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WAYSIDE ENERGY STORAGE STUDY
Volume IV - Dual Mode Locomotive: Preliminary Design Study

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FINAL REPORT

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16. Abstract

This is the fourth volume of a four volume report entitled the Wayside Energy Storage Study, which comprises the following volumes:

Volume I- Summary
Volume II-Detailed Description of Analysis
Volume III-Engineering Economics Analysis:Data and Results
Volume IV-Dual-Mode Locomotive: Preliminary Design Study

A preliminary design study was conducted to confirm the technical viability and economic attractiveness of the dual-mode locomotive concept based on the most common U.S. road locomotive, the SD40-2. The study examined the existing characteristics of the base locomotive and ensured that operation in the diesel mode would not be compromised by a locomotive which has a pantograph, transformer, converter, and choke added to permit operation from a 50 kV catenary. The study concluded that the concept is technically viable (although some equipment is only available overseas) and is economically attractive, the top line modification cost being $217,500.

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Engineering

PREFACE

This final report summarizes the results of the Dual-Mode Locomotive--Preliminary Design Study. It is submitted to the Transportation Systems Center by the AiResearch Manufacturing Company of California, a division of The Garrett Corporation, in accordance with U.S. Department of Transportation Contract No. DOT-TSC-1349, Modification No. 1 dated August 9, 1978. It is part of the Wayside Energy Storage Study Final Report which comprises four volumes as follows:

Volume No.	Title
1	Summary
2	Detailed Description of Analysis
3	Engineering Economics Analysis Data and Results
4	Dual-Mode Locomotive - Preliminary Design Study

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ACKNOWLEDGMENT

The Dual-Mode Locomotive Preliminary Design Study was conducted by the AiResearch Manufacturing Company of California with the continuing assistance and guidance of the Transportation Systems Center (TSC) Technical Monitor, Mr. John M. Clarke; the Federal Railroad Administration (FRA), Functional Coordinator, Energy/Environment, Mr. John Koper; and several members of the TSC and FRA staffs who were invaluable to the success of the study.

Major contributions were made by many U.S. railroads which contributed comprehensive information that was used to establish and maintain the necessary data base with particular reference to operating policies. The following railroads have given substantial assistance to AiResearch in the study:

Atchison, Topeka, and Santa Fe

Conrail

Denver and Rio Grande Western

Southern

Southern Pacific

Union Pacific

Specialist material and equipment suppliers were helpful in defining the locomotive modifications and commenting on the dual-mode locomotive concept. Those suppliers contributing to the study were the following:

Alco Power Incorporated

English Electric Corporation

General Electric Locomotive Department

General Motors Electro-Motive Division

Morrison-Knudsen Company Inc.

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SUMMARY

This report examines the feasibility of the dual-mode locomotive having both a diesel and an electric capability. The conclusion reached is that, by careful attention to detail, the concept of the dual-mode locomotive is technically feasible. An attempt has been made to reduce the cost of the modification by utilizing as many existing components as possible without modification. Where modifications are necessary they have been kept as simple as possible.

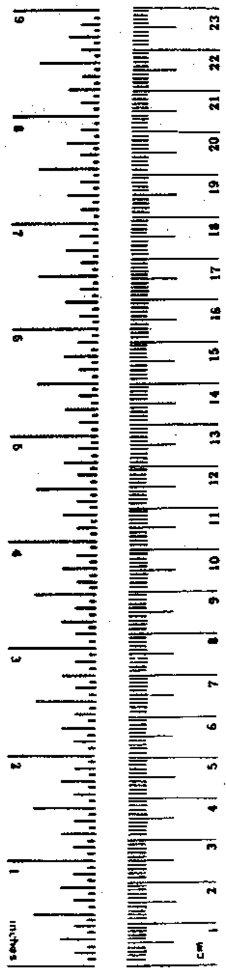
The SD40 and SD40-2 locomotives, on which the conversion is based, are among the most reliable locomotives of their type and care was taken not to impact the diesel mode operation.

Full utilization of the traction motor within its published current, voltage, and power limitations results in a higher powered locomotive in the electric mode. Therefore, if the steepest grades are traversed in the electric mode, above base speed (all railroads contacted provide sufficient power to negotiate all grades above base speed, even for drag operations) a saving in locomotives results.

METRIC CONVERSION FACTORS

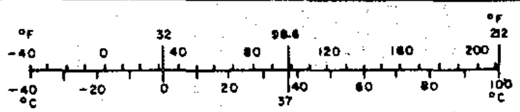
Approximate Conversions to Metric Measures

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



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	35	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



SECTION 1

INTRODUCTION

The purpose of this study was to confirm the technical feasibility of the dual-mode locomotive (DML) following its identification in the Wayside Energy Storage Study Final Report. That study showed that the DML could be used to enhance the existing railroad operation and by and large made use of existing equipment.

PROGRAM OUTLINE

The specific task which was added to the Wayside Energy Storage Study statement of work called for the following:

<u>Item 4</u> - <u>Locomotives</u> - add the following Paragraph b.

b. Conduct a preliminary study of the Dual-Mode Locomotive that will include the following:

Determine the extent of modifications necessary.

Develop preliminary specifications for new components.

Define control requirements.

Identify locomotive structural modifications.

Prepare preliminary layouts.

PROGRAM METHODOLOGY

The basic concept of the DML previously identified was re-examined to determine whether a more cost-effective and technically acceptable version existed. The original concept did not take into account the intention of the Association of American Railroads (AAR) to develop the "clean cab", positioning much of the equipment now located in the cab, in the short front hood. This clean cab has resulted in the toilet being positioned much further forward in the short hood in order to accommodate radio equipment, the water cooler, etc. As a result it was necessary to reposition the electric mode equipment to minimize the volume required at the front of the locomotive.

LOCOMOTIVE CONCEPT

The dual-mode locomotive is basically a diesel locomotive with the ability to operate from a 50 kV (or 25 kV) catenary. This dual mode concept is not new. Since the advent of electrified railroads the concept of a vehicle which could be self or electrically propelled has been pursued to meet particular operating needs. The end of an electrified section (no matter how long that section may be) is always an embarassment to the operating department and a bottleneck to the customer.

Normally a dual-mode vehicle operates at reduced performance in the secondary mode. In the case of the DML based on the SD40-2 locomotive this will not be the case due to that locomotive being equipped with traction motors having a power capability in excess of the prime mover. The removal of the prime mover limitation by supplying power from a catenary enables the traction motors to be fully utilized. From this increase in power capability, it is possible to reduce the size of the locomotive fleet by maintaining maximum tractive effort to the adhesion, rather than prime mover, limit.

DUAL MODE LOCOMOTIVE ADVANTAGES

The benefits of the DML With or without WESS may be summarized as follows:

- Increased tractive effort available at speeds above the minimum continuous rating speed results in either;

  (a) Fewer locomotives required, or

  (b) Shorter journey times

- The concept of evolutionary electrification becomes possible, whereby railroads, for a modest outlay, can gradually electrify a major route and steadily reduce the diesel locomotive fleet as DML's become available and thereby reduce the dependence of the railroad operation on petroleum products

- The DML has the benefit of the mass production of the mechanical parts associated only with diesel locomotives in the U.S. and is therefore cheaper than an electric locomotive

The WESS study has assumed that the railroads will reduce the size of their locomotive fleets rather than aim for shorter journey times. This is because the evaluation of the benefit of shorter journey times involves the use of proprietary information not available at this time. A reduction in the fleet size shows the following significant savings:

(1) Capital Cost

The smaller fleet size results in an immediate capital saving brought about by the transferring of locomotives to other duties.

(2) Locomotive Replacement

The number of locomotives to be replaced annually is reduced because the same percentage of a smaller fleet is replaced each year.

(3) Idling Fuel

A typical road locomotive spends 12 hours/day idling (of which it has been estimated that 8 hrs is unnecessary). At a rate of 5.5 gal/h (for an SD40) this amounts to 44 gal/day or 13,640 gal/year/locomotive.

Clearly significant energy saving is available in this area.

(4) Dead Weight

The reduction in the number of locomotives reduces the total weight of the train and improves the peak hp/total ton ratio.

(5) Maintenance

Significant locomotive maintenance savings result since the remaining fleet does not have its mileage for locomotives increased significantly.

SECTION 2

EXTENT OF MODIFICATIONS

BASIC LOCOMOTIVE

The locomotive to be considered for this modification is the most common in the U.S.; the General Motors, Electro-Motive Division (EMD) SD40 and its derivative, the SD40-2. This locomotive type accounts for approximately 30 percent of the road locomotives in service in the U.S. (reference 1.).*

The SD40-2 is a six axle C-C locomotive equipped with a 16-645E 2 cycle diesel engine which is able to supply 3100 hp to the main alternator and rectifier assembly, from which direct current is supplied to the six series field traction motors.

The locomotive weight, as built is nominally 368,000 lb and may be ballasted to 410,000 lb (reference 2), giving a maximum axle load of 68,330 lb. It is the ballasted weight which has been used for all locomotive performance calculations. It is recognized that it is desirable to reduce axle loads, particularly because of track maintenance considerations, but in order to take full advantage of the potential energy savings resulting from the deployment of WESS and the DML it is necessary to adopt the heavier axle loading. A lowering of the axle load may result in lower energy savings due to reduced braking performance and a decrease in the Return on Investment (ROI).

The use of separately excited motors previously recommended in this study has not been rejected, even though the current design uses unmodified EMD D77 traction motors. In the interest of clarity it is recommended that the case for separately excited traction motors be investigated as a separate issue, taking into account such advantages as a higher tractive effort for the same axle load due to weight transfer compensation.

The general arrangement of the SD40-2 is shown in Figure 2-1 (reference 3).

The standard locomotive is designed for dynamic brake operation (if required by the railroad) and it is this control circuitry which will be used to control regenerative braking during electric mode operation.

Before determining the extent of the modification required to the basic SD40-2 locomotive, it is necessary to establish the power circuit to be used and the method of its control, thus enabling interfaces with existing equipment to be identified and defined.

POWER CIRCUIT

A number of options exist in the choice of the power circuit to be adopted for the DML in both the diesel and electric modes. It is necessary to determine the philosophy of the locomotive conversion before the options can be evaluated. Clearly the characteristics of the locomotive must not be impaired in the diesel mode but it may be permissible to accept a lesser or greater performance (in

*References are listed in Section 9 of this report.

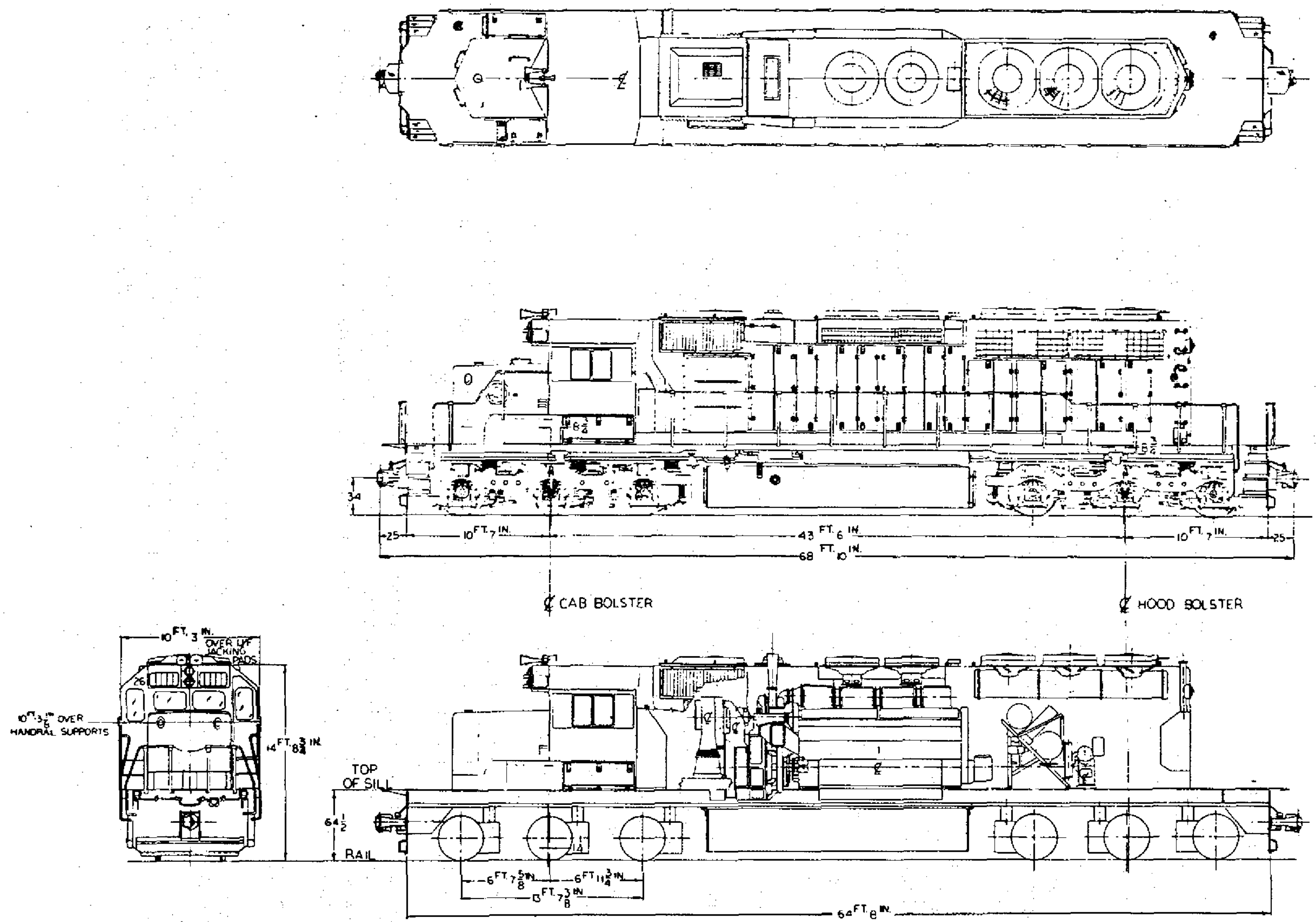


Figure 2-1. General Arrangement of SD40-2 Locomotive

terms of control, etc.) in the electric mode if a positive financial trade-off can be identified. It is desirable therefore, to consider all the relevant characteristics of the existing SD40-2 locomotive and use these as the baseline to evaluate the DML circuit options available.

