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RAILROADS AND THE ENVIRONMENT: ESTIMATION OF FUEL CONSUMPTION IN RAIL TRANSPORTATION

Volume III - Comparison of Computer Simulations with Field Measurements

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16. Abstract

This report documents comparisons between extensive rail freight service measurements (previously presented in Volume II) and simulations of the same operations using a sophisticated train performance calculator computer program. The comparisons cover a variety of lengthy freight movements over a differing terrain, for TOFC, boxcar, and branchline operations. The simulation shows excellent agreement (within 2%) for aggregated data, although some specific runs or run segments show substantial diviations. Uncertainty is typically plus or minus 10% to 15%, a range equivalent to the scatter generally found within sets of measured data. The report also includes a full description of the simulation program and a general analysis of the major factors which bear upon the validity and accuracy of train performance calculations. Proposed modifications to conventional train resistance equations are suggested.

Volume I, Analytical Model, has 90 pp. Volume II, Freight ~~Surface~~ Service Measurements, has 46 pp.

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PREFACE

The research described in this report was carried out in the context of an overall project at the Federal Railroad Administration to provide a technical basis for the improvement of rail transportation service, efficiency, and productivity. The project was sponsored by the Office of Research and Development, Office of Freight Systems.

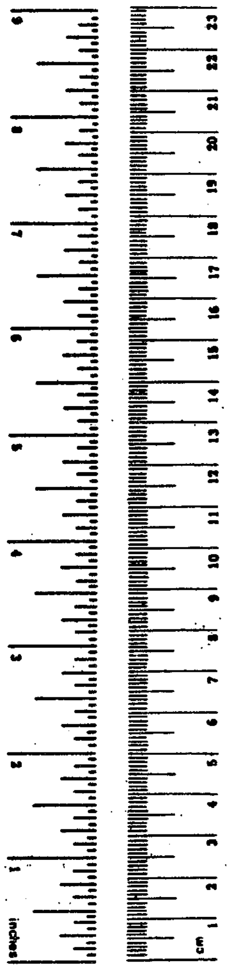
This report is the third and final volume documenting studies relating to fuel consumption in rail freight service. Volume I (Report No. FRA-OR&D-75-74.I) applied a simplfied physical model to a variety of rail transportation services, with the primary objectives of estimating sensitivity of fuel consumption to operating and equipment parameters. Volume II (Report No. FRA-OR&D-75-74.II), presented measured fuel consumption data for a wide range of freight trains operating under a variety of circumstances. This document, Volume III, presents a comparison of these experimental measurements to computer simulations using a relatively sophisticated train performance calculator originally developed by the Missouri Pacific Railroad and extensively modified by TSC.

The overall analysis and comparison has been the responsibility of J. Hopkins. M. Hazel has directed development of the computer simulation and its use. A major portion of the actual simulations have been run by T. McGrath. The authors wish to express their great appreciation to Ms. K. Keefe, who had responsibility for much of the early data reduction and analysis. It is appropriate to indicate again our gratitude to A. T. Newfell of TSC, and to the numerous individuals within the railroad industry, listed in the preface to Volume II, who contributed so greatly to the measurement effort which made the comparisons possible.

METRIC CONVERSION FACTORS

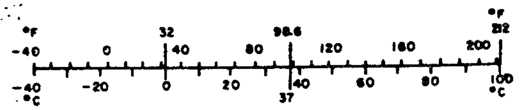
Approximate Conversions to Metric Measures

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



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1. INTRODUCTION

1.1 Background

Railroads long ago recognized the need to be able to estimate the freight service operating schedules which would result from alternative power (locomotive) assignment policies, train sizes, speed limits, etc, on specific routes. Physically, the problem is well defined and amenable to relatively simple analysis: calculation of the movement of a mass (the train) moving under the influence of a small number of forces (tractive effort, gravity, rolling resistance, aerodynamic drag, etc). This computation can be made within a wide range of levels of sophistication. In recent years the widespread availability of high-speed digital computers has encouraged many in the railroad industry to develop detailed computer programs to carry out the necessary calculations. In general, the input data includes (as a minimum) specification of train weight and motive power, track grade, speed limits, and stops. An equation is formulated which expresses the total resistance force acting on the train, several elements of which are functions of train speed. Tractive effort (also dependent on speed) is assumed to be applied to the maximum amount available at any time the train is moving below the speed limit, unless a speed reduction is imminent. Braking is accommodated by an assumed available braking effort, a specified maximum deceleration rate, or a more complicated simulation of a real braking system. The program must in some fashion look ahead to determine when deceleration must begin in order to avoid exceeding any speed limit; this is a fundamental requirement. Adhesion limits should also be incorporated. In operation, one applies Newton's first law (net force equals mass times acceleration) to determine the change in the train's position and velocity for a small increment of time or distance. Resulting new values of all variables are calculated, and this process is continued until the destination is reached.

The customary functions of such Train Performance Calculator (TPC) computer programs have been related to running time and the ability of trains of specified power and weight to ascend the ruling grade of a route. More recently, fuel consumption has taken on increased importance, so that it has become desirable that the model include a good representation of locomotive fuel rate and efficiency. The high degree of random variability in normal freight operations often renders high precision in a simulation unnecessary. Moreover, the input data necessary for high accuracy (such as wind direction and velocity for the entire route) rarely exists. Commonly, TPC's have been used as estimation tools, and for evaluation of the sensitivity of schedules to variations of particular parameters. One finds virtually no published documentation concerning the absolute accuracy of these models, although their widespread usage suggests an adequate performance level.

Recent interest in high-speed passenger trains (velocities well above 100 MPH) has also spawned a number of TPC's constructed around this application. These have usually emphasized calculation of running time and/or energy consumption, and generally treat the train as an entity defined by a single resistance equation, with a fixed deceleration rate for braking. Here, too, there has been little attempt at rigorous validation of the simulations.

Virtually all such simulations, for both freight and passenger service applications, are proprietary and relatively undocumented, in terms of structure and algorithms as well as procedures for use. Typically, each has been developed to meet particular situations and needs, so that flexibility, detail, and form of output may not be suitable to other applications. The type of input data and format required generally differs widely among TPC's, so that track data, for example, is seldom readily transferable. Thus, when in 1974 the Office of Research and Development of the Federal Railroad Administration (FRA) commissioned the Transportation Systems Center (TSC) to explore a variety of rail fuel consumption questions, the initial studies were based on simple and very general analytical models. These assumed steady-state operation only, and did not include a capability for route-specific simulation. Results of this phase of the research have previously been documented in Volume I of this report(1). However, these initial findings made clear the desirability of having available a general-purpose simulation which could be used for a variety of applications. A highly sophisticated TPC was purchased from the Missouri Pacific Railroad and later modified substantially at TSC to provide for the wider range of Departmental needs, to increase the flexibility of its use, and to provide alternative forms of output. The resulting computer program will here be referred to as the TSC Train Performance Simulator, or TPS.

1.2 Objective

In order to increase the value and utility of the TPS, and to assess the confidence with which this tool could be applied to various subjects, it was judged appropriate to carry out specific comparison of computer results with actual operational data. The basic objective of the research reported here has been to determine the basic validity of the TPS and the degree of accuracy it can provide, particularly with respect to fuel consumption. Given the great similarity at the heart of almost all TPC's, and the relatively sophisticated nature of the TPS, such results also provide a good measure of the basic limitations on the accuracy of any TPC.

As a second major objective, this research is intended to make possible a calibration or "fine tuning" of the TPS, particularly with respect to resistance equations. The basic goal is to make a judgement as to which of the common forms of train resistance equation are preferable for performance simulation, and, within the limitations of available information, to develop appropriate modifications.

1.3 Approach

Concurrently with the refinement and elaboration of the TPS, TSC made arrangements with several railroads to obtain fuel consumption data for normal freight operations in a variety of categories. In each case this was a cooperative endeavor, usually involving installation of fuel meters on locomotives, and in some cases, use of a test car. The measurements are described in detail in Volume II of this report(2). Results of these projects were then compared to simulations of the same runs.

There are two basic types of information one generally seeks with a TPC: running times and fuel usage. If one knows the intended speed profile -- speed limits, stops, etc. -- and the train is not subjected to unexpected delays or slowdowns, or strong and ill-defined winds, running times can normally be calculated relatively easily, and with considerable accuracy. Except for trains operating at low power-to-weight ratios, the results will even be relatively independent of the particular form of train resistance equations used. However, the situation is somewhat more complex with respect to energy usage. If a locomotive is at full throttle rather than 3/4-throttle when travelling at the specified speed limit, this will make a substantial difference in fuel consumed. Further, in normal freight operations -- either prospective or in the past -- one seldom has a precise representation of the actual speed profile. (Correlation of locomotive speed recorder tapes, when available, with track charts is a highly labor-intensive undertaking.) Thus, it is of interest to determine to what degree variations of speed (as well as locomotive engineer, weather, malfunctions, etc.) will effect computer estimation of fuel usage under realistic operating conditions.

2. THE TSC TRAIN PERFORMANCE SIMULATOR

The purpose of a Train Performance Calculator is to predict or replicate the movement of a train along a given track. The results of such a program are contained in tables or graphs that show the speed, time, distance, energy or fuel consumption, and throttle positions as the train moves along the route. Additional information about the route, such as grades, curves, mileposts, and speed limits may also be shown. Typical uses of a TPC in scheduling include determining the operating time over a stated route for a train, the motive power necessary to make a run in a given amount of time, the effect of changing the number of locomotive units, and the effect of varying the tonnage of the train. Additional uses can be to show the effect of a track relocation or reconstruction (which eliminates or reduces grades or curves) upon the operating speeds, motive power requirements, and energy consumption; to compare the operational problems presented by various proposals for a new line; and to determine the effect of eliminating or introducing a speed restriction or station stop. Other railroad applications may be to determine tonnage ratings for a route, based on a train operating over the ruling grade at a specified minimum speed, and to compare runs over different routes. This subject is discussed briefly in this section. A more lengthy treatment will be found in Reference (3).

