitted, depending upon the perturbations of kinetic energy supplied compared to the increased train resistance at higher speed.

A parametric analysis was done on the effects of train resistance on energy consumption using the locomotive hauled train on the NY-BO and NY-WA segments of the corridor. The 3" curve unbalance speed restrictions were used with maximum speeds of 120 and 140 MPH. The results are presented in Figure 5.9. The same analysis was also completed with level, tangent track in the two corridor segments with no speed restrictions. The results are also displayed in Figure 5.9.

The principal difference between the NY-BO and NY-WA results using the level, tangent track profile is the additional stop from maximum speed in the NY-WA section. With the 3" unbalance speed restriction profile, the NY-BO energy consumption

TABLE 5.5 SPECIFIC TRAIN RESISTANCE INFORMATION FOR THE LOCOMOTIVE-HAULED TRAINS USED IN THE PARAMETRIC ANALYSIS

		← COEFFICIENT →			
TRAIN WEIGHT (TONS)	FRONTAL CROSS SECTION (SQ. FT.)	r_0 (LBS/TON)	r_1 (LBS/TON/MPH)	r_2 (LBS/TON/MPH^2)	t_R @ 120 MPH (LBS/TON)
310	140	3.91	.045	0.0020	38.31
450	140	3.10	.045	0.0014	28.52
570	140	2.72	.045	0.0011	23.95