ESTABLISHED CHARACTERISTICS OF SD40-2 (BASELINE)

Electrical

A diesel engine driven alternator (Model AR10), operating over a 315 to 900 rpm speed range is the source of electrical power for traction. This is a 10 pole rotating field machine with 3-phase output. The field supply is derived from the auxiliary alternator (Model D14) which is mechanically attached to, but electrically separated from, the AR10 main alternator. The ac output from the rotating machine is rectified to give a dc supply with a ripple level of approximately 3 percent. The ripple frequency varies from approximately 52.5 Hz to 150 Hz, dependent on alternator speed.

The six traction motors are the D77 model. This is a dc series field machine, the characteristics of which are shown in Figure 2-2. The motor frame is of solid iron construction. The elimination of field weakening has reduced the incidence of flashover by 50 percent. Railroads have described the commutation of this machine as adequate but not exceptional. This aspect will require careful study when operating in the electric mode on dc with a ripple content significantly higher than that which is present in the diesel mode.

When accelerating from rest or slow speed, the traction motors are connected in three parallel groups of two series pairs across the rectifier dc output (shown in principle in Figure 2-3a). The excitation of the main generator is used to regulate the output voltage at sensibly constant current, thereby resulting in a controlled acceleration of the locomotive. The current applied to the traction motor during slow speed operation is determined by the voltage applied to the motor and the back emf generated by that motor. As the motor back emf increases, the applied voltage is increased to maintain the required net voltage across the motor. For the engine rpm selected (determined by the throttle position), there is a limit to the power that can be developed (proportional to the volt-amps product). When the power limit is reached, the voltage generated cannot be increased to maintain same net voltage across the motors. From this point on (called the motor base speed), the motor current falls as the back emf overcomes the generated voltage. The rate at which this current reduction takes place is lessened by the ability of the alternator to maintain an approximately constant volt-amp product. Therefore, as the current demand decreases, the voltage applied can increase by alternator excitation adjustment, maintaining a constant volt-amp product and thereby reducing the rate of fall of current. The result is that the motor is able to produce a constant power output over a wide speed range.

It will be seen from the above that there are two major criteria which determine the size of the alternator:

(a) Maximum output current

(b) Maximum output voltage

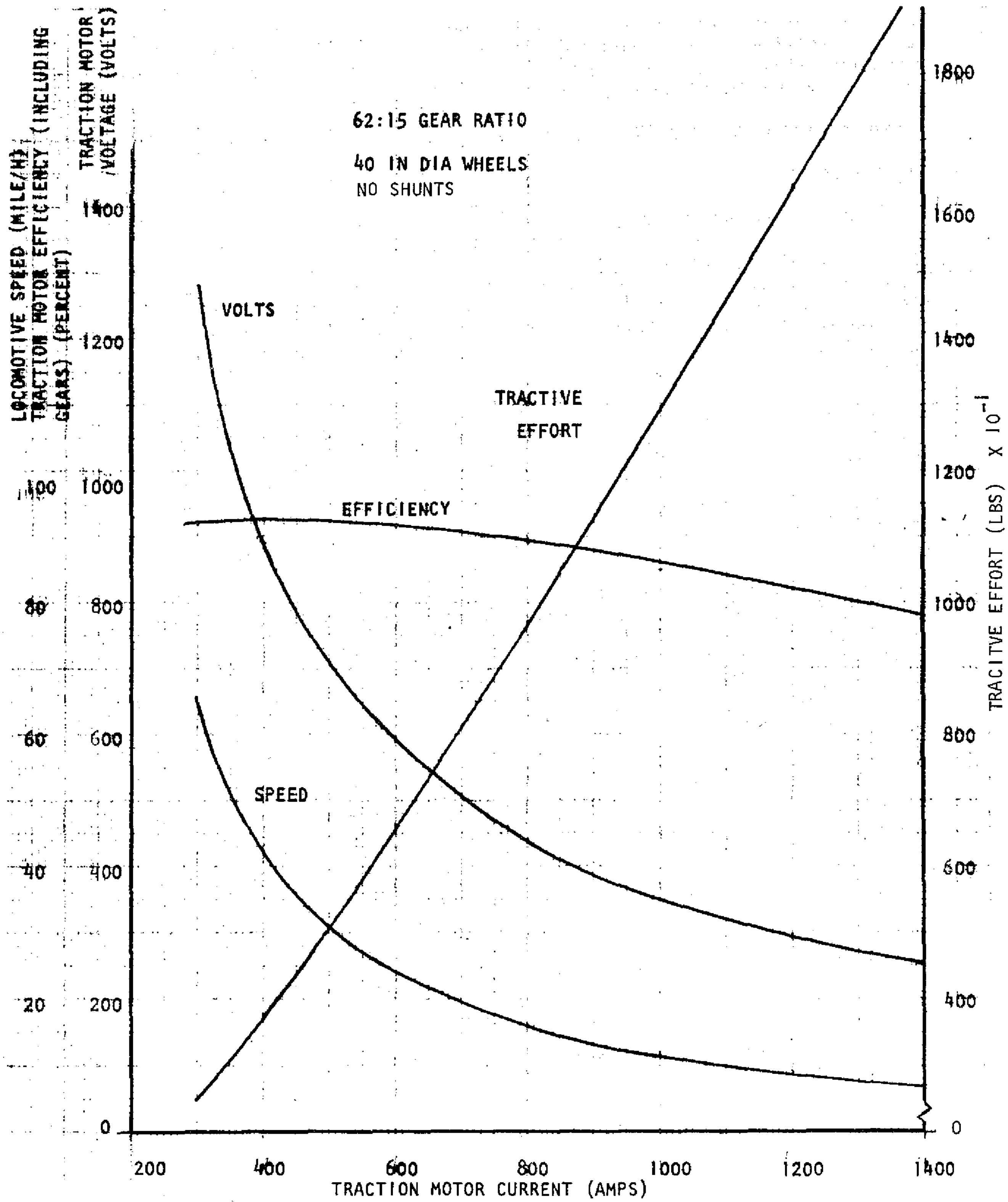
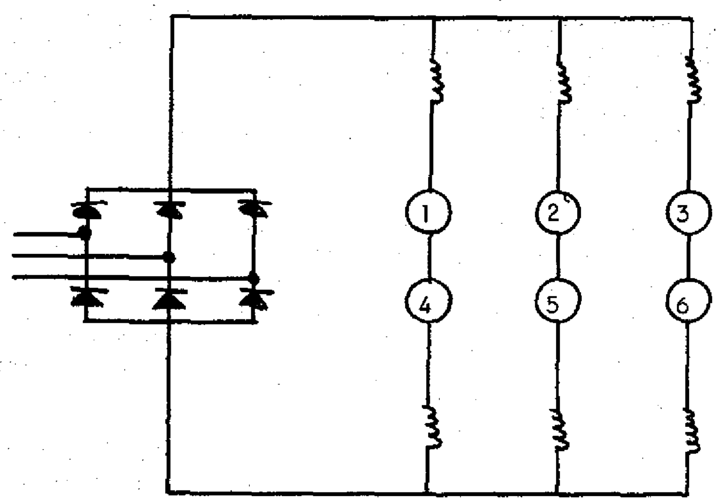
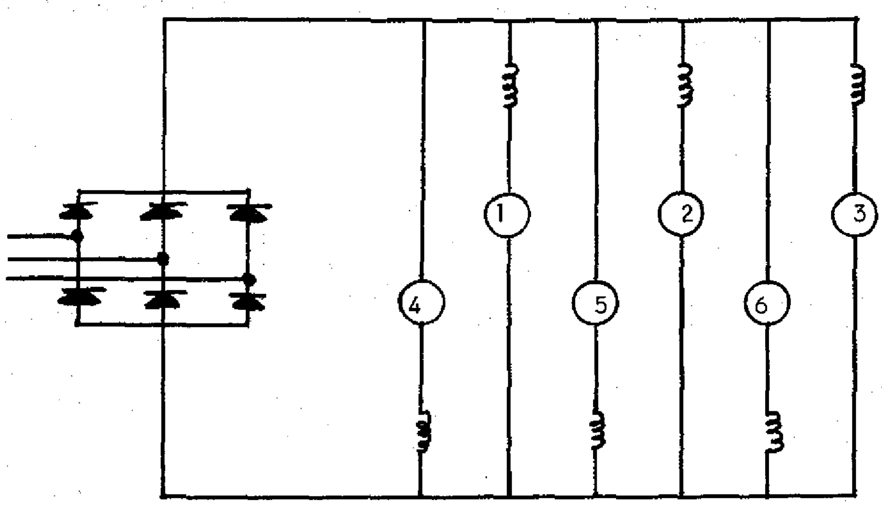


Figure 2-2. Characteristics of D77 Traction Motor at 356 kW



(a) before



(b) after

Figure 2-3. Power Circuit Transition

It is to minimize the effect of these two constraints that the motors are connected in 3 parallel groups of two series pairs at low locomotive speeds (when voltage is a limiting factor). The changeover from one configuration to the other is called transition and occurs in the speed increasing mode at approximately 600 amps motor current. The conditions before and after transition are shown in Figure 2-3. This allows the alternator to be sized for approximately 3600 amps (dc output) and 1000 v (dc output) rather than 6300 amps (the total traction motor continuous rating) if the motors were in permanent parallel, or 2000 volts if the motors were connected in permanent series parallel.

When braking electrically, the traction motor armatures are connected in series-parallel with the braking grids. All motor fields are connected in series with the alternator, therefore, the traction motors operate as separately excited dc generators. The braking effort produced is determined by the field excitation which in turn is determined by the main alternator output voltage. This is related to the position of the dynamic brake handle and is therefore under the direct control of the engineer.

From the above it will be seen that in the event of wheel spin/slide, it is only possible to reduce the tractive/braking effort on all axles. It is not possible to individually control the tractive/braking effort applied to each axle.

Performance

The fundamental parameters requiring definition before describing the locomotive performance are:

(a) Adhesion

(b) Axle load

The Air Brake Association (reference 4) defines the variation of average adhesion with speed to be as shown in Figure 2-4 for dry rail with good joints and slight dirt and oil contamination. This average value takes into account the weight transfer that occurs when tractive or braking effort is applied by a traction motor to the wheel and is a function of truck/locomotive geometry.

The adhesion level assumed is a question of confidence. Theoretically, the coefficient of friction between wheel and rail can exceed 0.5 but this value cannot be reliably achieved in practice due to excessive rail contamination, weather conditions, bad joints, and track geometry. It is the question of confidence which leads each railroad to determine its own adhesion level based on many years of operating experience. For this study, the Air Brake Association data was used.

Definite advantages have been shown for welded rail over jointed rail (particularly if the latter is in poor condition) as far as assumable adhesion level is concerned, but no advantage was claimed for this aspect in the study although this will become more significant as the railroads progress with their welded rail programs.

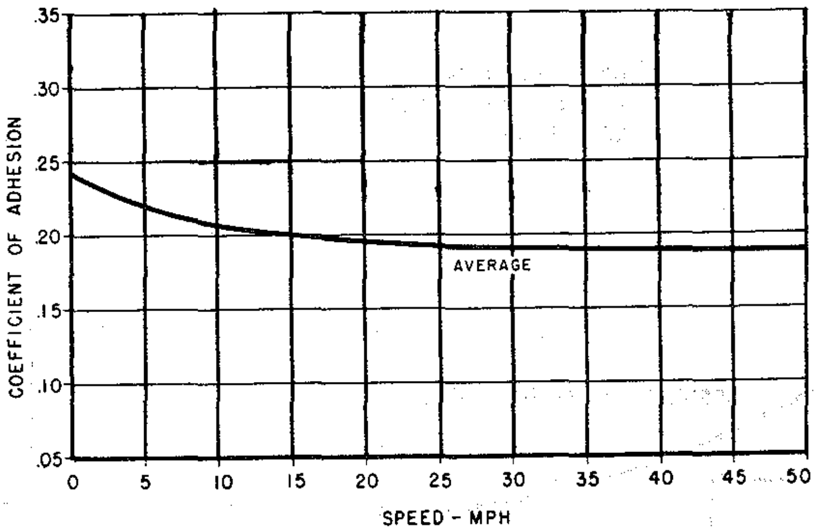


Figure 2-4. Variation of Average Adhesion with Locomotive Speed

From the Wayside Energy Storage Study Volume 2 it can be seen that the power available at the rail to move the train is 2590 rail horsepower (rhp) of the 3100 shaft horsepower (shp) available.