2.1 General Characteristics of a TPC

2.1.1 Input Requirements

In order to simulate the running of a train the TPC needs information about the route and about the train. Route data will be discussed first.

The TPC must have a description of the track over which to run the train. A set of values describing the characteristics of a point on the track constitutes one record of track data. A group of records, usually beginning at one station and ending at another (not necessarily the next), constitutes a route segment. The TPC will link together a number of such segments and run a train with or without stops from one end to the other. Typically, a record is required where speed limits change, at every significant change in gradient, and (to the degree practical) at the beginning and end of every curve. A record is also needed for each significant station, junction, or inspection stop.

When the route has been described, information about the train is needed in order to run it over the route. The car weight and number of axles determine the resistance from friction in the bearings and flanges and from rolling contact. Car length is needed to determine where each part of the train is at any point in time. The locomotive characteristics required include weight, length, number of axles, tractive effort capabilities, transmission efficiency, and the fuel or energy rates both idling (e. g. gallons per minute) and running (e. g. gallons per horsepower-hour). The number of locomotives being used must also be stated. Given the above information, the TPC can run the train over the route. However, one may wish to provide for variations from the normal operating conditions (those inherent in the track/route data), such as starting time, alterations to the route (grades, curves, etc.), more or fewer stops and different stop times, temporary changes in speed limits, changes in consist (locomotives and/or cars) at stops enroute, and variation in adhesion ratio. Modification of resistance characteristics to account for unusual cars or locomotives is also possible.

2.1.2 Basic Model (Algorithms)

The basic mathematical model for operation of the train is based on simple Newtonian laws of motion. The forces involved are those due to train resistance, locomotive tractive effort, and braking.

Train resistance is made up of a number of components. When viewed in terms of the underlying physical causes, each is complex to describe, and is generally dependendent upon a number of parameters, including velocity. For purposes of analysis and simulation, four terms can be identified -- rolling, bearing, and flange friction, and aerodynamic drag -- and the following simplifying assumptions are generally made:

1. Rolling friction resistance is proportional to the weight and independent of velocity.
2. Bearing friction resistance is proportional to the number of axles but independent of weight and velocity.
3. Flange friction resistance is proportional to weight and velocity.
4. Aerodynamic resistance is a function of size and shape and is proportional to the square of the velocity but independent of the weight.

The train resistance due to gradients and curvature can be added conveniently to the resistances listed above. Both are independent of velocity but proportional to weight and to the gradient or degree of curvature. The basic equation used for train resistance was formulated in the 1920's by W. J. Davis(4). Expressed in pounds of force, the resistance of a single rail car is

$$R = F*W + 20*q*W + .8*c*W + b*n + f*W*V + K*(V**2)$$

where

b is the bearing friction coefficient
c is the curvature in degrees
f is the flange friction coefficient
F is the rolling friction coefficient
q is the gradient in percent
K is the air resistance coefficient
n is the number of axles
V is the velocity in miles per hour
W is the car weight in tons

* indicates multiplication
** indicates exponentiation

The power required to overcome this force will be proportional to the product of the force and the velocity. Therefore, the locomotive horsepower required at high speed will be approximately proportional to the cube of the velocity.

Davis determined coefficient values which were considered accurate for the rolling stock of his day. More recent tests have supported the use of alternative coefficients which are often used (5); these are presented later in this report. An extensive examination of this subject has recently been carried out for FRA by MITRE Corp. (6)

Tractive effort is the force which a locomotive exerts at the driving wheels to move itself and its trailing consist. It is limited by the power available from the traction motors, by the velocity, and by the adhesion characteristics of the wheel-rail interface. For a given locomotive horsepower, a typical tractive effort curve is a hyperbola of the general form

$$TE = 375*E*HP/V$$

where

E is an efficiency factor
HP is the locomotive horsepower
V is the velocity in miles per hour
TE is the tractive effort in pounds

When the train needs to be slowed because of a speed restriction or station stop, brakes are applied. This results in a retarding force at the wheel-rail interface (for all locomotives and cars in the train) which is adhesion limited but which acts as an additional resisting force. The force applied is a function of brake system parameters, time, velocity, and weight of lading.

If the forces due to train resistance, tractive effort, and braking are in balance, the velocity will remain constant; otherwise there will be an acceleration (or deceleration) resulting from the familiar F=m*a of Newton. The acceleration will thus be equal to the algebraic sum of the forces divided by the mass of the train.

2.1.3 Output

Since a TPC may be used for different purposes, the output content and format should flexible. Some users might need only a timetable listing, others may want merely the total running time. Other possibilities are instantaneous speed at every time or distance interval, average speed for the whole run, drawbar pull, acceleration, throttle notch settings, and brake application or release. Users interested in energy consumption may want incremental energy used at every time or distance interval or just the total for the run, expressed as kilowatt-hours or gallons of fuel or even in terms of cost in dollars.

Obviously all these data cannot be presented in a single format which will be useful and convenient for everyone. Therefore a TPC should offer a variety of alternative outputs differing in degrees of complexity and which can be specified simply.

2.2 Details of the TSC Simulation

A TPC can be designed with any degree of sophistication, depending upon the form and accuracy of the input data and the desired application. The TSC TPS (3) is a relatively complex example. It incorporates all of the characteristics described above. In addition, a number of other features are included which increase its usefulness. It has built-in (default) values for almost every relevant parameter, including the complete specification of a train. (That is, if no train specifications are provided by the user, the computer will run a freight train pulled by three GP-35's and consisting of 40 loaded cars and 29 empties, all 50 feet long, with 3684 gross trailing tons.) One computer run, called a "job", can run up to 99 different trains over a route, with changes enroute to the track data and train consist.

Track data may be read either from a previously prepared (library) file or from the input data. Stops, dwell times, curvature, gradients, and speed limits can be readily changed from the value specified in the library data file for a given train and will be restored automatically for the next train. The train can be made to start and end its run virtually anywhere along the specified route.

Conventional freight or passenger trains with up to nine diesel or electric locomotives and as many cars as desired can be accommodated. Multiple-unit passenger trains may have up to 18 cars, any number of which may be powered. Data is maintained in a TPS library file for virtually all commonly used standard locomotives, including complete characterization of the tractive effort curves. Non-standard locomotives may be specified easily. (The standard tractive effort curve for each locomotive will be computed by the TPS unless an indicator is provided with the locomotive data, which allows for non-standard tractive effort data to be provided as a simple list of tractive effort values at increments of one mile per hour.)

Freight car consists can be specified in a variety of different ways, such as provision of detailed data on each car, specification of only total trailing weight and number of cars, etc. The TPS will provide default values as necessary. Passenger train consists can also easily be specified. A simple code indicates conventional power or multiple-unit operation. The locomotives, if conventional, are specified as for a freight train, and the number of passenger cars and their weight, length, and number of axles are given. Any standard resistance coefficients may be overridden if desired.

The five train resistance equations which follow have been programmed in the TPS for user selection. The default equation is that of Davis as modified by Tuthill(7); any of the others may be specified. The gradient and curvature terms are identical for each equation and are omitted.

In these equations:

L is the car length in feet
n is the number of axles
R is resistance of a single car in pounds
V is the velocity in miles per hour
W is the car weight in tons

* indicates multiplication
** indicates exponentiation

1. Davis, optionally modified by Tuthill above 40 mph.

```
R = 1.3*W + 29*n + .045*W*V + .045*(V**2)
```

2. "Canadian National"[†].

```
R = 0.6*W + 20*n + .01*W*V + .07*(V**2)
```

3. "Canadian National - Erie Lackawanna" for TOFC[††].

```
R = 0.6*W + 20*n + .01*W*V + .20*(V**2)
```

4. Totten streamlined passenger(8).

```
R = 1.3*W + 29*n + .045*W*V
        + [.0005+.060725*(L/100)**(.88) ]*(V**2)
```

5. Totten non-streamlined passenger.

```
R = 1.3*W + 29*n + .045*W*V
        + [.0005+.1085*(L/100)**(.7) ]*(V**2)
```

Alternatively, the user may specify individual coefficients for the locomotive consist or the train consist or for each unit in each consist, in essence generating custom resistance equations. To suggest the relationship of these equations, the first three are plotted in Figure 2-1 for a 75-ton car weight. (The normal weight for a fully loaded TTX car for which the CN-EL equation is used is somewhat higher than this.)

[†] This equation is often referrred to as "modified Davis".

[††] The coefficient of the V-square term is .20, reflecting the program as originally received from the Missouri Pacific; conventionally a coefficient of .16 is used.