$t_R = r_0 + r_1 v + r_2 v^2$

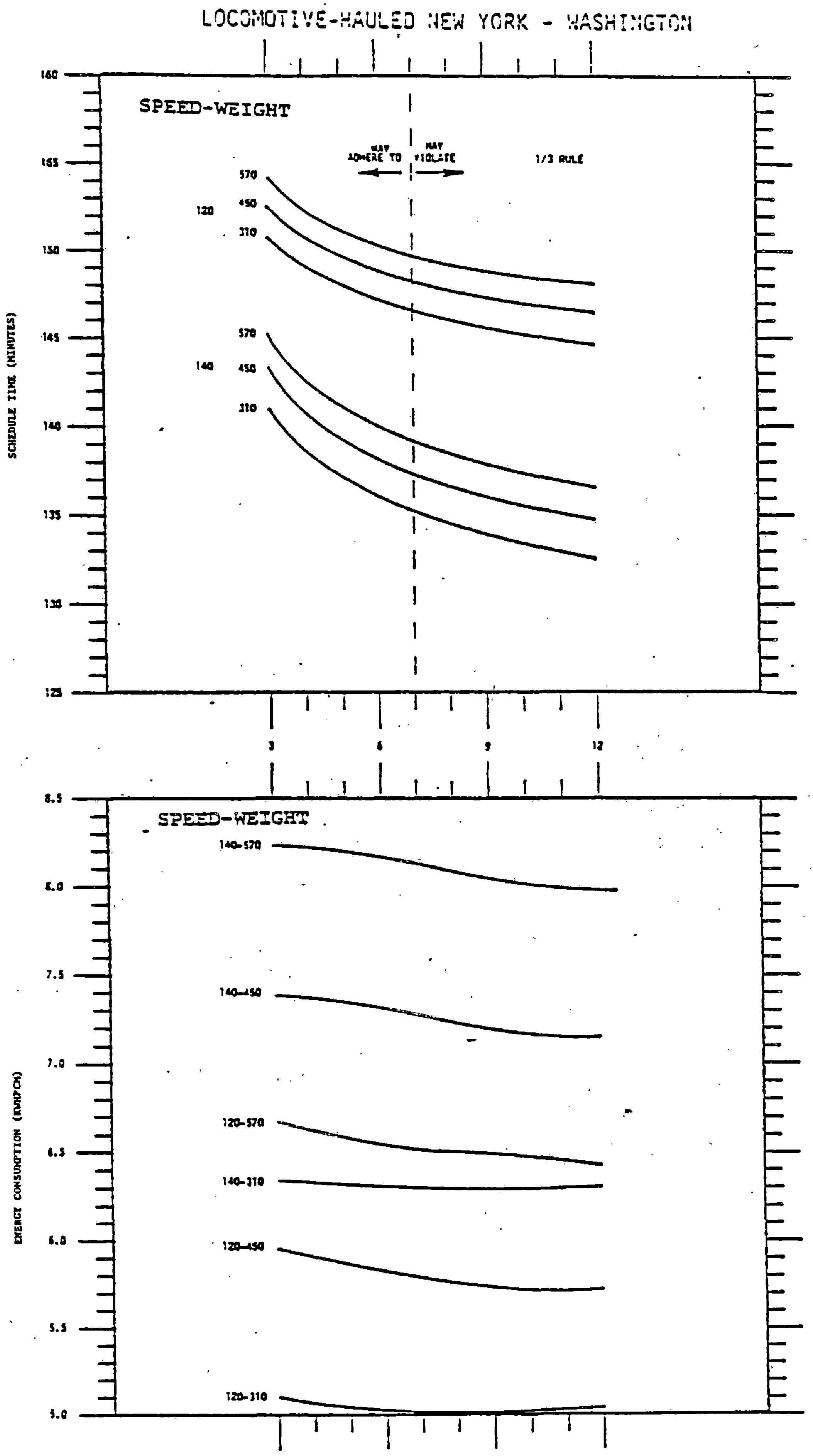


FIGURE 5.6 SCHEDULE TIME AND ENERGY CONSUMPTION VS. CURVE UNBALANCE--LOCOMOTIVE HAULED TRAIN--NEW YORK-WASHINGTON

LOCOMOTIVE-HAULED NEW YORK - BOSTON

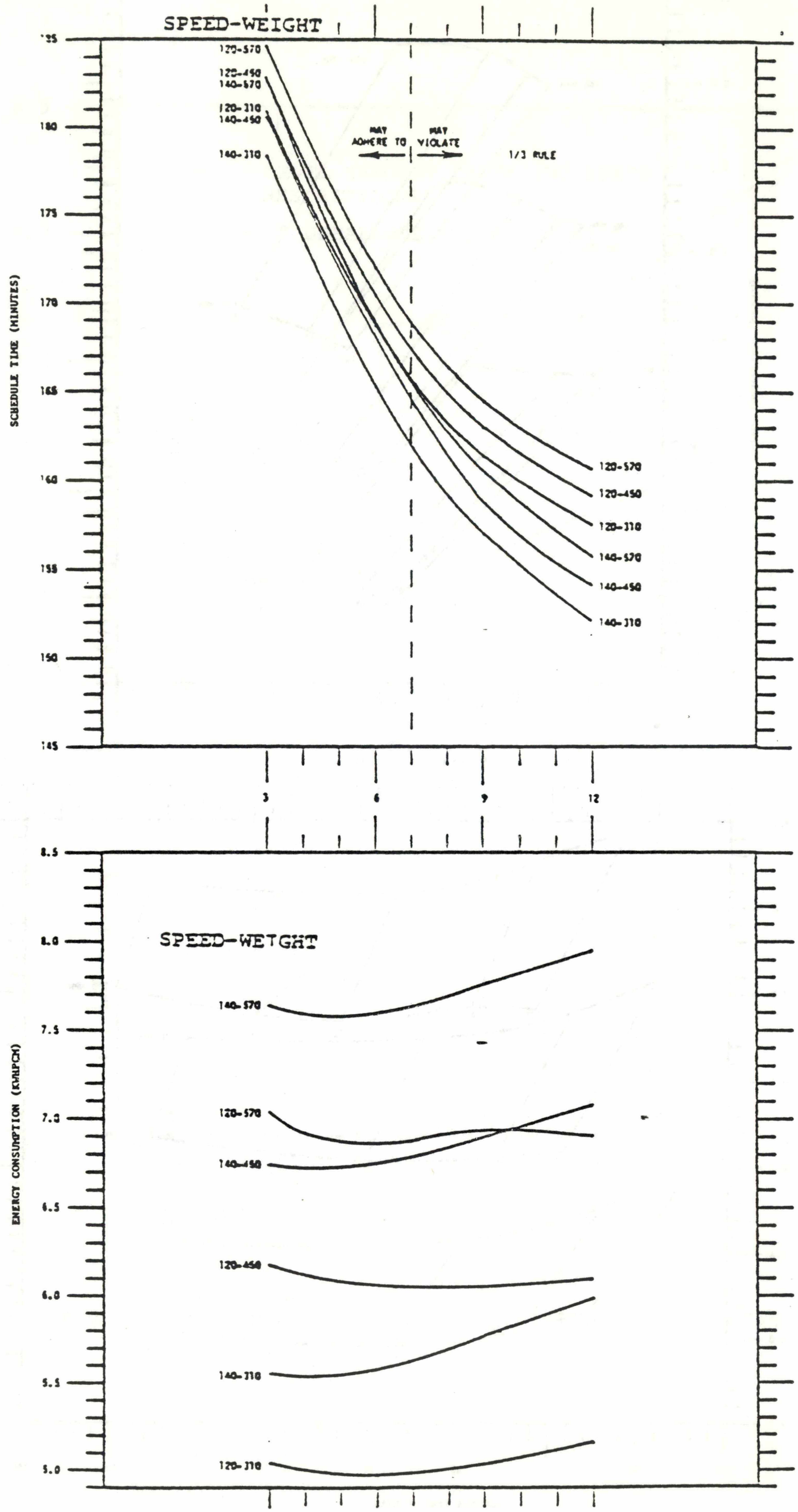


FIGURE 5.7 SCHEDULE TIME AND ENERGY CONSUMPTION VS. CURVE UNBALANCE--LOCOMOTIVE HAULED TRAIN-- NEW YORK-BOSTON

increases more slowly with increasing aerodynamic train resistance than does that on the NY-WA segment because more of the energy consumption is due to slow downs (kinetic energy perturbations) on former segment.

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   Volume 9, SPV2000 (U.S.A.),
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APPENDIX
LIST OF 24 TECHNICAL PAPERS COMPRISING THE 6 VOLUMES OF THE PASSENGER TRAIN EQUIPMENT REPORT

VOLUME 1. ADVANCED PROPULSION SYSTEMS AND PROPULSION SYSTEM REQUIREMENTS.

- "Review of Advanced Propulsion Systems," R.A. Uher and J.W. Marchetti, March 1979.
- "Propulsion System Requirements," R.A. Uher, March 1980.

VOLUME 2. PROPULSION SYSTEM COMPONENTS AND FUTURE TRAIN ENERGY CONSUMPTION.

- "Traction Motor Drives," Louis T. Klauder and Associates, September 1979.
- "Review of Modern Slip Detection and Control Systems for Electric Locomotives and Multiple-Unit Cars," Transportation Research Institute, Carnegi-Mellon University, September 1979.
- "On-Board High Voltage Switchgear for M.U. Cars and Locomotives," Louis T. Klauder and Associates, May 1979.
- "NEC Vehicle High Voltage Protection and Switching Control," Louis T. Klauder and Associates, February 1980.
- "Pantographs," Louis T. Klauder and Associates, January 1979.
- "Analysis of Energy Consumption of Future Passenger Trains," Transportation Research Institute, Carnegi-Mellon University, July 1979.

VOLUME 3. SUSPENSION AND GUIDANCE SYSTEMS