The maximum continuous current allowable for the D77 traction motor (reference 5) is 1050 amps which, at the most common gear ratio (62:15) results in 13,850 lb tractive effort and a maximum locomotive speed of 65 mph (reference 5). With the above parameters defined the upper boundaries of the locomotive performance are defined and are shown in Figure 2-5.

It can be seen therefore that in normal operation the SD40-2 locomotive under the assumed conditions is prime mover limited in the tractive effort it can produce.

The dynamic brake maximum performance is shown in Figure 2-6 with and without the extended range feature (reference 5). In dynamic brake each motor is developing 640 rhp. This maximum performance is obtained with an armature current of 700 amps and a field current of 975 amps. The limit on the dynamic brake performance is the rating of the resistor grids (reference 6) since the motor is rated for a continuous current of 1050 amps in both field and armature simultaneously. Therefore, if the armature current could be increased, then the braking power capability of the locomotive could be increased significantly since the braking power varies as the square of the armature current.

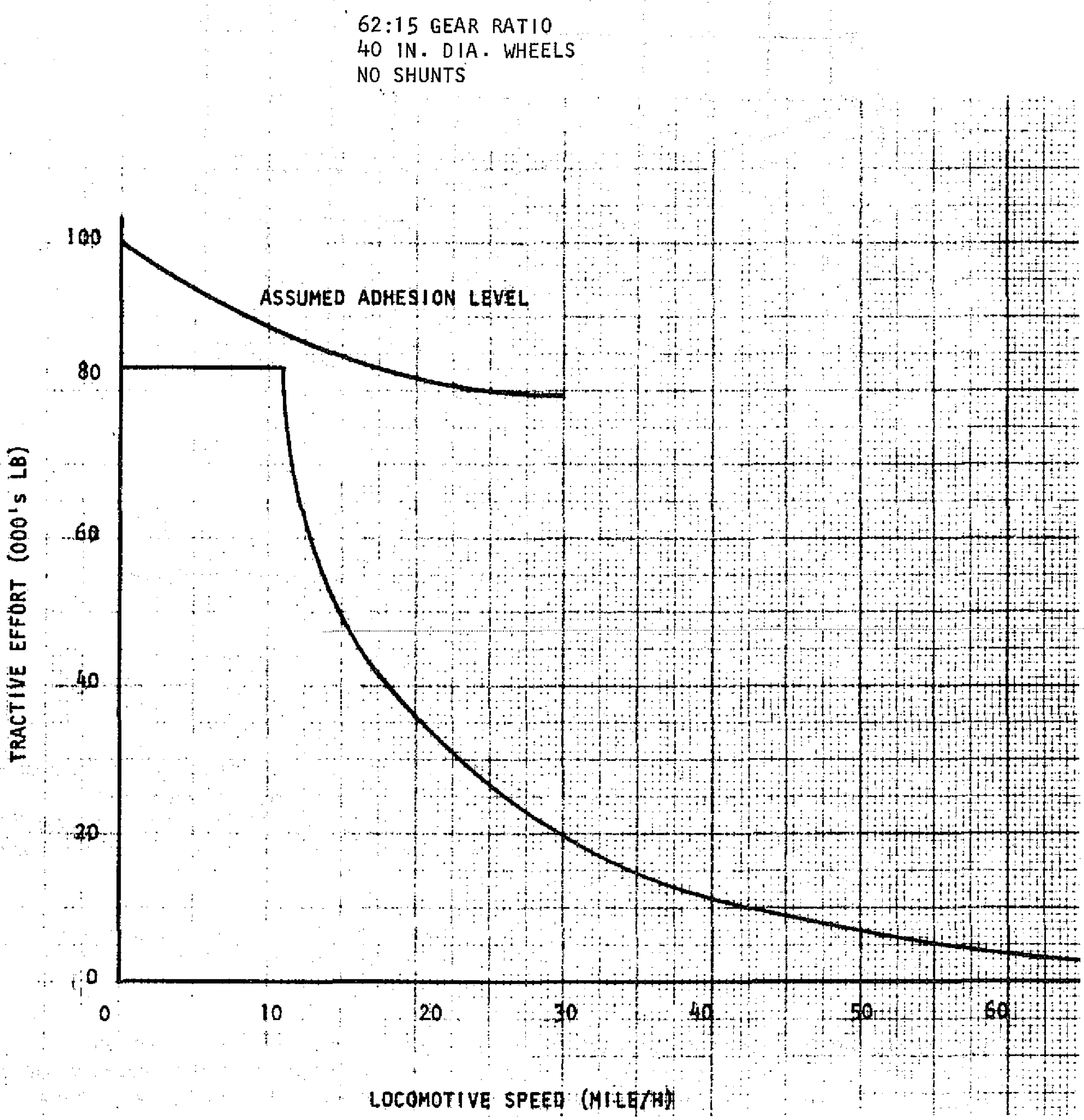


Figure 2-5. SD40-2 Locomotive-Variation of Tractive Effort with Locomotive Speed

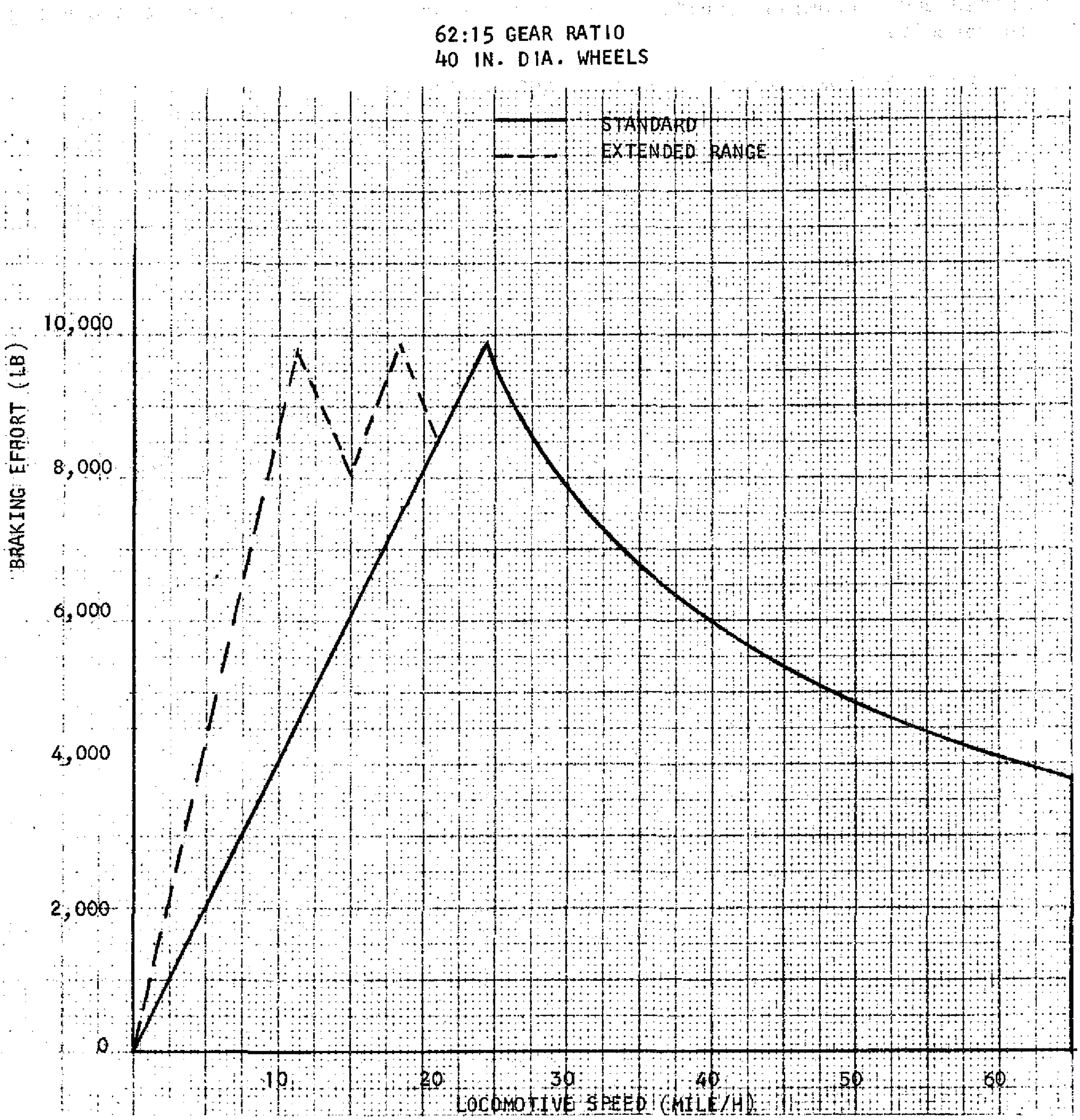


Figure 2-6. Dynamic Brake Characteristics of the SD40-2 Locomotive

When considering braking it is essential to insure that the adhesion level assumed is virtually always available. For this reason the adhesion level assumed in brake should be lower than that assumed in motoring. Figure 2-7 shows the motoring adhesion curve already established and the adhesion curve required under braking conditions for the defined motor performance and braking grid capacity.

PROPOSED CHARACTERISTICS OF DUAL MODE LOCOMOTIVE

Before the various options available can be evaluated, it is necessary to clearly define the basic objective in terms of overall locomotive response compared with the existing diesel locomotive performance. In no case may the DML response be worsened in the diesel mode. The possible objectives are:

(a) Electric and diesel mode control equivalent to baseline.

(b) Electric mode control superior to baseline with diesel mode control unchanged.

(c) Electric and diesel mode control superior to baseline.

The options available to meet each of the above are described below. In all cases it is proposed to operate the motor at the maximum rated power.

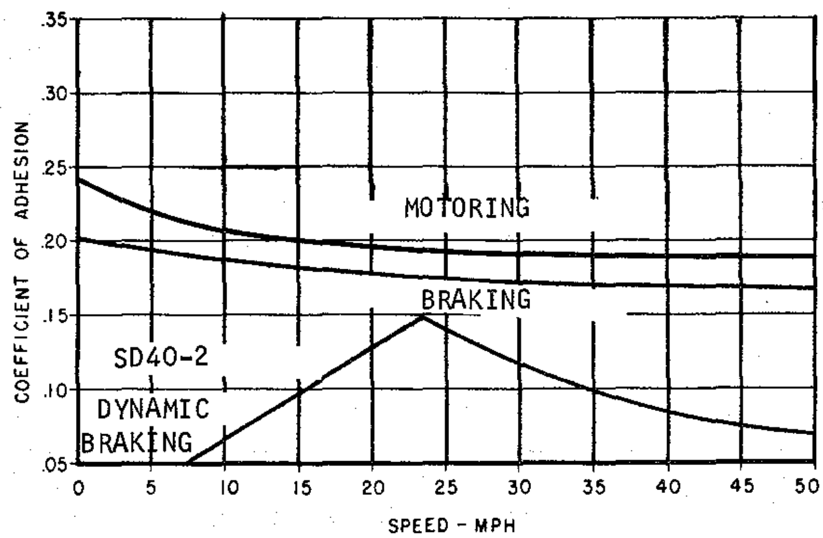


Figure 2-7. Adhesion Values for Motoring and Braking

Baseline Performance

The operation, control and performance of the locomotive in the diesel mode are unchanged. In the electric mode, the power circuitry remains the same with, in principle, the main transformer taking the place of the alternator. This option has the advantage of using the existing traction motors without the need for modification. The constraint of adhesion previously indicated by reference 4 applies equally to the electric mode. It is often (wrongly) stated that an electric locomotive has more adhesion than a diesel locomotive. It is inaccurate to state that a locomotive has an adhesion capability since adhesion is the coefficient of friction between the steel rail and the steel wheel and is independent of the locomotive type (apart from second order effects such as ambient dirt around a locomotive which would be worse for a diesel locomotive). Therefore, the same adhesion constraint applied to the SD40-2 will be applied to the DML.

It is known that the D77 motor has a rating of 536 kW (input) (reference 7). Operation in the electric mode allows the prime move limitation on power developed to be eliminated and replaced by the traction motor limitation assuming that the transformer rating is adequate for the motor rating. Therefore, maximum continuous current can be maintained to either the adhesion limit or the motor power limit, whichever is the more restrictive. Figure 2-8 shows the interaction of these two limitations and that the limiting condition is the traction motor performance.