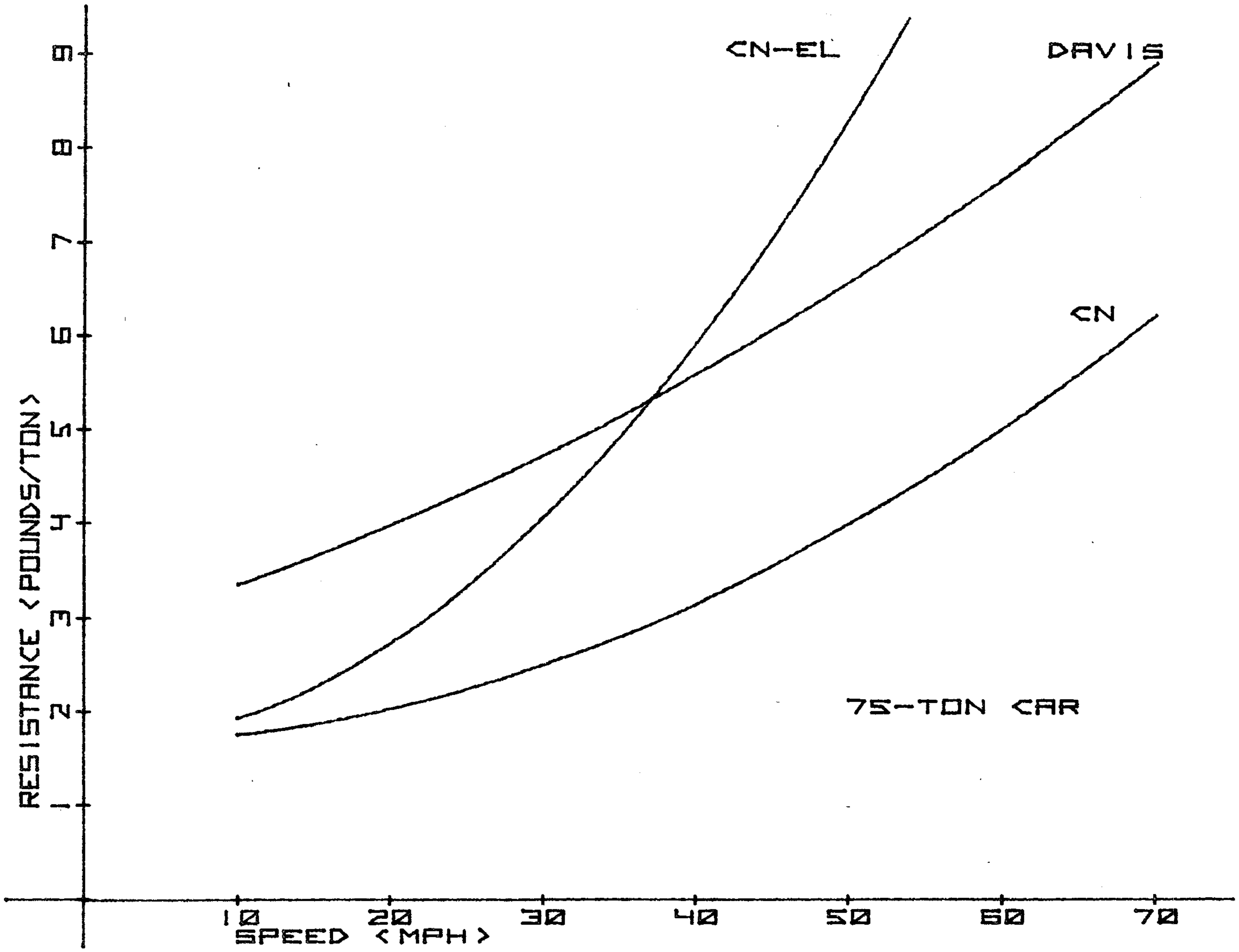

FIGURE 2-1. TRAIN RESISTANCE AS A FUNCTION OF SPEED
FOR THREE ALTERNATIVE RESISTANCE EQUATIONS

For improved accuracy in rolling terrain, the train is "blocked". That is, the trailing consist is divided among up to 25 blocks of cars. Each block is considered as an independent point mass upon which the train forces act. In the model these masses are considered to be separated by spacings consistent with the car lengths. This is particularly significant in long trains where part of the train may be ascending while another part is descending. The length of the entire train is determined and no acceleration is permitted until the last car has left a speed-restricted zone.

A simplified explanation of the basic iterative procedure is as follows. The TPS compares the present train speed to the speed limit. If below the limit, all tractive effort available will be applied, subject to the limit of adhesion specified. The velocity will be incremented (normally by 1 MPH) and the time and distance to achieve that velocity change will be calculated. If the train is already at the speed limit, then the distance is increased by 528 feet (1/10-mile) and the new time is calculated. In this case the tractive effort is taken as equal to the train resistance, with power and fuel usage calculated accordingly.

The TPS looks ahead in the track data (scanning up to 30 track data records) for stops and speed limit reductions and calculates in advance the distance required for braking. When that point is reached, the brakes are applied. Brake pipe propagation time and the variation of brake shoe friction coefficient with speed are both taken into consideration. A normal service brake application is assumed. When deceleration is called for, the velocity will be decremented, and the time and distance to achieve the change will be calculated as for acceleration, based upon the available braking effort.

The model requires the train to attempt to accelerate to the speed limit whenever possible, and to run at that speed. The user can modify the speed limits contained in the basic track data at will anywhere along the track where there is a data record. The TPS can simulate speeds up to 200 mph. Caution is advised, however, in interpreting results of runs at over 80 MPH, due to the greater uncertainties in train resistance at the higher speeds.

The user has a choice of Summary or Detail Printout. The Summary Printout contains a line only at stations along the route and includes only location, time, speed, and energy information. The Detail Printout contains a line every time the speed changes by one mile per hour or the distance is incremented by one mile. In addition to the same types of information as are found in the Summary Printout, a Detail Printout gives drawbar pull, throttle notch, and acceleration. Both printouts provide a complete description of the train (length, weight, horsepower, resistance coefficients, etc.) at the beginning and both give a Run Summary (total time, energy, and average speed) and a timetable at the end. A Throttle Position Summary and a Velocity Range Summary are available as options, as is a data file consisting of values at each iterative step which can be used later by another computer program to plot graphs of speed, speed limit, energy, elevations, grades, or curvature against time or distance.

3. LIMITATIONS ON THE COMPARISON PROCESS

3.1 Introduction

In the real world of railroad operations, both simulation and measurements are prey to a high degree of variability and uncertainty in almost all aspects. An awareness of these considerations is essential to proper evaluation and use of simulation tools. In this section a wide range of these elements will be identified and subdivided somewhat arbitrarily into: measurement limitations, constraints inherent to simulation of train movements, lack or ambiguity of data required by the computer model, and elements not yet implemented in the TPS. Section 5 of this report includes a number of simple analyses intended to facilitate estimation of the relevance and impact of these constraints in particular situations.

3.2 Limitations Associated with the Measurements

In most cases, the ability to measure and characterize operation of a freight train over a specific route will be limited in a variety of ways. At the most basic level, certain key parameters, such as train weight, may not be known to high accuracy. Fuel consumption data can be obtained at frequent intervals only if meters are installed on each locomotive and are read throughout the run. Just as different motor vehicle operators have a variety of driving styles, different locomotive engineers may achieve significantly different fuel efficiency under apparently equivalent circumstances, and since crews seldom operate a train more than 200 miles, a number of engineers will be involved in a lengthy run.

In practice, speed profiles tend to be far from the relatively constant value one might expect. Figure 3-1 shows a graph of the speed (measured at one mile increments) of a freight train travelling from Winslow, Arizona to Barstow, California. The causes of the many marked variations can be numerous -- curves, grades, train dynamics, local speed limits, slow orders, traffic, etc. -- but the effect is such as to preclude precise recording, prediction or simulation.

The very marked composite effect of these many factors is clearly seen in the measurement results reported in Volume II (Reference 2). One finds a variability approaching plus-or-minus 20% within each of the several test series for gross ton-miles per gallon.

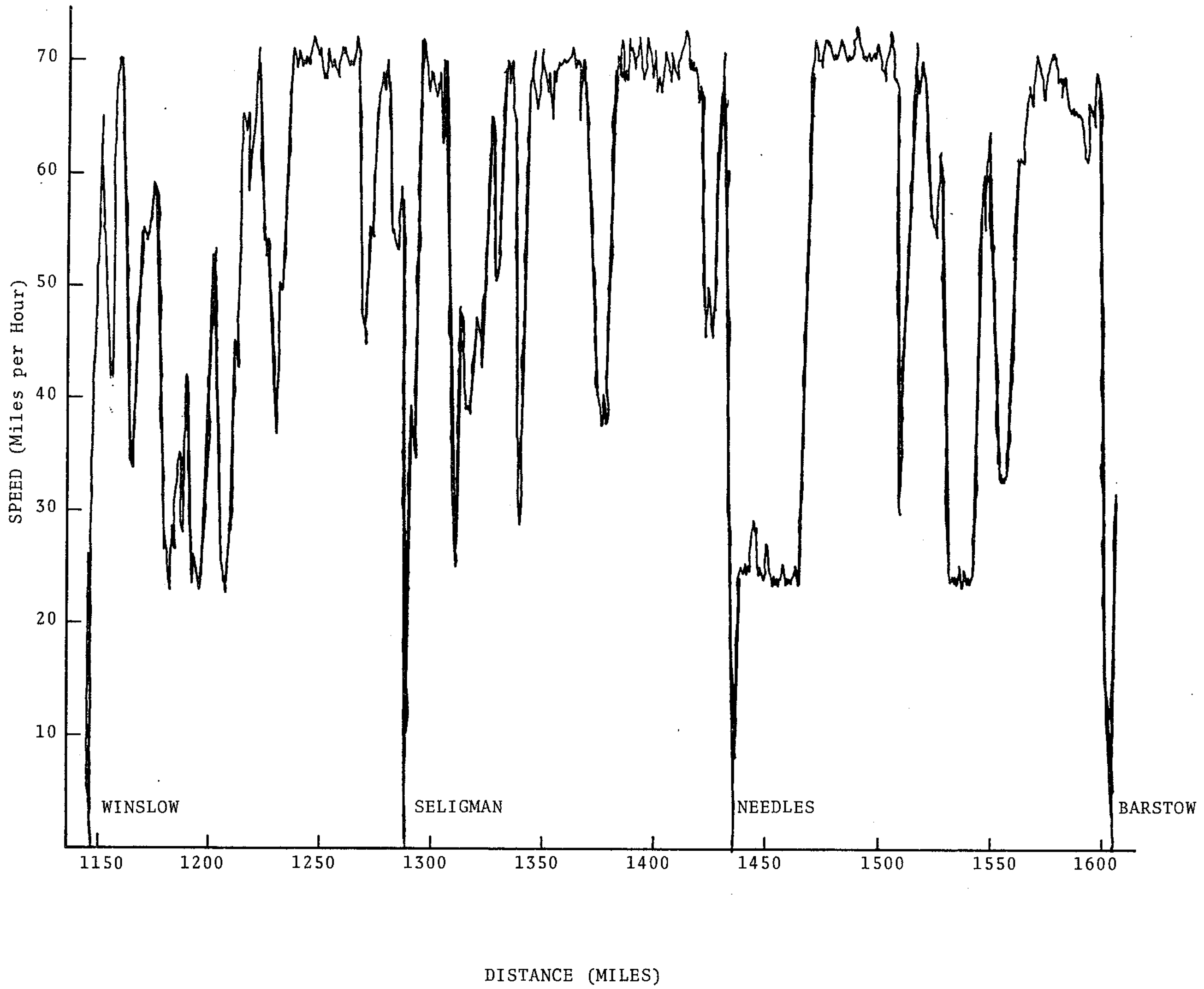

FIGURE 3-1. MEASURED SPEED OF TOFC TRAIN BETWEEN WINSLOW, ARIZONA AND BARSTOW, CALIFORNIA (MEASUREMENTS AT ONE-MILE INTERVALS.)