- "Axle Loads of Modern Rail Passenger Vehicles," H.C. Meacham, October 1977.
- "Criteria for the Qualification of Rail Vehicles for High-Speed Activity," F.E. Dean and D.R. Ahlbeck, October 1977.
- "Review of Railroad Steering Systems for High-Speed Passenger Trains," J.A. Hadden, August 1979.
- "Government Versus Self-Steering Radial Tracks for High Speed Passenger Trains," G.R. Doyle, Jr., August 1979.
- "Considerations for the Selection of Wheel Profiles for High-Speed Passenger Trains," J.A. Hadden, December 1979.
- "Sensitivity of Wheel Size to Induction and Synchronous Traction Motor Drives," Louis T. Klauder and Associates, November 1978.
- "Influence of Unsprung Mass on Rail Vehicle/Track Performance," J.A. Hadden, G.R. Doyle, J.C. Kennedy, and D.R. Ahlbeck, January 1980.
- "Measurement of Wheel/Rail Forces by Instrumented Wheel Sets," D.R. Ahlbeck, December 1979.

VOLUME 4. BRAKING SYSTEMS.

- "Minimum Braking Rate and Worst-Case Braking Distance Characteristics Required for Advanced High-Speed Passenger Train Operation in the U.S.," Joseph A. Hoess, April 1979.
- "Braking System for Advanced High-Speed Passenger Trains," J.A. Hoess, September 1979.
- "Effect of Articulation on Train Brake System," J.A. Hoess, August 1979.

VOLUME 5. BANKING SYSTEMS AND ARTICULATION.

- "Clearance Considerations of Tilting Body Vehicles on the Northeast Corridor," Louis T. Klauder and Associates, March 1980.
- "Articulation," Louis T. Klauder and Associates, July 1978.
- "A Review of Carbody Tilt Systems On Modern Rail Passenger Vehicles," W.D. Kaiser and H.C. Meacham, February 1980.

VOLUME 6. PASSENGER CAR CONSTRUCTION.

- "Carbody Structural Technology for Intercity Passenger Trains," H.C. Meacham, August 1979.
- "Influence of Materials on Crashworthiness of Rail Car Bodies," Louis T. Klauder and Associates, November 1978.

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