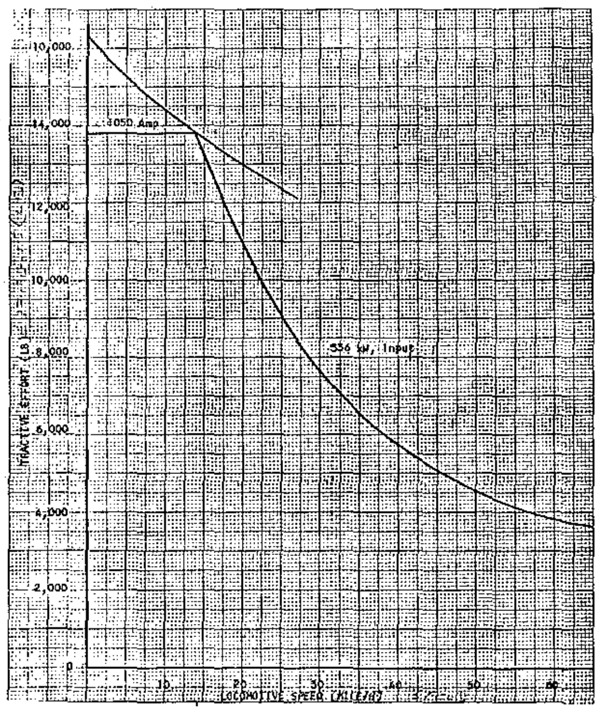


Figure 2-8. Interaction of Adhesion and Motor Power Limitations

The limit of constant current operation is defined by the limit of the volt-amp product of the motor. As the motor speed increases, the current tends to fall due to the rise in back emf. The motor has the capability to accept an increase in applied voltage so the next decision required concerns the characteristics of the power and control supply equipment.

A conventional electric locomotive (above base speed) performs at an essentially constant voltage, determined by the catenary voltage and transformer turns ratio. The only increase in applied voltage as motor current decreases with speed is the result of transformer regulation. However, in order to perform at constant power, the volt-amp product must be constant which requires that above base speed the applied motor voltage must increase above the level that normal transformer regulation would permit. It is possible to design a transformer which has regulation characteristics such that at 100 percent current the output voltage is 50 percent of the output voltage at 50 percent current. Such a transformer would have extremely high copper losses and consequentially a high heat generation rate. Therefore, the combination of low efficiency and large cooling group size makes this option unattractive. The preferred option is to control the applied motor voltage over the complete speed range of the locomotive, thereby allowing the transformer to be designed for minimum load losses. Normal railroad practice is to avoid this technique because of the impact of prolonged operation at partial conduction on the signalling system and the relatively low power factor which results. Since most of the electrification schemes proposed in the U.S., and certainly those proposed in the WESS schemes, allow for the complete resignalling of the railroad (in most cases to eliminate dc track circuits which are incompatible with any form of ac electrification), the signalling system will be designed to withstand the inteference resulting from prolonged operation at partial conduction.

The lower than normal power factor may be handled in two ways. Power factor correction capacitors can be connected to the catenary (or onboard the locomotive, if space permitted) to supply at least part of the reactive power demand or, in the case of WESS electrification the flywheel machine can be over-excited to a leading power factor to compensate for the locomotive's lagging power factor.

Therefore, the locomotive performance, above base speed, will be determined by the traction motor rating, the applied voltage being increased to match the decreasing current, thus maintaining constant power as speed increases. The characteristic of the D77 under these conditions is shown in Figure 2-9 and the variation of motor voltage and current with locomotive speed is shown in Figure 2-10. From this characteristic the locomotive tractive effort-speed curve shown in Figure 2-11 can be derived. Constant power is maintained to 61 mile/h when the voltage limit of the machine is reached (reference 7) at 1300 v. Constant voltage operation to 65 mile/h results in the rapid fall in tractive effort shown in Figure 2-11.

The performance characteristics and control requirements in the electric motoring mode are now fully defined and the complete DML performance characteristic is shown in Figure 2-12.

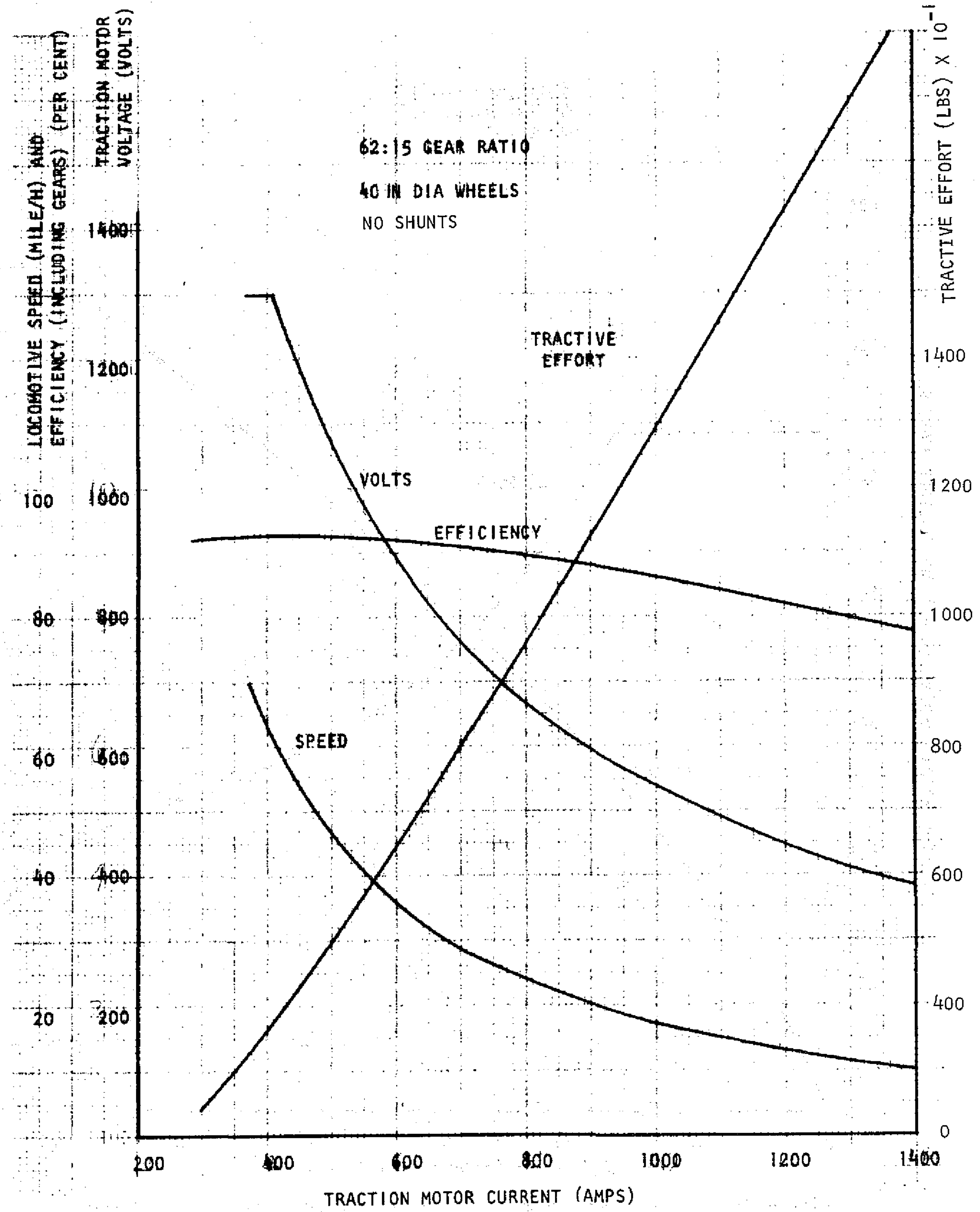


Figure 2-9. Characteristic of the D77 Traction Motor at 536 kW

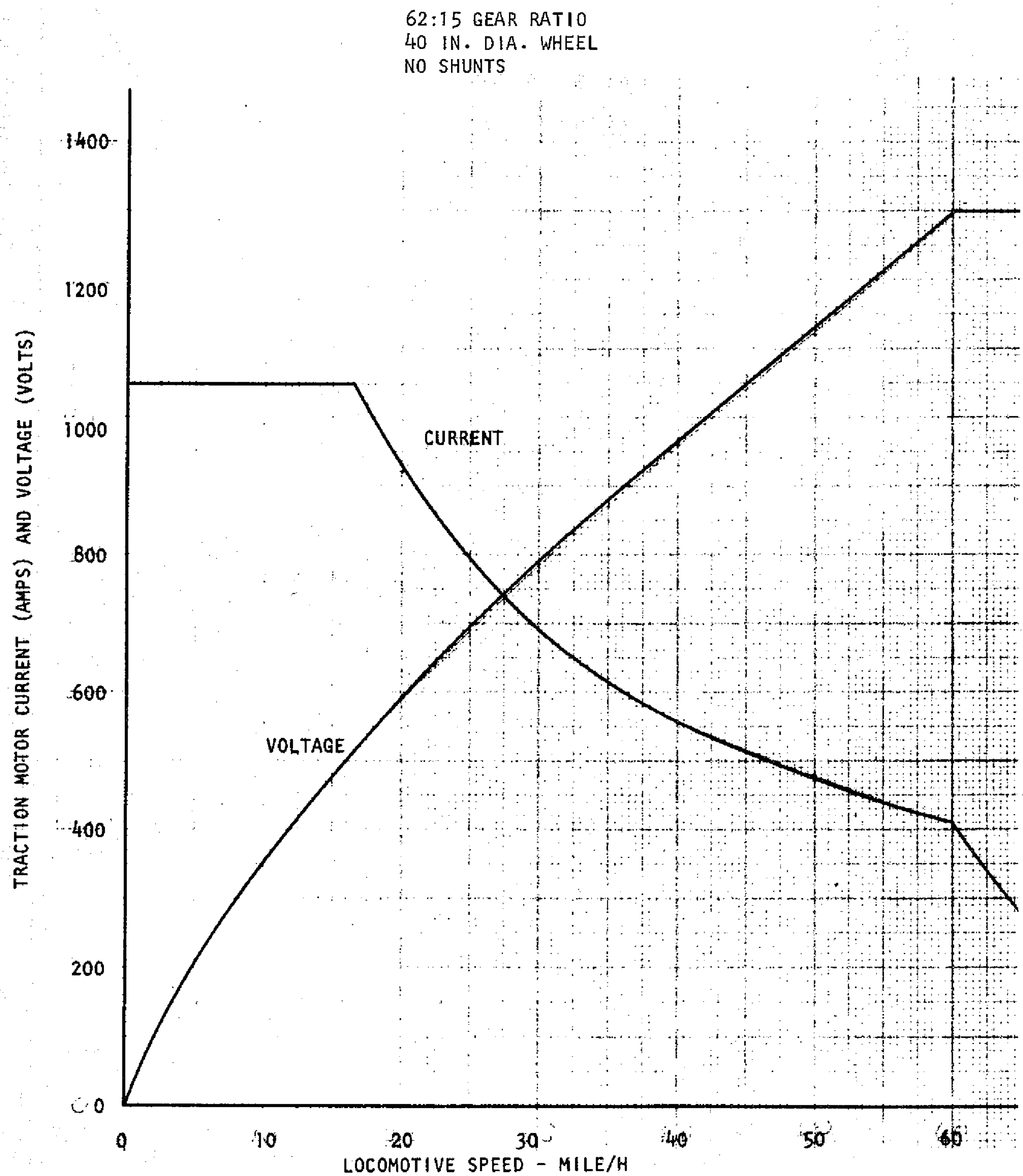


Figure 2-10. Dual Mode Locomotive-Traction Motor Current and Voltage Variation with Locomotive Speed