3.3 Limitations Associated with the Simulation

3.3.1 General Comments

A number of practical and theoretical constraints upon train performance simulation limit the ultimate accuracy which may be expected. Most of these are small, and in most cases the total impact can be expected to be relatively insignificant. However, it is to factors such as these that one must attribute the occasional marked differences between simulation and reality which do occur. Train resistance equations and wind effects are the most noteworthy uncertainties, but any TPC user should also be aware of the many other possible sources of error. These constraints can be divided, with some overlap, into three basic categories. One must assume values for certain basic data which could, in a particular case, be somewhat in error. Other constraints are associated with aspects of train operation which are sufficiently arbitrary and variable to preclude meaningful analytical modeling. In a few areas, a somewhat more rigorous approach is possible than is now embodied in the TSC TPS, although the effects of potential refinements are clearly very small. All of these considerations are addressed below.

3.3.2 Uncertainties in Basic Data

The major uncertainty embodied in any train performance simulation lies in the selection of the resistance equation from which the total force required to move a train at a specified speed is calculated. The forms commonly used (Section 2.2) are based on a simple physical model and data collected at least a decade ago for specific rolling stock. The alternative formulations give significantly different results for nominally equivalent situations. At higher speeds the problem is intensified due to the greater significance of aerodynamic forces which are complicated and not well understood. The specific order and type of cars in the consist must be known for a truly accurate formulation of aerodynamic resistance. It is probable that track and substructure conditions also affect the train resistance. Rail and lubricant temperatures and the types of bearing and bearing seals used presumably have some impact, possibly of the order of a few percent. All of these factors and others are considered in detail in reference (6), which convincingly documents both the complexity and the quantitative uncertainty surrounding this area. However, each factor tends to draw one further into an abstract and academic perspective which is of limited relevance to most practical simulation activities.

For most of the cases simulated, track curvature data were either not available or would have required excessive labor to utilize. These computer runs therefore are generally based upon an assumption of zero curvature. Previous TSC consideration of the impact of this parameter indicated that fuel consumption was underestimated by 4% to 10% in the simulation of low-speed trains operating on eastern routes with relatively frequent and substantial curves. A brief analysis of the probable impact for the western routes used in this study can be found in Section 5.8.

3.3.3 Elements Not Susceptible to Modeling

The effect of wind (its direction and velocity) can be substantial, but is virtually impossible to model in a truly satifactory manner. A quartering wind, which interacts strongly with the inter-car spaces, can have an effect even greater than that of a headwind. However, since a train will often be a mile or more in length, and may be in a region of substantial track curvature, the wind effects may even differ over the length of the train at any given moment. Furthermore one would have to accumulate very precise track curvature data to relate instantaneous direction of the train to the (presumably constant) wind direction. Track data of sufficient precision and detail is extremely unlikely to be available. (Track charts often give only magnitude of curvature.) Successful incorporation of a this refinement would almost certainly require development of necessary data from U. S. Geological Survey maps, a very labor intensive undertaking.

The efficiency of the conversion of diesel fuel to tractive effort depends on factors such as locomotive condition, temperature, altitude or barometric pressure, and the particular fuel used. There is no practical way to incorporate these factors into a simulation, since necessary data would rarely be available. Another inherent difficulty is the ambiguity in the manner in which a train may be operated. For example, use of dynamic braking rather than train air brakes, or power braking (applying train brakes and locomotive power simultaneously to keep the train stretched) could, in principal, be modeled, but there would be no assurance that any actual train matched the algorithm used.

Similarly, in the simulations, the TPS attempts to hold the train to a constant velocity. In mountainous regions, particularly if curves are moderate or entirely absent, an engineer might be expected to allow the train to accelerate (under gravity) on downgrades, possibly even slightly exceeding speed limits for some track segments. This would build up kinetic energy which could then be "spent" on a subsequent ascent, at the expense of speed, which might be allowed to drop significantly. If this were the case, the TPS calculations would show somewhat higher fuel consumption than would be measured. This topic is addressed in Section 5.7. For level terrain the constant simulated speed profile will lead to prediction of a more efficient operation than actually occurs if there are significant speed variations.

The standard diesel-electric locomotive operates only in eight discrete power settings (throttle "notches"), whereas simulators normally assume a continuous range of power to be available. If eighth-notch on a particular track gives a speed of 65 MPH, and seventh-notch gives 55 MPH, the means by which the engineer deals with a speed restriction of 60 MPH becomes somewhat arbitrary, and any algorithm used in a computer could be at odds with normal practice.

Whether one sees these kinds of difficulties as shortcomings of the simulation or as inadequacies in the data, they inherently limit, to some degree, the accuracy one could expect from a computer model. The effect will be small in most situations, but could be significant for special circumstances of terrain or operating practices.

3.3.4 Elements Not Now Modeled in the TPS

Several refinements are planned for incorporation into the TPS, but have not yet been implemented. At present, neither dynamic nor power braking is simulated by the TPS. During braking, the fuel rate is assumed to be that associated with idling (typically 5 to 6 gallons per hour). If locomotive power is applied during braking, or if dynamic brakes are used, the actual fuel rate could be several times this value. For example, the rate in dynamic is 25 gallons per hour for an SD-45, or 100 gallons per hour for a four-locomotive consist. In mountainous terrain this could produce errors in fuel consumption in the range of 2% to 4% for typical runs, and substantially more under certain circumstances. Approximate manual correction for this factor is possible, since the TPS computes total hours of braking. This will be discussed in Section 4.6.

Locomotive power transmission efficiency is taken as a constant (82% is the nominal value), whereas it might more properly be represented as a function of instantaneous power and possibly speed. The basic efficiency of conversion of fuel to motive power, or fuel rate (gallons per horsepower-hour) is also specified as a constant for each locomotive. It would be more precise to represent this, too, as a function of instantaneous power. The effect of these factors is, however, quite small in most line haul applications, since most of the fuel is then consumed at relatively high power levels and moderate or high speeds. This correction has principal relevance to low-speed, low-power situations, such as branchline service.

Another factor which should more properly be seen as a function of speed is wheel-rail adhesion. However, this correction is also of limited relevance in normal freight operations. Adhesion-limited situations are more likely to occur in the medium speed range where adhesion is relatively constant. The greatest impact would be expected for highly powered, high speed passenger trains, since adhesion is significantly reduced at high velocities.

4. SPECIFIC MEASUREMENT/SIMULATION COMPARISONS

4.1 General Approach

For purposes of analysis each set of measured data was subdivided to the extent that fuel and operating data would allow. The segments thus generated ranged from less than twenty miles (for branchline operations) to over 1000 miles. Most, however, were between 100 and 300 miles. This procedure permitted some degree of examination of variability in the simulation process. No comparison was attempted among results for different railroads, in view of the many differences in each set of tests. Some of the measurements previously described in Volume II were not subjected to comparison, due to the relatively scanty information available, particularly with respect to speed profile and delays.

For each segment, simulations were prepared according to nominal speed limits to the degree that these were known. Since actual operations often differ markedly from the optimal case defined by these limits (some delays are almost inevitable), the TPS generally computed running times significantly shorter than those occuring in practice. In some cases, nominal speed limits were generated instead from actual average velocities over segments or major portions; agreement was normally better in these cases. The next step was selection of nominal speed limits and delay times which more nearly approximated the true running time; usually one or two iterations were sufficient to determine acceptable values. For some runs this involved adjustment of the stop times associated with enroute delays; otherwise speed limits for part or all of the segment would be modified. In all cases, these variations were well within a range consistent with such data as was available. This procedure was necessitated by ambiguity in the measured situation, or by the impracticality of simulating the highly variable actual speed profile.

The final stage of the comparison was based upon computations of the ratio of TPS fuel used to actual consumption, and variations in this parameter. In general, these data were analysed in terms of the degree to which the computed findings for the selected speeds and resistance equations matched the measured data. Results for individual segments as well as entire runs were compared, and variation among the segments was examined. Although standard deviations could readily be calculated, this is not a particularly meaningful index, since the distribution of error appears to be distinctly non-Gaussian. As an alternative, results are presented here in terms of the percentage deviation range which includes approximately two-thirds of the data points, representing segments of runs. In some respects this may be thought of as equivalent to a standard deviation, since 68.8% of the results for a Normal (Gaussian) distribution will fall within one standard deviation of the mean. Aggregated findings were based upon fuel-weighted averaging; that is, ratios were calculated as the total computed fuel divided by total actual consumption for the group of segments or runs of interest.

In some cases both the data and limited information concerning a segment would suggest that the segment in question was not adequately characterized for meaningful use. Most commonly this involved cases of traffic delays or stops which were made to set out cars with mechanical defects, and the resulting switching and delay time was not adequately differentiated from running time. In such cases, overall TPS measurement comparisons are presented both including and excluding the questionable segments.