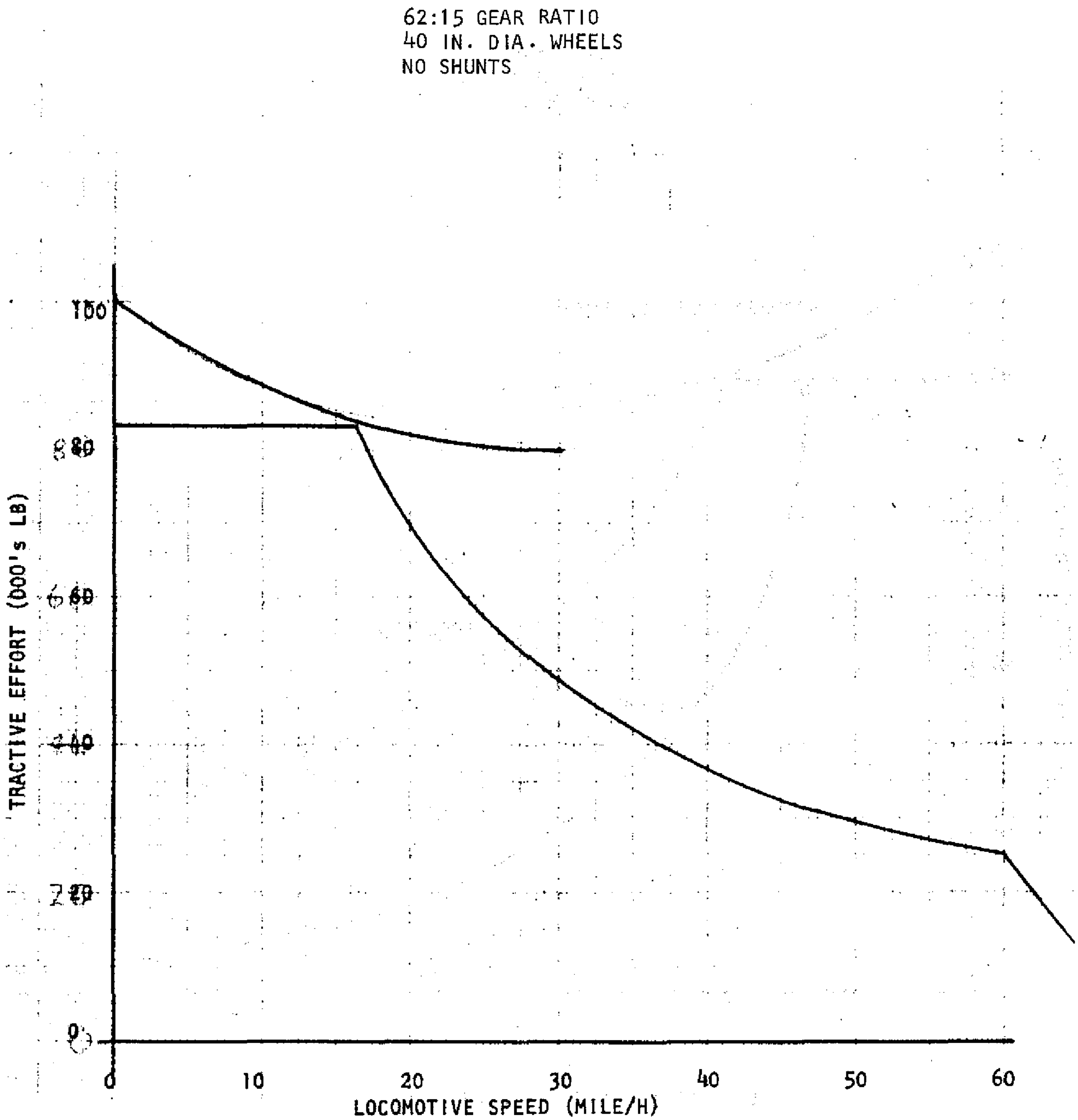


Figure 2-11. Dual Mode Locomotive-Secondary (Electric) Mode Variation of Tractive Effort with Locomotive Speed

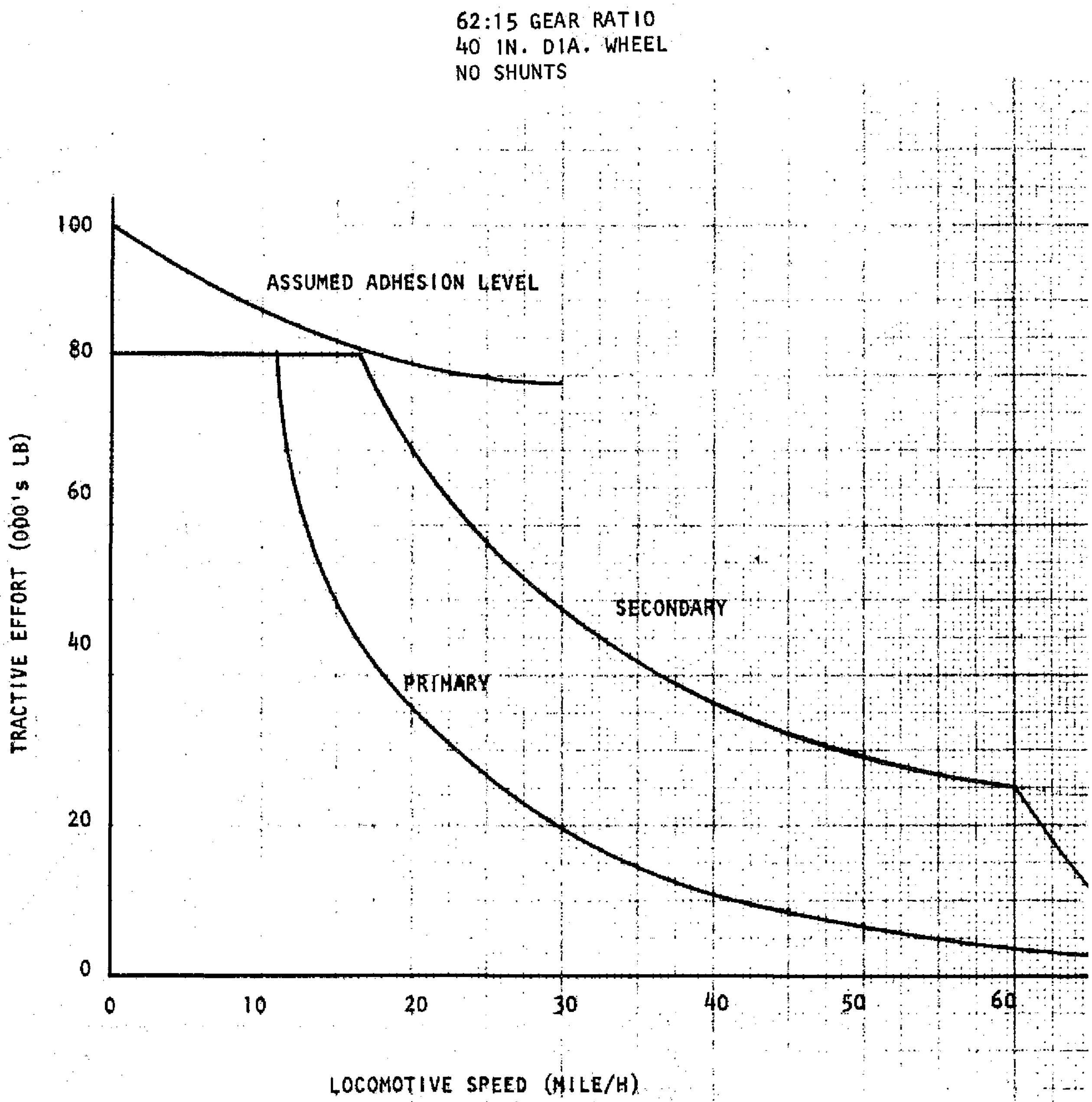


Figure 2-12. Dual Mode Locomotive-Primary and Secondary Mode Variation of Tractive Effort with Locomotive Speed

It has already been shown that the continuous rating of the D77 traction motor is 1050 Amps. This current can be utilized in braking provided that:

(a) the resistor grids limitation is removed

(b) sufficient adhesion is available

(c) Commutation is adequate

During regenerative braking, the grids are not used except for periods when complete loss of contact between the pantograph and the catenary occurs. This condition will only last at the most a few seconds (normally for less than one second) and it is considered that the braking grids will be able to withstand the high currents for this period (although this requires verification).

The adhesion level assumed during braking is usually less than that assumed for motoring. As already pointed out the adhesion level assumed is a question of confidence and therefore in braking, with safety aspects to consider, a higher degree of confidence is required. The adhesion level assumed in braking is shown in Figure 2-7 and represents a 12 percent reduction from the assumed motoring adhesion. This is typical of the reduction with which railroads throughout the world feel comfortable.

The variation in braking effort with armature current is shown in Figure 2-13 which also shows that the higher the armature current, the higher the speed at which the adhesion limit is reached. In order to determine the armature current to be used in regenerative braking, it will be necessary to carry out tests on motors to determine commutation and thermal conditions. Recommendations for these tests are contained in Section 7 of this report.

At the adhesion limit two options are available. Either the armature current can be controlled to give constant braking effort to approximately 5 mile/h or it can be controlled such that the braking effort follows the adhesion limit as it increases with decreasing speed. A detailed design study will determine the optimum system.

Improved Control

As already referred to, the basic locomotive tractive effort is controlled on an "all axle" basis, that is, to reduce or increase the tractive effort on one axle requires a similar adjustment to all axles. There are benefits to be gained from providing individual axle control to a locomotive, particularly an electric locomotive with high power/weight and tractive effort potential/weight ratios. This can be achieved by using separately excited motors with individual field control.

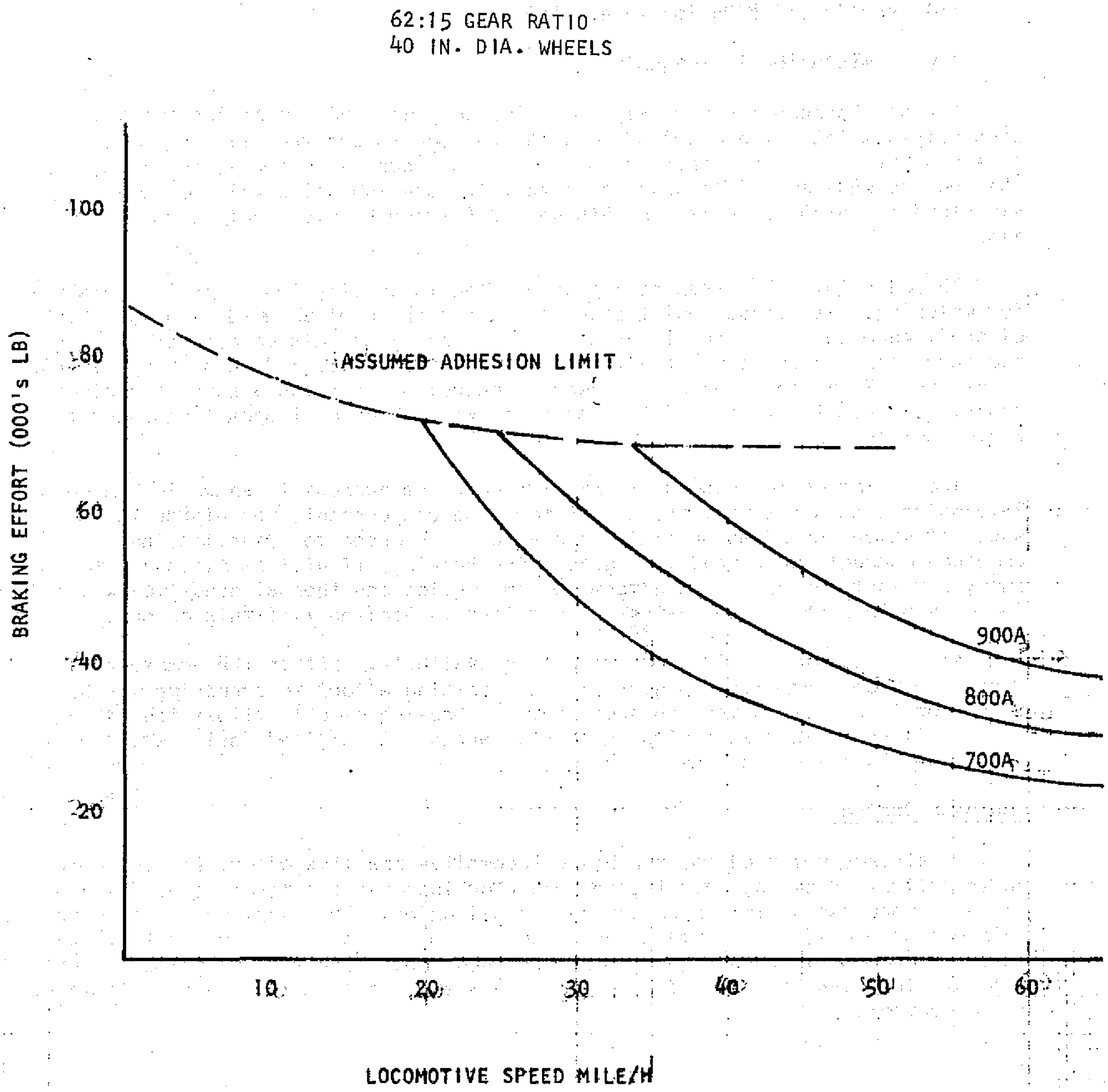


Figure 2-13. Variation of Brake Effort with Armature Current and Locomotive Speed

The advantages of individual control of each axle in the electric mode result from weight transfer compensation, locomotive weight reduction compensation as consumable supplies are used, and the ability to work at a higher assumed adhesion level with the same confidence level as all axle control since, in the case of individual axle control, if one axle slips only 1/6 of the total tractive effort is lost and this tractive effort can be quickly reapplied on re-establishing a stable condition. Figure 2-12 has already shown, however, that in motoring the DML, even the electric mode at the higher performance than the diesel mode is limited by the traction motor performance and not by adhesion considerations for the axle load assumed in this study. Separately excited motors, enabling higher adhesion levels to be assumed, will result in the same tractive effort being available on a lower axle load. Recommendations for the quantification of this are contained in Section 8. During regenerative brake, Figure 2-13 has shown that the performance is adhesion limited below approximately 25 mile/h (dependent on armature current) and therefore advantages would accrue from being able to assume a higher adhesion level. In regenerative braking these advantages are difficult to quantify since there are many external influences on the permitted braking level:

(a) The head end braking limit is recommended to not exceed 200,000 lb and should never exceed 240,000 lb (reference 4). This currently limits the number of locomotives employing dynamic brake at the head end to 4 SD40-2's. Figure 2-13 showed that by increasing and maintaining the armature current to the present adhesion limit the head end brake limitation would be encountered with 3 DML's, therefore, raising the adhesion limitation would only be of benefit in the few cases where small trains with only two DML's were used.