4.2 Train Resistance Equations

As indicated in Section 2, the TPS offers the option of using any one of several train resistance equations for a particular run. [As originally purchased from the Missouri Pacific, the TPS CN-EL equation utilized an aerodynamic coefficient of .20, rather than the conventional .16. This value (.20) has been used in lieu of any strong evidence to the contrary, and is implied wherever the CN-EL equation is referenced in this report.] One is thus faced with the question of which equations are best used for the various cases to be considered. In general, the choice is between the original Davis equation and some form of the modified Davis, or "Canadian National" formulation. For several measurement series a large number of computer runs were made utilizing a variety of resistance equations. This was found to have little effect on running time, but was significant for fuel usage. Consumption for each equation was compared to the measured value. Since much of the data was for TOFC service, the "Canadian National - Erie Lackawanna" (CN-EL) equation was compared to two "quasi-Davis" forms. (The original Davis equation is for boxcars, whereas TOFC trains are known to have substantially higher aerodynamic drag.) In one case, the normal coefficient for the velocity-squared term (which represents the aerodynamic losses) was increased by a factor of .16/.07 (=2.286). This is identical to the change normally used in converting from the standard "Canadian National" (CN) equation to the conventional form of the CN-EL (TOFC) version. In the alternative Davis-like TOFC formulation, each loaded TTX car (trailer-carrying flatcar) is thought of as equivalent to two box cars, each having half the total weight and length of a TTX car.

The results of the comparison of these equations, applied to more than 20 runs, showed no significant differences among the three approaches for medium speed TOFC service. The increased V-square-term technique typically gave computer-calculated fuel consumption 1% to 2% above the CN-EL, with the "two-box-car" approximation running about 5% higher. The overall average for the CN-EL equation (with k=.20) in these comparisons was within 1% of the measured consumption, although the scatter was substantial from run to run. Basically similar results were obtained for a small set of higher-speed runs, with the Davis formulations giving results equal to the CN-EL values or slightly lower. In view of the somewhat stronger theoretical and experimental basis for the CN-EL equation, and its widespread use within the industry, it was selected for use in these comparisons.

For boxcar trains, the CN formulation, which gives significantly lower values than the Davis, was found in preliminary TPS runs to be a better approximation. It was subsequently used for boxcar consist simulations. One particular segment provided strong substantiation for this choice; details are presented in Section 5.6. An advantage of using both CN and CN-EL forms is that they are mutually consistent, differing only (as is reasonable physically) in the aerodynamic term. One can readily approximate a mixed (boxcar/TOFC) consist by using an appropriate intermediate value for the aerodynamic coefficient. In Section 6.2.2 effort is directed toward utilizing the results of these comparisons to develop modified resistance equations which will be preferable for simulation of fuel consumption.

4.3 Branch-Line Operations

In late 1974 measurements were carried out for FRA/TSC by the Missouri Pacific Railroad on a branch line between McGehee, Arkansas, and Delhi, Louisiana, a distance of 87 miles. Speeds were generally either 10 or 25 MPH, with consists of 0 to 38 cars plus the GP-7 locomotive on which fuel meters had been installed. Six round trips were carried out over a period of two weeks. For analysis, the route was divided into three segments over which speed and consist were relatively constant.

The results for these operations (in the form of percentage deviations of TPS calculations from the measured consumption data) are shown in Table 4-1. Overall, the TPS prediction is 31% below the fuel usage actually observed. For the 36 segments, two-thirds of the data fall between -16% and -46%, for a deviation of 22% about the mean value. Aggregation separately by runs and segments shows a marked narrowing of this uncertainty.

TABLE 4-1. MISSOURI PACIFIC FUEL USAGE COMPARISON RESULTS: TPS DEVIATIONS IN PERCENT BY RUN AND SEGMENT

Segment	Run: 1	2	3	4	5	6	Average
Southbound							
1	-18	-21	-12	-19	-38	-39	-24
2	220	-43	-16	-25	-41	-44	-25
3	-12	-8	-22	-27	-49	-53	-34
Northbound							
1	-43	-13	-38	-32	-49	-33	-34
2	-24	-41	-31	-43	-38	-46	-39
3	-7	-15	-23	-13	-39	-48	-28
Average	-21	-20	-29	-24	-44	-33	-31

The TPS underestimation by almost one-third obviously requires examination and explanation. A number of factors must be considered. The practical limitations on accuracy in railroad fuel usage measurements are a problem here as in all tests. Accurate differentiation between fuel used while running (45%) and that associated with switching and standing (55%) poses a problem, and the idealized computer speed profile may be significantly different from the actual case. The relatively small amounts of fuel involved -- sometimes only a few gallons -- also increase the likelihood of a large percentage error, although this factor should not introduce any systematic overall inaccuracy. Car weights were estimated, and should be considered only an approximation. It is often found that such estimates err on the low side. The low speeds make the test situation particularly sensitive to the mechanical component of rolling resistance, so that this term could be modified to achieve better agreement. However, use of the original Davis equation, rather than the Canadian National form, would lead to a TPS overestimate. More importantly, other factors are known which readily explain the magnitude of the observed discrepancy.

The MITRE study by Muhlenberg (Reference 6) identifies two highly relevant effects. one concerns bearing temperature. Curves are presented in (6) which show a drop in train resistance presumably arising from heating of the bearings during the first 10 to 15 miles following a stop, after which a nearly constant lower value is found. Although this relates primarily to friction bearings, many cars thus equipped are still in service. Since most of the segments of the Missouri Pacific test involved distances of this magnitude or less between stops, the high cold (starting) values of resistance -- which occur for such a brief period that this factor is of limited importance in linehaul operations -- could be quite significant.

The second point brought out by Muhlenberg involves the tracks. A convincing argument is made that train resistance is significantly greater for lighter-weight rail, which is common to branch operations in general and to this case in particular. Physically, this phenomenon appears to be associated with a wave-like action in the rails. Finally, one should also consider general track and roadbed condition. Branchline track is typically maintained only to Class 1 (10 MPH maximum speed) or Class 2 (25 MPH) tolerances. Relatively damp conditions, with a moist substructure, were also characteristic of the test conditions. The uneveness and softness of the resulting track structure would be expected to contribute to a substantial increase in train resistance. Consider, for example, the additional effort required to operate a bicycle in sand or rough terrain.

In summary, although rigorous quantitative conclusions cannot be drawn concerning these possible effects, the results are generally consistent with them. In a practical sense, it appears appropriate to increase predicted fuel usage by approximately 50% to compensate for these real but poorly quantified effects. A more rigorous approach for branchline applications, were data available, would be to include in the model the distance between stops, stop times, track class and general condition, and the nature of the subgrade.

4.4 Long-Distance TOFC

In June, 1975, the Burlington Northern Railroad collected a variety of information relating to fuel usage on a scheduled TOFC train operating daily from Chicago to Seattle, a distance of 2200 miles. On this run, trains normally carried a number of cars the full distance, with other cars being set out and picked up enroute. With the exception of an occasional mail car, it was purely TOFC, with almost all trailers loaded. No empty cars were hauled. Eight further runs were monitored early in 1976. In this case only the Chicago-Minot portion of the route was involved, and the trains included several boxcars in addition to the TOFC cars. The data collected included computer-generated consist lists and total fuel added at Minot and Seattle. It was not possible to weigh the trains, and the estimated weights used for simulation were judged to be highly approximate. Errors of 10% or greater are considered possible.

For analysis, the runs were divided into three groups: Chicago to Minot, First Series (922 miles); Minot to Seattle, First Series (1257 miles), and Chicago to Minot, Second Series. These provided groupings which were relatively uniform in both consists and terrain. Since on-board fuel monitoring was not possible in this case, subdivision to shorter segments would not have been meaningful. The CN-EL resistance equation was used for all cases, although a small number of boxcars was present in trains used in the second series.

Basic results for each segment are shown in Table 4-2, and are summarized in Table 4-3 according to the three major groupings identified above. The overall finding is that computed fuel usage was 1.8% less than that actually measured, with variation of -28% to 56% for various segments. Two-thirds of the segments yielded simulation values within 16% of the measured fuel usage. Uncertainty in train weights and speed

TABLE 4-2. BURLINGTON NORTHERN COMPARISON RESULTS (BY SEGMENT)

Chicago - Minot, First Series		Minot - Seattle, First Series		Chicago - Minot, Second Series	
Run	TPS Deviation(%)	Run	TPS Deviation	Run	TPS Deviation
1	-4	1	58	2	30
2	-6	2	21	3	4
3	-7	3	30	4	-10
4	8			5	-31
5	-10			6	-16
6	-12	6	32	9	4
7	0			10	8
8	-16	8	-4	11	15
9	-14			13	-31
10	-23				
11	-9				
12	-6				
13	-26				

TABLE 4-3. BURLINGTON NORTHERN COMPARISON RESULTS (SUMMARY)

Series	TPS Deviation(%)	Range* (Actual)	Range* (TPS Mean)
Chicago-Minot, 1st Series	-10	8%/-12%	11%/-5%
Minot-Seattle, 1st Series	24	32%/-4%	6%/-7%
Chicago-Minot, 2nd Series	-5	15%/-16%	21%/-12%
Overall Total	-1.8	16%/-16%	18%/-14%

profiles obviously contributed to this discrepancy. Indeed, the measured values showed a substantial variation among themselves, even when normalized to units of gross trailing ton miles per gallon (GTTMPG). For the total measured test data and for each of the groups alone two-thirds of the segments are within approximately 15% of the average for all runs in the series. Any special or unknown factors which might have caused certain trains to be above or below the mean for the tests obviously could not be included in the simulation. This view is supported by an examination of the rank correlation between the measured and simulated cases. The segments within each grouping were ranked by (TPS fuel)/(actual fuel), and separately by the ratio of actual GTTMPG to average measured GTTMPG for the group. Table 4-4 shows the results; a significant rank correlation(9) is found for the first and third groups (Chicago to Minot), but not for the second. This demonstrates that a significant part of the divergence between the TPS and measured values for the two correlated data sets arises from the experimental situation and not the simulation.

TABLE 4-4. BURLINGTON NORTHERN RANK CORRELATION RESULTS [ACCORDING TO SPEARMAN RANK-CORRELATION TEST (9)]

Series	Rank Correlation	Confidence
Chicago-Minot, 1st Series	.85	99%
Minot-Seattle, 1st Series	.40	75%
Chicago-Seattle, 2nd Series	.65	95%

The overall results for the first and third groups are quite good, considering the experimental uncertainties. In addition, the absence of track curvature effects and the limited replication of the actual speed profile must be recognized. Both would be expected to produce underestimates of several percent in the simulation.

The Minot - Seattle group, while showing a large error (TPS overestimate of 24% on the average) is characterized by the smallest range: deviation from the mean is between -7% and 6% for two-thirds of the runs. This strongly suggests the presence of a systematic error in the simulation for this data set. This route consists predominantly of moderate descending grades, a condition under which simulation results are highly sensitive to the resistance equation coefficients. This is discussed at length in Section 5.4. Overspeeding or coasting on downgrades, followed by slowing to speeds substantially below the nominal limit on a subsequent upgrade, could also contribute to significant TPS overestimation for the terrain involved. This case is discussed in Sections 3.3.3 and 5.7. These factors are judged to provide a satisfactory explanation for the discrepancy. A possible modification to the TPS which could minimize these inaccuracies is mentioned in Section 5.7.

4.5 Medium-Distance Varied-Consist Operations

During July, 1975, the Southern Pacific Transportation Company collected detailed data concerning operational and fuel consumption characteristics for eight trains (four in each direction) running between Roseville and Bakersfield, California, a distance of 287 miles. The terrain -- the Great Central Valley of California -- is relatively flat. On most trips several stops occurred at which minor changes in consist were carried out. All trains were weighed. The power consist throughout comprised two SD-45 locomotives on each side of a dynamometer test car housing the test crew and measurement apparatus. Fuel consumption was determined with calibrated meters connected from the test car to each of the diesel units. Distance traveled, milepost, fuel consumed, speed, time, and other factors were recorded at 10 mile intervals, as well as at stops or otherwise noteworthy points.

Three types of trains were involved. Two runs consisted of TOFC only. These relatively light trains (2200 to 3600 tons) operated at power-to-weight ratios of 2 to 3 HP per gross trailing ton, with speeds of 50 to 60 MPH or higher. Four other runs involved low-speed heavy mixed-freight trains -- two of over 10,000 tons, and two of 5000 to 6000 tons -- operating at .7 to 1.4 HP per gross trailing ton. The remaining two runs were intermediate cases, approximately half TOFC and half boxcar. In the case of the mixed consists, a basic CN resistance equation was used for the simulations, using an aerodynamic coefficient 'k' intermediate to the boxcar (CN) and TOFC (CN-EL) forms. The actual value used reflected the proportion of the two car types. Track curvature data was available for use in the simulations. The data collected on these runs did not permit precise delineation of speed profiles. For the heavy boxcar trains, there were a number of stops and delays which complicate the simulation process, and which thwarted attempts to divide the runs into shorter segments. However, all consist changes which occurred in the course of a run were included in the TPS simulations.

The results for all runs are shown and summarized in Table 4-5. For the overall test series, TPS computations differed from actual consumption in the aggregate by only -5%, ranging from a low of -19% to a high of 10%. The summary findings are fuel-weighted, which causes the boxcar runs to dominate. Uncertainties in the simulation process were also greatest for the boxcar trains, for which speed profiles were the most uncertain. On the other hand, fuel usage would be expected to be relatively insensitive to variations in velocity at the lower speeds involved.

TABLE 4-5. SOUTHERN PACIFIC FUEL USAGE COMPARISON RESULTS

Run	Consist Type	TPS Deviation (%)
1	TOFC	16
2	Mixed	-3
3	Boxcar	-9
4	Boxcar	-19
5	Boxcar	-8
6	Boxcar	-5
7	TOFC	15
8	Mixed	-11
All Runs	TOFC	15
All Runs	Boxcar	-10
All Runs	Mixed	-7
All Runs	Overall Average	-5

The TOFC trains showed almost identical simulation overestimates on the two runs (15% and 16%), suggesting a systematic rather than random effect. Similarly, calculations of fuel usage for the six boxcar and mixed freight runs, taken together, averaged 91% of measured consumption, with two thirds of the results falling beween 89% and 95%. It is likely that the relatively even terrain contributed to the uniformity of the results. Mountain operations tend to bring into play many of the mechanisms which introduce variation.

4.6 Long-Distance TOFC and Boxcar

In the first half of 1976 the Santa Fe Railway Company carried out detailed measurements during three round-trips between Kansas City, Kansas and Los Angeles or Barstow, California. These tests included two TOFC trains and one consisting primarily of box cars, hauled by either 3 or 4 SD-45 locomotives. Average speeds overall were in the range of 45 to 50 MPH, with running speeds for the TOFC trains exceeding 70 MPH. A test car, located behind the power consist, was always used, equipped with a variety of instruments and data processing and recording equipment. All trains were weighed in Kansas City. The first (eastern) half of the route is relatively level, with a moderate continual ascending grade. In the west, several mountain ranges are crossed, with substantial and sometimes very lengthy grades (both ascending and descending). The westbound TOFC trains generally carried a full complement of loaded trailers. When traveling eastbound the trailers were predominantly empty.

For comparison with simulation, the analysis was based upon subdivision of the runs into 13 segments, ranging from 64 to 239 miles (with an average value of 135 miles). The CN-EL resistance equation was used for the two TOFC round trips, and the CN for the boxcar train. The topography varied considerably among them, as did the rail traffic. The segments are described briefly in Table 4-6. The high degree of variation in speeds within segments has already been mentioned in Section 3.2. The procedure used for simulation was to separate out significant delays (extended stops) and choose as a nominal speed limit a value giving approximately the correct average speed. All known stops were included. This generally resulted in simulation speed limits slightly less than those actually specified by the railroad, typically in the range of 55 to 60 MPH. Resulting TPS running times for each segment were very close to actual values, with two-thirds in error by 1% or less. Only 10% deviated by more than 2%. Table 4-7 shows the percentage difference between measured fuel usage values and those calculated by the TPS, including averages over both runs and segments. Overall results for fuel usage are in

TABLE 4-6. ROUTE SEGMENTS FOR SANTA FE TESTS

Segment	End Points	Length (Miles)	Terrain (Westbound)
1	Argentine - Emporia	107	Level
2	Emporia - Wellington	111	Level
3	Wellington - Waynoka	107	Level
4	Waynoka - Amarillo	202	Gradual ascent
5	Amarillo - Clovis	107	Gradual ascent
6	Clovis - Belen	239	Steep ascents/descents
7	Belen - Gallup	145	Steep ascent
8	Gallup - Winslow	128	Moderate descent
9	Winslow - Seligman	142	Steep ascents/descents
10	Seligman - Needles	148	Mainly steep descent
11	Needles - Barstow	169	Steep ascents/descents
12	Barstow - San Bernadino	79	Steep ascent/descent
13	San Bernadino - Los Angeles	62	Gradual descent

TABLE 4-7. SANTA FE FUEL USAGE COMPARISON RESULTS: TPS DEVIATIONS IN PERCENT BY RUN AND SEGMENT

Run:	TOFC		TOFC		BOXCAR		
Segment	1WB	1EB	2WB	2EB	3WB	3EB	Average
1	-21	-41	-4	-16	-36	-26	-25
2	-23	-15	12	23	-34	-18	-13
3	-14	-15	25	5	-21	-15	-8
4	-10	-18	23	1	-11	-10	-5
5	2	20	-7	28	-26	-13	-2
6	-1	8	13	-10	-12	-12	-3
7	0	37	11	25	-6	-5	7
8	-16	26	7	12	-19	-0	5
9	-14	2	13	19	-6	-4	-0
10	-6	9	15	3	-22	-5	0
11	-11	2	7	-5	-13	-13	-6
12	0	-14	-15	-23	-13	0	-16
13	0	-8	-23	-30	-57	0	-28
Average	-10	1	9	1	-17	-9	-5

generally good agreement. Two-thirds of the segments fall within a band of -18% to 15% of the actual measured value, and the total fuel actually used is only 5% greater than calculated.

A significant number of segments did show serious discrepancies. In particular, those for Kansas City to Emporia (segment 1), Barstow to San Bernadino (segment 12), and San Bernadino to Los Angeles (segment 13) consistently show a much higher actual fuel consumption than predicted by the simulation. These segments are all characterized by high densities of rail traffic, where right-of-way may be shared with other railroads. The stop-and-go nature of the movements in those places would be expected to increase fuel usage above that which would be needed for relatively constant velocity operation assumed by the TPS. If one deletes these segments from consideration on the grounds that the special conditions destroy their validity for the comparison, the resulting overall TPS error is -2% and deviations range from -15% to 13%. When aggregated by runs the reduced results show a "two-thirds" deviation of -9% to 9%; for segment aggregation the range is -6% to 0%.

The difference between the first and second runs is of some interest. For the round trips (westbound plus eastbound), the TPS was 4% low on Run 1 and 6% high for Run 2. Run 1 was operated at maximum speed (70 MPH) whenever possible. Run 2 called for application of power only below 55 MPH; coasting to 70 MPH was permissible if allowed by speed limits. This type of operation, somewhat similar to that analysed in Section 5.7, reduces average speeds but also has a marked influence on fuel consumption. For the measured data, the decrease (in gallons per ton mile) is 14%, accompanied by a 9% drop in velocity. This appears to provide a mechanism with which to explain the 10% difference in the accuracy of the TPS between the two runs. The second run utilized a more fuel-efficient type of operation which the TPS did not attempt to emulate. This "drifting" mode can be simulated through setting locomotive available tractive effort to zero above 55 MPH. This was tried for the first westbound train, with the result that computed average speed decreased by 8% while fuel usage dropped by 15%. These values are very close to the measured change from Run 1 to Run 2.

Several segments in addition to 1, 12, and 13 show particularly high deviations between measurement and simulation for certain runs. Various general effects described elsewhere in this report undoubtedly contribute to these discrepancies. However, a significant portion of the error in these cases may be related to the terrain, with high descending speeds allowing partial coasting on the following ascent. This condition would lead to TPS estimates well above measured values. (See Sections 3.3.3 and 5.7.)