(b) The railroad is extremely sensitive to safety matters and therefore the institutional difficulties involved in raising the adhesion level during braking would be expected to exceed the technical difficulties in providing such a system.

(c) The WESS ROI is not particularly sensitive to the value of the energy saved, therefore, the improvement in energy recovery which would result from this improved capability would probably not enhance the savings sufficiently to justify the additional expenditure over and above the baseline case.

The additional hardware required for this modification compared to the baseline case (such as individual field controllers) has to be weighed against the advantages of weight reduction and/or tractive effort increase. In the interest of clarity this study is restricted to the proven technology of the series-field motor.

RECOMMENDATION

The AiResearch recommendation is that the baseline option should be adopted at this stage, until the benefits of other systems have been separately identified. Therefore, the remainder of the effort concentrates on the optimization of this concept.

Selected Circuit

The selected circuit is shown in Figure 2-14 with the associated sequence chart. Operation in the diesel mode is unaffected by the electric mode equipment and the only modification to the diesel mode is the provision of a continuous gating signal to the braking thyristors (BT1-3*) during resistive braking. It is possible that these thyristors may not be required and could be replaced by contactors. Their purpose is to provide an instantaneous alternate path for regenerated energy in the event of pantograph bounce. A more detailed study of this problem will determine whether there is a need for thyristors in this application.

MCOS is normally in the diesel mode position. Operation to the electric mode position requires the detection of voltage at the auxiliary winding of the transformer which operates relays to inhibit the diesel mode relay and operate the motorized switches MCOS. When voltage is lost at the auxiliary winding MCOS automatically reverts to the diesel position.

During electric mode dynamic brake BCOS operates from signals derived from the operator's brake handle which in conjunction with the operation of MB&B places all the motor fields in series with the auxiliary winding of the transformer, and the traction motor armatures in series parallel with the thyristor converter series bridges. Resistive or regenerative brake is then selected by gating BT1-3 (which prevents T1-8 from being gated) or not respectively.

MODIFICATIONS

For the selected circuit shown in Figure 2-14, the modification required to convert a standard SD40-2 into a DML can be described.

EQUIPMENT

The selected circuit identifies several items of new equipment which require installation into the locomotive:

Pantograph

Vacuum circuit breaker

Roof insulators

Roof busbars

Lightning arrestor

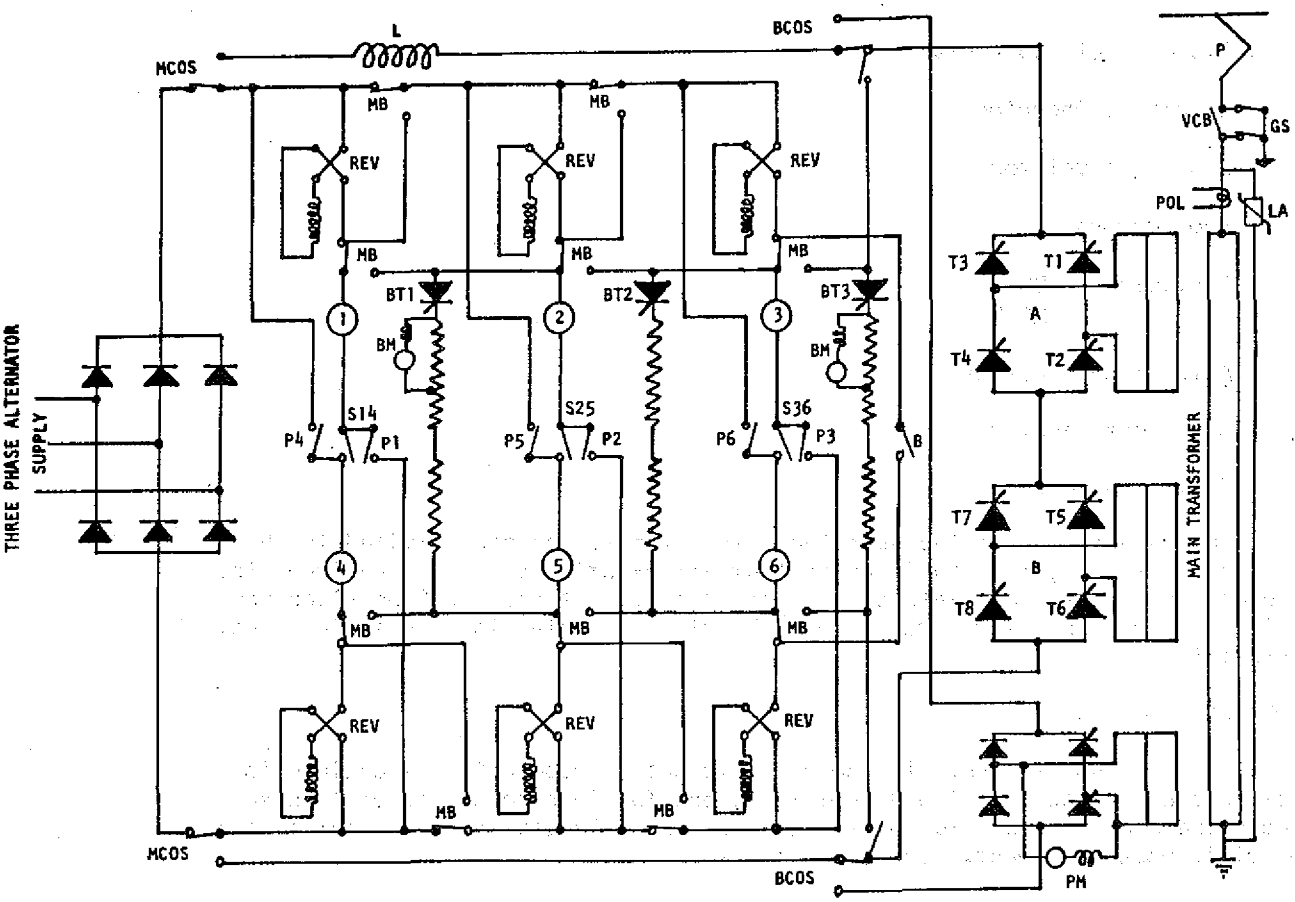
Ground switch

Primary overload current transformer

Main transformer

Thyristor converter

*The abbreviations that follow are defined in Figure 2-14



NOMENCLATURE

SYMBOL	EQUIPMENT
A & B	Series bridges of thyristor converter
B	Braking power contactor
BCOS	Brake changeover switch
BM	Blower motor
BT1-BT3	Braking thyristor
GS	Ground switch
L	Smoothing inductor
LA	Lightning arrestor
MB	Motor/brake transfer switch
MCOS	Mode changeover switch
P	Pantograph
PM	Pump motor
POL	Primary overload current transformer
P1-P6	Power contactors (parallel connection)
REV	Reverser
S14	Power contactor (series connection)
S25	Power contactor (series connection)
S36	Power contactor (series connection)
T1-T8	Thyristors
VCB	Vacuum circuit breaker
1 - 6	Traction motors

SEQUENCE CHART

	MCOS	BCOS	MB	S14	S25	S36	P1	P2	P3	P4	P5	P6	B	VCB	GS	BT1	BT2	BT3
DIESEL MODE																		
SERIES/PARALLEL				●	●	●												
PARALLEL							●	●	●	●	●	●						
RESISTIVE BRAKE			●	●	●	●							●			●	●	●
ELECTRIC MODE																		
SERIES/PARALLEL	●			●	●	●								●				
PARALLEL	●						●	●	●	●	●	●		●				
REGENERATIVE BRAKE	●	●	●	●	●	●							●	●				
RESISTIVE BRAKE	●	●	●	●	●	●							●	●		●	●	●

Figure 2-14. Selected Dual Mode Locomotive Power Schematic

Field supply converter

Smoothing inductor

Braking thyristor

Pump motors

Contactors - BCOS
- MCOS

Axle ground brushes

Stand-off insulators

Cable and conduit

The interface with the existing power circuit has been limited to the provision of MCOS, thereby insuring that all existing cabling downstream from the main rectifier terminals can be utilized without modification since the existing traction motor circuits will be utilized retaining the series/parallel transition.

CONTROL CIRCUITRY

Clearly the DML must, in the electric mode, respond to the engineer's commands as it would in the diesel mode, and for this reason several interfaces are required to take command and feedback signals and feed them to the electric mode equipment. These signals are:

Power/brake

Notch position

Wheel spin/slide*

Transition

In addition to the above, the converter control logic will have current and voltage feedback signals to enable closed loop control to be maintained in the electric mode. The only interface required between the electric and diesel mode control systems is the translation of the engineer's commands.

*In the electric mode wheel spin/slide protection may be independent of the existing SD40-2 system.

SECTION 3

CONTROL REQUIREMENTS

The control requirements for the DML can be considered in three parts- interface with existing control scheme, control requirements internal to the electric mode equipment, and modification to the existing diesel mode control system.

INTERFACE WITH EXISTING CONTROL SYSTEM

Throttle Position

The selected throttle position is translated to the existing throttle response circuit by using relays energized singly or in combination. These relays in turn produce an output from the throttle response circuit to which the main alternator field is directly proportional and also control the engine speed by actuating solenoids within the engine speed governor. During electric operation, it is necessary to run the engine at the speed equivalent to throttle position in order to provide cooling air to the traction motors. The feasibility and cost of installing an electric blower to cool the traction motors should be investigated before making a final decision on this aspect.

The relationship between the throttle position, throttle response relays, engine speed, and engine speed train lines energized is shown in Table 3-1. (references 6 and 9).

TABLE 3-1

ENGINE SPEED CONTROL TRAINLINES

Throttle Position	Throttle Relays Energized	Engine Speed	Train Lines Energized
Stop	D	-	3
1	None	315	None*
2	A	395	15
3	C	480	7
4	AC	560	15, 17
5	BCD	650	13, 7, 3
6	ABCD	735	15, 12, 7, 3
7	BC	815	12, 7
8	ABC	900	15, 12, 7

*None of the four "engine speed" trainlines

The electric mode equipment will take the input from the four engine speed trainlines (3, 7, 12 and 15) and convert this into discrete maximum voltage levels in a similar way to the existing TH module in the diesel mode.

This approach, taking the basic input signal, from train lines, will enable the electric mode equipment to be kept completely separate from the diesel mode equipment and therefore will minimize the impact on the reliability of the locomotive in the diesel mode.

Wheel Spin/Slide Protection

The existing spin/slide protection system compares traction motor currents on different trucks to detect differential wheel slip. To detect simultaneous wheel slip with motors in series/parallel a bridge circuit is used. Wheel overspeed protection appears to be the only method of controlling the unlikely event of simultaneous wheel slip at higher speeds. The electric mode equipment may make use of the output signals from the existing spin/slide protection system but corrective action by the reduction of power will be optimized within the normal characteristics of a thyristor controlled locomotive such that tractive effort is immediately reduced and quickly ramped back to approximately 90 percent of the original value, the final 10 percent being achieved relatively slowly. This operation can take place much faster on an electric locomotive since the time constant of the main alternator is not a limiting factor.

Transition

Transition from series/parallel to all parallel operation is initiated by the Forward Transition Auxiliary Relay. This relay will also be used to recalibrate the current/voltage characteristic of the converter to insure that the current output is the same before and after transition but the output voltage doubles.

ELECTRIC MODE CONTROL

The detail of the electric mode control can only be finalized in the detail design. However, fundamental parameters that can be identified are described below.

Throttle Position Response

The response to each throttle position will be such that a constant DC volt amp product is maintained above base speed. This product will be increased in steps of 12.5 percent for each throttle position to 100 percent (3216 kW) at notch 8. Below base speed constant traction motor current, proportional to the throttle notch selected to a maximum of 1050 amps in notch 8, will be maintained.

In order to provide for emergency conditions which may occur when a locomotive consist has traction motors isolated and is stopped on an adverse grade in the electric mode, an increased tractive effort switch will be available to the engineer (effective only in the electric mode) to allow operation into the short term rating of the traction motor.

Power/Brake

With the selection of power or brake BCOS will operate to connect the motor circuits in the desired configuration. Interlocks on BCOS will insure that correct operation has taken place. The control signal to effect this changeover will be derived from the appropriate trainline (17).

During power operation thyristors T3, T4, T7 and T8 will be continuously gated to provide a freewheeling path through the bridge circuit. Interlocks on BCOS can be used to determine the operation mode.

MODIFICATION TO DIESEL MODE OPERATION

The modification to the diesel mode operation has purposely been minimized in order to avoid jeopardizing that mode of operation. However, certain modifications described below are unavoidable.

Mode Selection

MCOS is normally in the diesel mode position and changeover only occurs on detection of voltage at the transformer auxiliary winding. At the end of an electrified section, an electrical feed must be applied to MCOS to revert the switch to the diesel mode. This can be accomplished by the use of a single relay. In a detailed design study the implications of eliminating MCOS and relying on the reverse biasing of the main rectifier to prevent transformer derived power circulating in the alternator circuits should be considered. A non load breaking isolating switch would still be required for fault conditions.