The Santa Fe trains were operated using dynamic brake wherever applicable. The relevance of this factor lies in the difference between the 6 gallon per hour fuel rate at idle (for each locomotive) and the 25 gallon per hour rate when in dynamic brake. The TPS does not at present include provision for this, but a simple manual correction is possible. The TPS provides a summary of time in each throttle notch, including braking. If one somewhat arbitrarily assumes that half of the braking is dynamic, the appropriate correction for total fuel usage can be calculated. For all runs, the increase is 2% overall, yielding a total consumption for the test series extremely close to the TPS values. However, this apparently excellent agreement is somewhat diminished by the fact that track curvature was not included; under these circumstances the TPS should have been about 2% under the actual data.

5. ANALYSIS OF INDETERMINANT FACTORS

5.1 Effects of Cyclic Speed Variation

It has previously been noted that actual freight train speed profiles can be highly variable, to the point that precise computer replication may be impractical. Figure 5-1 repeats the measured profile of Figure 3-1, and overlays the speed limit profile and running speeds associated with the TPS simulation. Given this obvious discrepancy between the real world and the analysis, it is important to estimate the impact on computed fuel use of problems in this area.

The fuel usage effect of cycling of train speed (as in Figure 5-1) can be addressed in a relatively simple manner. Consider two alternative scenarios by which a train could complete a trip at an average speed V. One possibility would be to operate at all times at V. Another would be to run part way at (V-v), and the remainder at (V+v), the partitioning chosen to be such that the overall run achieves an average of V.* One can readily compute the work done per unit distance the resistance of a train or freight car for each of the three velocities under consideration: V, V-v, V+v. It is then

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*The fraction of the total distance at V+v is (V+v)/2V; the fraction at V-v is (V-v)/2V.

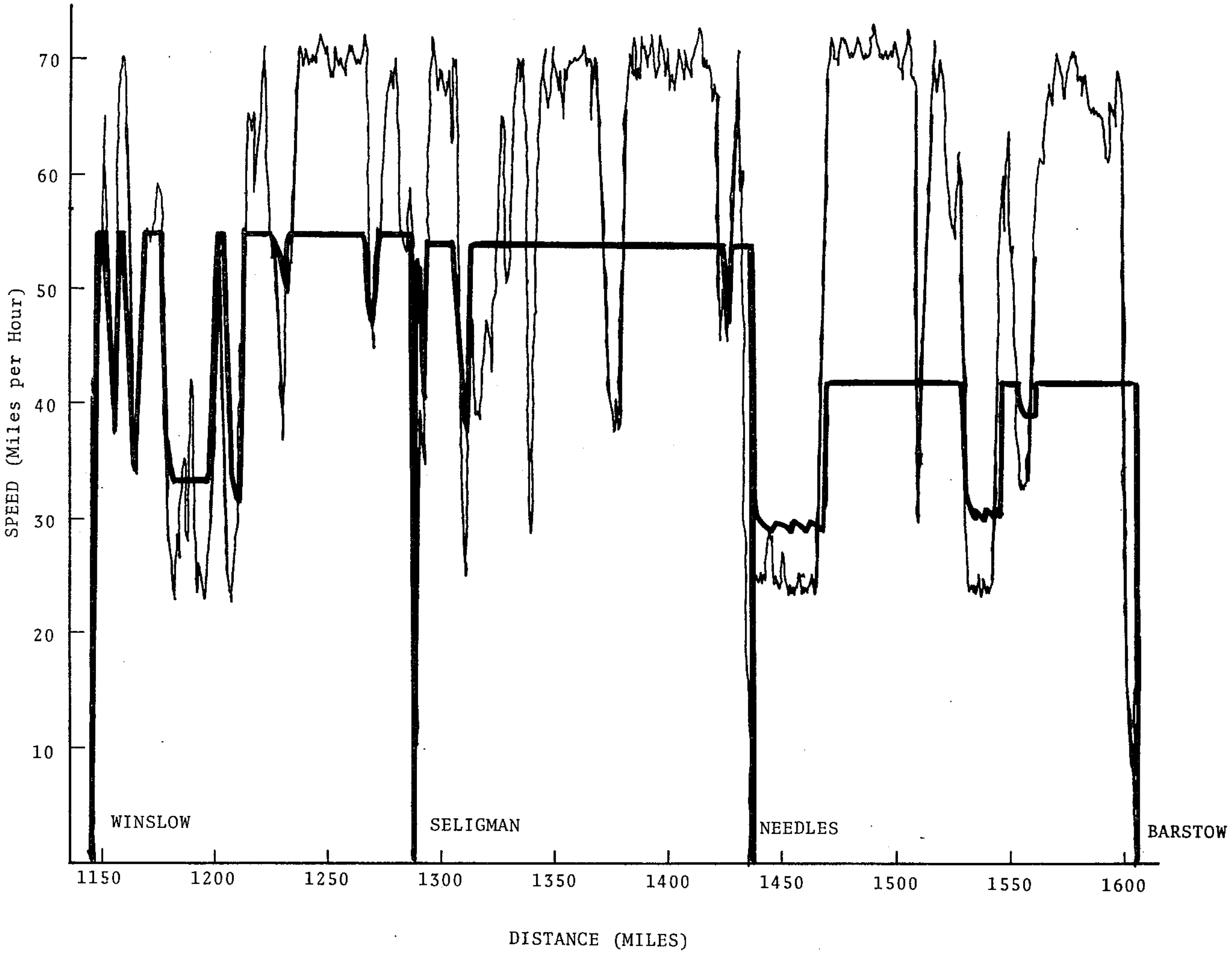

FIGURE 5-1. COMPARISON OF MEASURED AND SIMULATED SPEEDS FOR TOFC TRAIN BETWEEN WINSLOW, ARIZONA AND BARSTOW, CALIFORNIA

possible to calculate a relative energy index consisting of the ratio of the work done in the constant-velocity (V) scenario to the energy required for the two-velocity [(V-v), (V+v)] case. Results of this type of computation are graphed in Figures 5-2 and 5-3, respectively, for a 75-ton boxcar using the CN equation and an 85-ton trailer-carrying car with the CN-EL (TOFC) equation. The curves are for V = 35, 50, and 65 MPH with the energy index shown as a function of V.

Although real situations involve a far more complex array of speeds to be averaged, the simplified scenarios analyzed here provide a "worst" condition. However, this clearly illustrates the magnitude of the effect, and suggests that a non-uniform velocity profile may readily consume as much as 5% to 15% more fuel than would be the case for a constant-speed case yielding the same average speed.

5.2 The Impact of Stop Times

A problem similar to that of cycling arises when an average velocity V results from a constant actual velocity V' plus a significant period of idling. Idle fuel rates are only a few percent of those near full power, so that the idle fuel consumed during a short time period is generally a negligible part of the total. However, operating at the higher speed V'