Diesel Mode Dynamic Brake

The use of braking thyristors BT 1-3 has already been discussed. If these components are required it will be necessary to provide a permanent gating signal during dynamic brake control and performance but would, if the railroad wished, provide a means of isolating faulty grids - a facility not currently available. Whether this is required, or indeed desirable, will be decided during detail design.

SECTION 4

EQUIPMENT INSTALLATION

The original DML concept (Volume 2) had the transformer installed in the short hood, and the converter and choke in the compressor compartment. This configuration did not take into account the AAR Phase II Clean Cab, in which the following modifications impacting the original DML concept have been made:

- o Short hood lengthened 7 in.
- o Separate toilet compartment in nose with access door, floor drain and outside air ventilator.
- o Alcove in short hood for refrigerator/water cooler
- o Recessed stairs into short hood

Clearly to compromise the clean cab concept would not be acceptable and it was necessary therefore, to reconfigure the locomotive so that the clean cab layout shown in Figure 4-1 was not affected. The revised general arrangement of the DML is shown in Figure 4-2.

A visual inspection of the locomotive underframe has confirmed that the secondary mode equipment may be installed without extensive modifications being required. The transformer and choke designs will be such that they are able to withstand the longitudinal/lateral/vertical accelerations imposed in traction duty, using only a bottom foot mounting which will locate on the main longitudinals of the underframe.

Compressor Compartment Installations

The transformer and converter installation requires that the compressor compartment be extended by approximately 3 ft. This can be accomplished without restricting the walkway around the rear of the locomotive or between locomotives in a multiple consist. A minimum walkway width of 2 ft is maintained at all times.

Access to existing equipment (compressor, radiator group etc.) for normal maintenance purposes is not affected by the new equipment. Compressor removal is achieved in the usual way although access to the front end of the compressor is now more restricted and all work would have to be accomplished from either side of the compressor. Removal of the radiator group may necessitate the removal of the 50 kv roof bus in the area over the radiator group, a task which should take no more than 10 minutes.

The removal of the sandbox to the guard rail will make the task of filling the sandbox easier due to the filling cap being at a lower height.

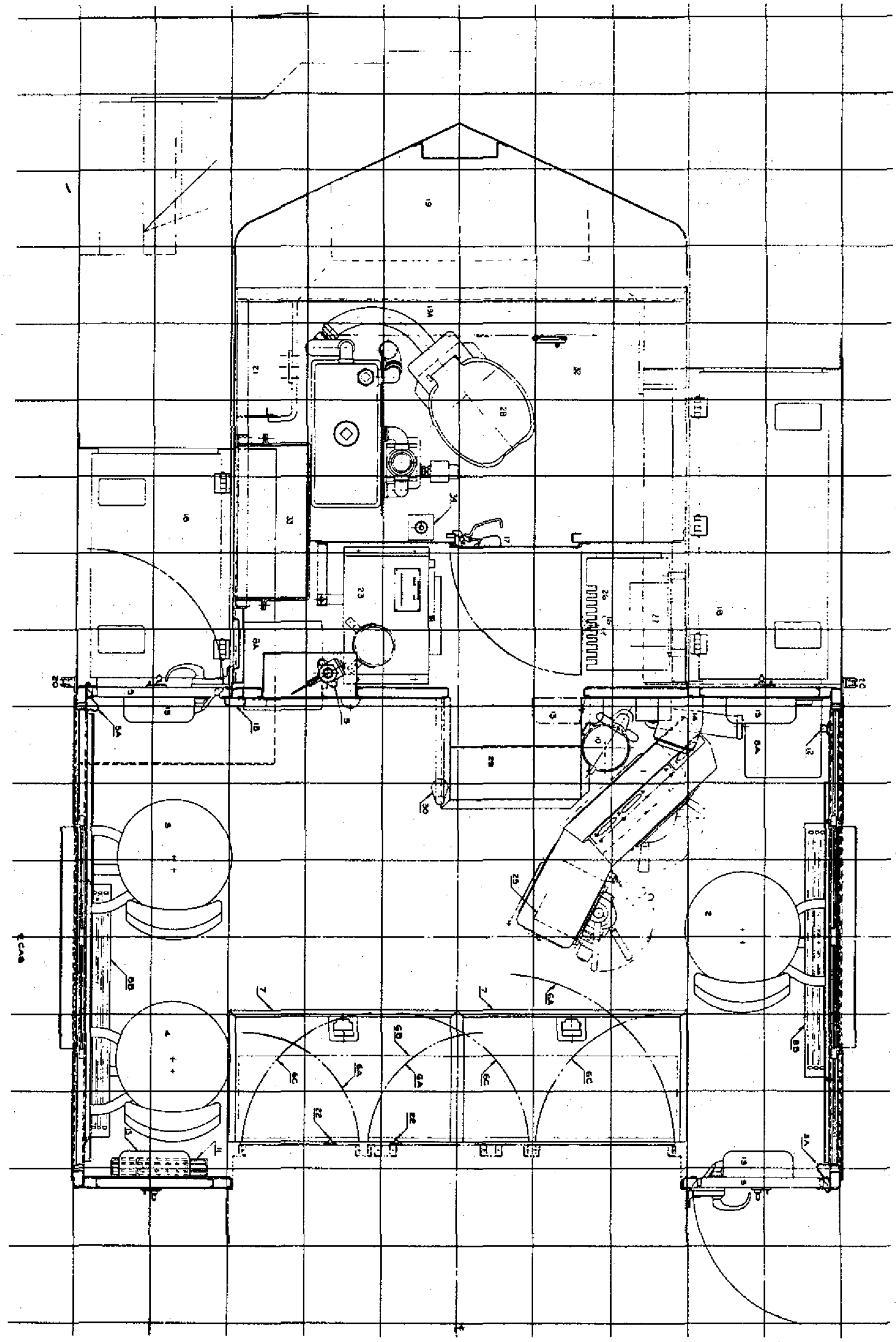


Figure 4-1. AAR Clean Cab (SD40-2)

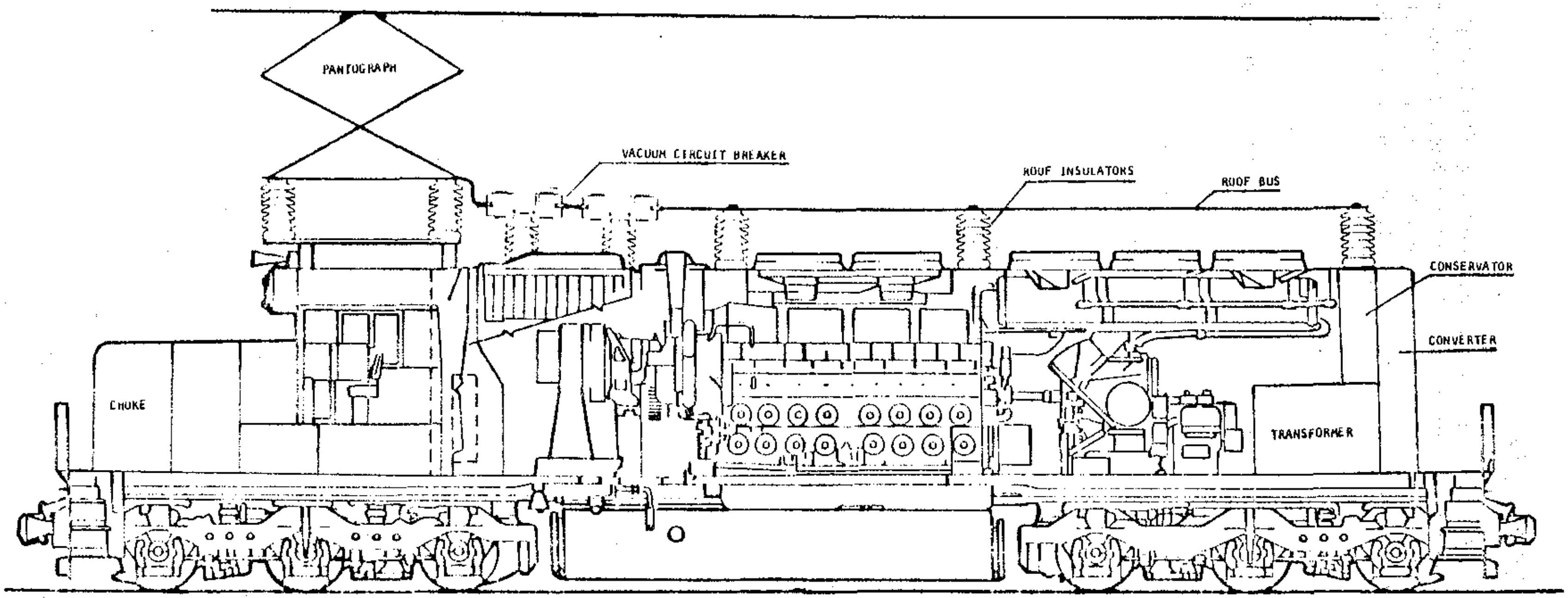


Figure 4-2. General Arrangement of Dual-Mode Locomotive

Short Hood Compartment Installation

The removal of the sandbox from the short hood and its installation on the guardrail, coupled with an extension of the short hood allows room for the installation of a choke up to 3.5 ft diameter and 5 ft high while still maintaining an adequate walkway. No maintenance functions are affected by this modification.

Roof Installations

The roof equipment installation will have little impact on the existing locomotive or its maintenance.

SECTION 5

PRELIMINARY SPECIFICATIONS

Having identified the circuit to be used and the space available within the existing SD40-2 locomotive, it is now possible to produce specifications for the performance, volume, and weight of the new equipment.

PANTOGRAPH

The only roof area available to take the pantograph is located over the cab. It has already been established in Figure 4-1 that the height of the reinforced platform for mounting the pantograph will be 16'. In order to meet a static clearance of 21" (Reference 9) and a creepage path of 60", insulators described later in this section are required. The same insulators will be used to support the copper bus bar between roof equipment in order to minimize spares holdings at maintenance facilities.

The Pantograph Performance Specification is included as Table 5-1.

If it is found to be impossible to obtain a pantograph to fit the required space envelope and working height criteria, it will be possible to increase the height of the reinforced platform, thus reducing the working height. This will be subject to review as the design progresses. At this stage every effort is being made to keep the overall height of the locomotive as low as possible in the diesel mode (with pantograph down), thereby reducing the probability of a DML being restricted to operate only over routes with high vertical clearances.

Roof Bus

A roof bus is required to take the current from the base of the pantograph to the vacuum circuit breaker, and from the breaker to the roof through bushing leading to the transformer. The bus may be either rectangular copper bar or copper tube. The size is dictated by mechanical strength rather than current carrying capacity.

To avoid degradation of the bus material it must be either painted or cadmium plated, with bare joints covered with protective grease.

Roof Insulators

The insulators required to mount the roof equipment are determined from the electrical clearances required, as described in this section previously. The insulators used to support the roof equipment will be identical, and therefore the mechanical loading of the pantograph mounting insulators determined the mechanical strength required. Table 5-2 shows the parameters to be met in the roof insulators used on the DML.

TABLE 5-1

DUAL-MODE LOCOMOTIVE
PANTOGRAPH PERFORMANCE SPECIFICATION
(PRELIMINARY)

DIMENSIONS	
Maximum distance between mounting center (lateral)	5'0"
(longitudinal)	6'0"
Maximum height of assembly in housed position	6'0"
Maximum overall width of assembly	2'0"
Maximum overall length of assembly inhoused position	6'0"
Nominal working height (measured from the top of the mounting insulators)	7'3"
Working height variation from nominal	±6"
WEIGHT	
Target weight for complete pantograph assembly	500 lb
OPERATION	
Maximum operating speed	70 mile/h
Catenary type	simple
Number of pantographs in operation at one time	5
Upward force (over working height)	18 - 20 lb
Number of collector strips	2 minimum
Maximum current at 50kV	100 amps

The pantograph shall be dropped automatically in the event of the collector strips becoming displaced. The pantograph shall be raised by air pressure against spring force.

TABLE 5-2

ROOF INSULATOR SPECIFICATION

<u>Electrical</u>	
Static clearance (minimum)	21 in.
Dry creepage path (minimum)	60 in.
Basic impulse level	250 kV
<u>Mechanical</u>	
Compression load	750 lb
Tension load	100 lb
Cantilever load	750 lb
Fixing hole pattern top	4
bottom	4

Lightning Arrestor

There are two major types of lightning arrestor available, the expulsion and the valve types. Both the expulsion and the valve types perform the function expected of lightning arrestors. They are normally insulators, but they become conductors of relatively low impedance during lightning current surges. They re-establish themselves as insulators after the lightning current has disappeared, and they will operate repeatedly. Thus, they do not interfere with the flow of power in the system. The principal difference in the operation of the valve and the expulsion types of arrestors is the way in which they dispose of the system power-follow current. In the valve arrestor, the follow current is limited by the device itself regardless of the system capacity. In the expulsion arrestor, with its low arc voltage, the power-follow current is determined principally by the system impedances.

In order to avoid excessive currents which could cause damage the pantograph, the valve type arrestor is recommended for use on the DML.

Ground Switch

The purpose of the ground switch is to insure that the roof equipment and main transformer primary are at ground potential, thereby making the equipment safe for maintenance inspections and the like. Since inspections of below roof equipment can be carried out with the catenary alive it is essential that the ground switch and pantograph isolating cock are interlocked such that:

(a) With the isolating cock in the 'open' position the ground switch is locked in the 'open' position.

(b) When the ground switch is in the 'ground' position the isolating cock is locked in the 'isolated' position. Also, it should not be possible to move the ground switch from the 'open' to the 'ground' position until the air pressure in the pantograph air motor has been reduced to a value well below that at which the pantograph leaves the contact wire.

Provision shall be made for locking the isolating cock in the 'open' position by padlocks and for locking the ground switch in the 'ground' position by padlocks.

Primary Overload Current Transformer

The primary overload current transformer (POL) is required to monitor primary current so that a protective circuit can open the VCB in the event of an overload and to signal pantograph bounce, particularly during regeneration. so that BT 1-3 can be gated to provide an alternate path for the regenerated energy.

POL can be incorporated into the roof through brushing, thus minimizing the difficulties associated with mounting a current transformer around a 50 kV supply.

Main Transformer

The main transformer is the most difficult of new items to fit into the existing locomotive and therefore a major portion of the desing effort of the dual mode locomotive will be centered around the design of the transformer.

The transformer has a continuous rating of 4200 kVA which is matched to the continuous rating of the six D77 traction motors and auxiliary circuits which it supplies. It is cooled using silicone fluid, force circulated by a fully submerged pump, a technique which is novel by U.S. standards.

Inquiries have been made of the leading manufacturers of traction transformers. Both EMD and GE have indicated that they are unable to supply a transformer to meet the stringent volume and weight requirements. The transformer outline shown in Figure 4-2 is based on a transformer design proposed by a leading overseas traction company which has many years of experience providing traction transformers at low weight and volume and is the world's largest supplier of 50 kV traction transformers.

Thyristor Converter

The thyristor converter consists of two series bridges, each one being fully controlled. Each arm of the bridge contains four thyristors in parallel giving a total of 32 thyristors which will be oil cooled using the transformer cooling oil.

Field Supply Converter

The field supply converter is a half controlled thyristor bridge and is used to supply field power to the traction motors during dynamic brake in the electric mode. The converter is required to output up to 1000 amps at approximately 100 volts DC. Only one device per arm is required and the two thyristors will, if possible, be the same as those used in the main converter. An investigation will be carried out to ascertain whether the diodes used in the locomotive's existing main rectifier would be suitable for this application, again minimizing the necessary spares holding.

Smoothing Inductor

The smoothing inductor is required to ensure satisfactory commutation of the traction motor over the complete range of traction motor current. The ripple content at which the traction motor can operate will need to be determined by testing, and from this the inductance value can be determined.

However, a survey of smoothing inductors used in similar applications has revealed the data shown in Table 5-3.

TABLE 5-3

SMOOTHING INDUCTOR SIZES

Locomotive	Frequency Hz	Smoothing Inductor Volume per motor ft^3	Smoothing Inductor Specific Volume kw/ft^3
GEC Class 87/0	50	6	625
GE E42C	60	10	298
DML	60	9.33	319

It will be seen that the volume allowed for the smoothing inductor in Figure 4- is compatible with existing equipment. Final characteristics of inductance and dimensions must await the results of traction motor tests.

Braking Thyristors

The braking thyristors (BT 1-3) are required to handle up to 1000 amps at 1400 V. This duty can be met by a single device and, in order to minimize the spares holdings BT1-3 will, if possible, be the same device as main thyristors T1 - T8.

Pump Motor

The oil pump is required to circulate oil around the transformer and converters and should be fully submerged and cooled by the transformer oil. The motor will be a single phase capacitor start and run type, protected by a circuit breaker probably mounted on the transformer.

SECTION 6

COST VERIFICATION

STATEMENT OF WORK

Based on the design study reported in this document certain modifications to the previously published Statement of Work (Volume 2, Appendix A) are necessary and are described below.

PREPARATORY WORK

The following preparatory work is required before the installation of new equipment:

Ballast

Where possible, the locomotives selected for this modification will comprise the light underframe model with little or no ballast to be removed. However, as necessary, for heavy frame locomotives, ballast may need to be removed in order to meet axle load limitations. The weight of the transformer is estimated at six tons and the converter and choke at one ton each.

Sandboxes

The sandboxes at each end of the locomotive are to be repositioned on the guard rail (similar to the DD-40-X locomotive). The associated sand delivery pipes to each truck and pneumatic connections are to be rerouted and extended as necessary to be compatible with the repositioned sandboxes.

Short Hood

The short hood is to be cut off at the minimum length to facilitate the mounting of the smoothing choke. A protective grill is required around the choke.

Cab Roof

The cab roof requires strengthening to provide adequate support for the roof equipment (pantograph, circuit breaker, etc.) and to afford protection for the crew in the event of a mishap involving damage to the pantograph.

MAJOR ELECTRICAL EQUIPMENT

The following equipment will be supplied to the railroad for installation on the locomotive:

a. Roof equipment

b. HT cable

c. Transformer

d. Converter

e. Smoothing choke

f. Mode changeover switches

g. Brake changeover switches

h. Oil/air heat exchanger

i. Automatic power control equipment

ROOF EQUIPMENT

Install pantograph mounting feet insulators, roof bus and insulators, and lightning arrester(s). Install pantograph and pneumatic air pipe to pantograph air system. Install vacuum circuit breaker.

MAIN TRANSFORMER

Install transformer mounting feet and mount transformer. Make HT connection.

COMPRESSOR COMPARTMENT

Install mountings for transformer and thyristor converter and mount the equipment.

CABLES

Provide cable connection between converter output and smoothing choke, rated at 6000 amp continuous.

Run cables from choke and output of converter to supply changeover switch located in electrical cabinet.

Run cables to dynamic brake grid compartment from stabilizing resistor thyristors and smoothing choke.

DYNAMIC BRAKE GRID COMPARTMENT

Connect stabilizing resistor cables to existing dynamic brake grids and install braking thyristors.

TRUCKS

Weld automatic power control (APC) receiver mounting bracket to truck frame and mount APC receiver. Provide interface control wiring between APC receiver and pantograph control circuit.

CONTROL FUNCTIONS

Install mode changeover and brake changeover switches in electrical cabinet.

Install pantograph control equipment.

Miscellaneous control system modifications are required to ensure an engine speed of 900 rpm under electric power demand and to inhibit resistive brake when the pantograph is raised thereby biassing the electric brake system to the regenerative mode.

COMPLETED LOCOMOTIVE

Weigh locomotive to establish each wheel load and ballast as necessary.

COST ESTIMATE

Labor

A leading remanufacturer of locomotives assisted in this study by estimating that the labor content for this modification would be 5000 hours per locomotive. A railroad cooperating in the study indicated that at April 1978 price levels the labor rate (including fringe benefits) to be used in this type of project is $10.48, which, at May 1977 price levels becomes $9.70 using previously agreed inflation index for labor of 8 percent per annum. Therefore, the cost to the railroad of converting an SD40-2 locomotive to the DML configuration, at the same time as they overhaul the locomotive would be $48,500 plus major electrical items.

Transformer

As previously indicated the leading U.S. locomotive manufacturers have stated that they are unable to design and build a traction transformer of the required rating to meet the volume and weight restrictions imposed by the DML design. Overseas manufacturers were approached to establish the state of the art overseas, particularly those suppliers with a proven record in traction transformer design at 25 kV and 50 kV, designed to be accomodated in lightweight locomotives generally having a smaller loading gauge than that of the U.S. Formal quotations in response to the AiResearch transformer specification confirmed a transformer price of $50,000 (1977) although this price is subject to the fluctuating value of the dollar.

Roof Equipment

The pantograph needed for this application must occupy the minimum length of roof because of the limited space available. To meet the requirement a cross arm pantograph is proposed at $9,660 each.

The high voltage circuit breaker will be of the vacuum type in the interest of space minimization and, will include the grounding switch, at $17,304.

The above prices have been confirmed by formal quotation from a leading supplier of such equipment.

Total Cost

The total cost of the modification is shown in Table 6-1 to be $217,500 from which it can be determined that $128,500 (59%) of the total cost estimate has been independently verified by experts in that particular field. The major remaining item, the converter, is a component similar to one which AiResearch has previously supplied at a similar cost per kW. It appears therefore that only $29,000 (13%) of the cost (of which $24,000 is miscellaneous) remains unconfirmed.

It is concluded therefore that the DML cost of $217,500 is realistic.

TABLE 6-1

DUAL-MODE LOCOMOTIVE COST

Element	Cost (1977 $)
Roof Equipment	$30,000*
Transformer	50,000*
Converter	60,000
Smoothing Choke	5,000
Miscellaneous	24,000
Labor	48,500*
TOTAL	$217,500

*Confirmed by formal quotation.

SECTION 7

COMPONENT TESTING

During this preliminary design study, certain areas have been identified where it is considered that testing is either necessary or desirable in order for the design to proceed with confidence.

TRACTION MOTORS

The following aspects of the traction motor require an investigation which can best be carried out by testing:

(a) Operation at 1050 amps continuous

(b) Operation at 536 kW continuous over a wide speed range.

(c) Performance on an ac rectified supply

- heating
- commutation
- smoothing

(d) Smoothing inductance required for satisfactory operation.

The above may be investigated at the same time by one set of tests. The common method of load testing motors by the electrical supply of losses (Hopkinson method) would not be suitable for these tests since the dc supply from the generating motor would overwhelm the rectified ac supply.

The test would involve one machine (although results could be corroborated on other machines) and consists of a transformer and phase delay rectifier (PDR) feeding up to 1300 vdc to the traction motor. The complexity of the PDR will be minimized by controlling voltage from 0 through 1300 vdc in one bridge. Traction motor loading would be accomplished by using a brake wheel to accurately measure the output of the traction motor under specific input conditions.

The baseline reference point for these tests will be the performance of the motor when supplied by a dc supply (that is a multiphase rectified ac supply) operating at 356 kW (the power level used in the SD40-2 now).

EXISTING LOCOMOTIVE DYNAMIC BRAKE GRIDS

It may be necessary to direct full regenerative braking current into the dynamic brake grids as already described. The grids are continuously rated for 700 amps, but may be necessary to pass higher current through the grids (up to 900 amps dependent on the braking rate chosen). Therefore it is necessary to determine that the grids can pass this current for short periods (1 - 5 secs) repeatedly without breakdown or overheating.

It is recommended that a set of grids from a locomotive be tested using equipment from the traction motor test referred to above. The use of braking thyristors will not be necessary since for the purpose of this test a contactor can be used.

TRACTION MOTOR REGENERATIVE BRAKING CURRENT LIMIT

The traction motor current limit during regenerative brake will need to be established if a braking level in excess of that now used is to be obtained.

With the completion of the above tests all technical information will be available to make a final decision regarding the performance of the DML.

CHANGEOVER SWITCHES

The current carrying/breaking capacity of the existing motorized switches used in the EMD locomotives should be examined to determine whether these switches can be used for MCOS and BCOS without modification.

TRANSFORMER

Since the use of silicone fluid is largely unproven in U.S. railroad applications, an evaluation program should be initiated to determine the coolant/electrical characteristics of the fluid. Prior to installation of the transformer a full load test should be undertaken to confirm design data.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

The completion of the dual-mode locomotive design study has resulted in a more precise quantification of modification costs and a verification of operational advantages. On this basis, since the dual-mode locomotive is a key element of the WESS concept, the deployment of WESS on actual routes of U.S. railroads continues to appear economically attractive. In addition, by virtue of the higher power available to the rail from the dual-mode locomotive in the electric mode, the DML has been shown to provide cost advantages to railroads by the use of dual-mode locomotives with electrification of ruling grades to minimize locomotive consists. The specific conclusions and recommendations of the three month dual-mode locomotive design study are given below.

CONCLUSIONS

1. The DML is technically feasible and has a significantly enhanced performance in the electric mode.

2. The modification of the SD40-2 can be accomplished without degrading the reliability of the locomotive in the diesel mode.

3. Secondary mode equipment is readily available within the state of the art for high voltage ac electric traction.

4. The main transformer was shown to be the most critical component of the DML. It has been established that this tranformer is within the state of the art for overseas manufacturers even though U.S. suppliers are unable to meet the unusually stringent requirements of the DML.

5. The DML is economically attractive at $217,500, this being less than the cost of an electric locomotive.

6. All major cost elements have been confirmed by quotation from experienced manufacturers and therefore the WESS concept remains economically attractive.

7. The DML can be used as a means of progressively electrifying a railroad route and therefore can avoid the need for a large initial capital outlay.

RECOMMENDATIONS

1. A detail design study of the DML concept should be promptly initiated to enable a hardware procurement package to be assembled as recommended in Section 6, Volume 2 of this report.

2. The component testing described in Section 7 should be promptly initiated and used as an input to the detail design study.

3. The application of separately excited motors to the DML should be analyzed to determine whether a significant benefit could be realized.

SECTION 9

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