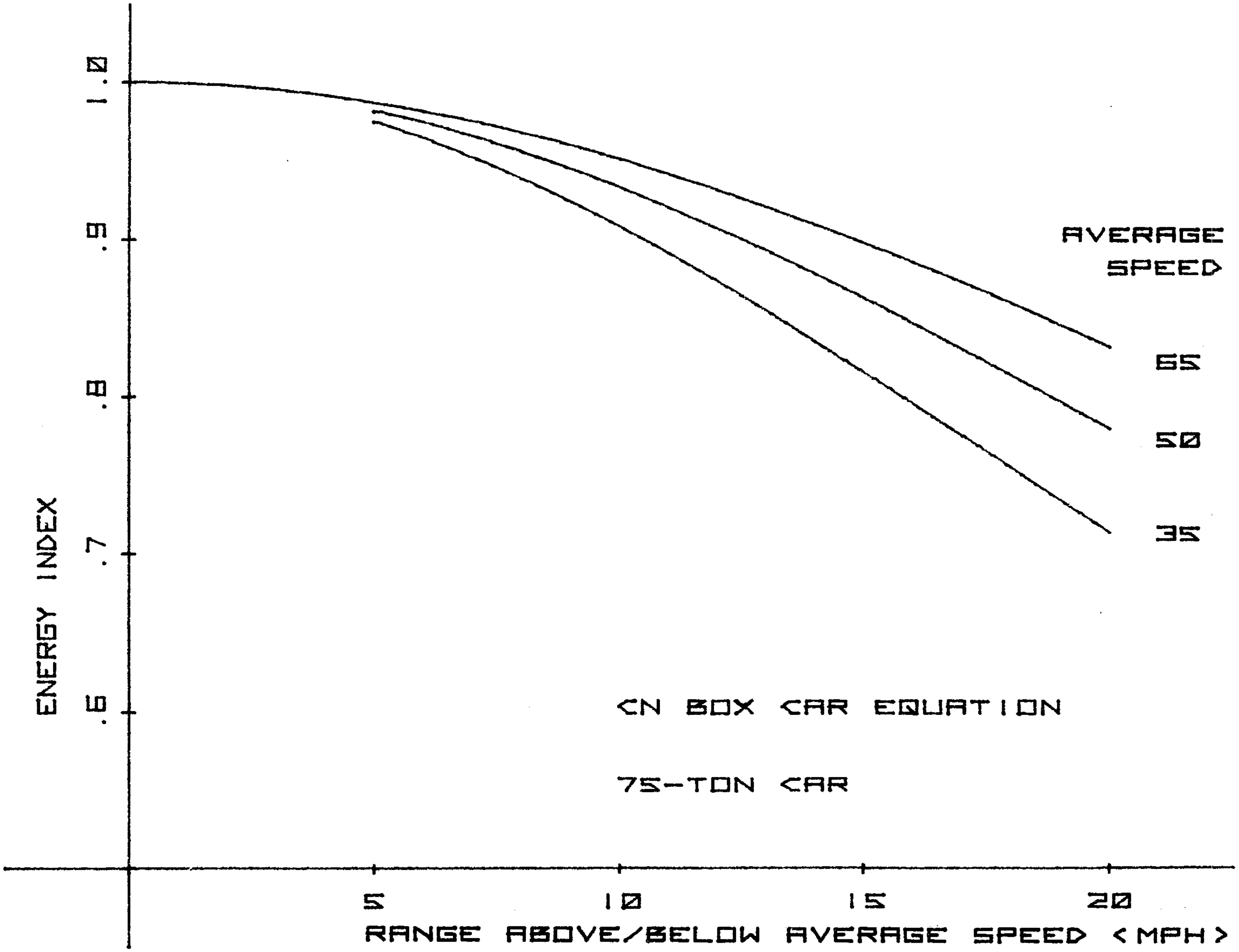

FIGURE 5-2. COMPARISON OF CONSTANT VELOCITY WITH CYCLING BETWEEN TWO VELOCITIES; 75-TON BOX CAR, CN RESISTANCE EQUATION

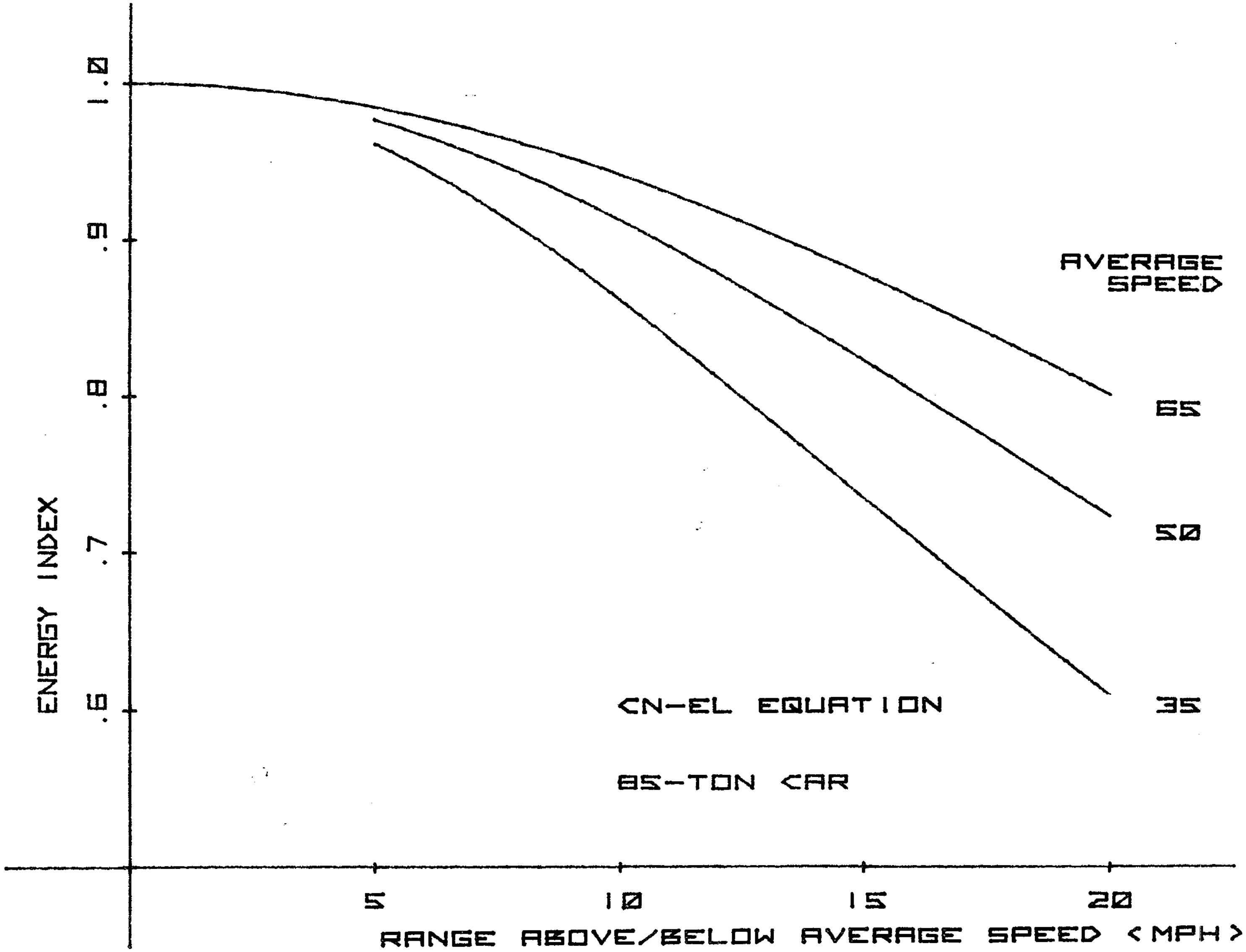

FIGURE 5-3. COMPARISON OF CONSTANT VELOCITY WITH CYCLING BETWEEN TWO VELOCITIES: 85-TON TTX CAR, CN-EL RESISTANCE EQUATION

can have a very substantial impact on fuel consumption. The work done (and hence the energy required at the drawbar) to move a train a given distance is proportional to the train resistance, which is a function of velocity. Figure 5-4 has been prepared to suggest the relative change in fuel consumption for a given change in velocity. It consists merely of a plot of the train resistance ratio R(V)/R(50 MPH) as a function of speed, for a 75-ton car using the CN equation and a 85-ton trailer-carrying car with the CN-EL formulation.* For a loaded TTX car, for example, a 20% increase in speed (from 50 to 60 MPH) increases fuel usage by over 30%. This effect is primarily due to the V-square term, and is therefore less at lower speeds and for other car types.

Thus, when one generates a nominal speed profile for the purpose of simulating a measured test run, considerable care should be used in accurate assessment of time lost through stops, since the fuel rate then is very low. For the measurements described in Section 4, average overall fuel rates have been in the range of 250 to 350 gallons per hour. (Eighth notch for 3 SD-45's is almost 600 gallons per hour.) The idle rate is 5 to 6 gallons per hour. Thus, if running time is

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*Note the relative linearity of train resistance with velocity in this range; a linear expansion about V=40 to 50 MPH is satisfactory for most analytical purposes.

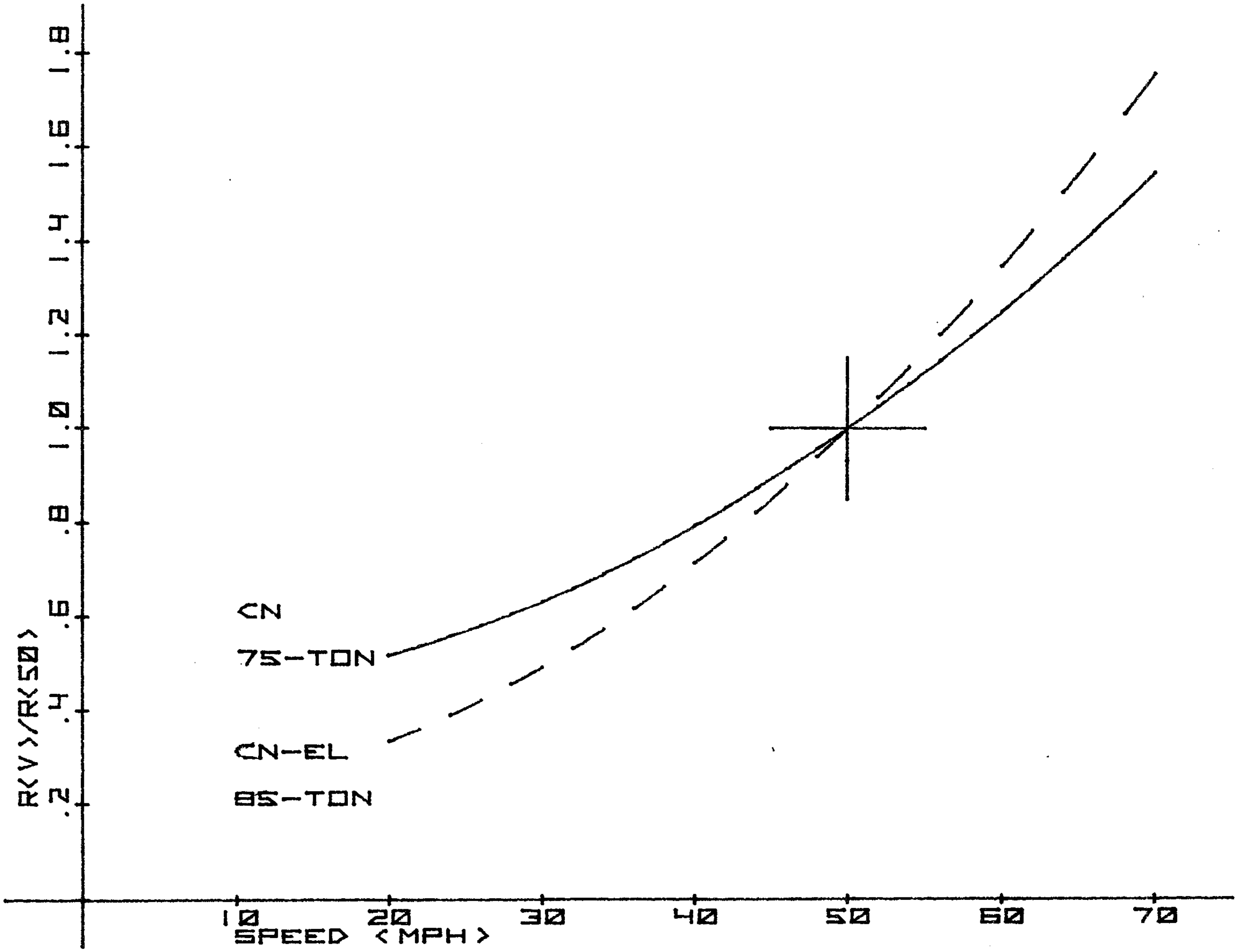

FIGURE 5-4. SENSITIVITY OF ENERGY USAGE (TRAIN RESISTANCE) TO SPEED, NORMALIZED TO 50 MPH

increased by 10% by a simple delay, the fuel used will increase approximately 1%. On the other hand, if the same net schedule change occurs because of a lowering of running speeds by 10%, one could expect a fuel usage reduction of 10% to 15%. Finally, if the lengthening is due to a shift from running at a constant speed to cycling between speeds well above and below the nominal velocity, a 5% to 15% increase might result. Accurate simulation thus requires a good understanding of the actual or proposed speed profile. A concomitant implication is that precise replication of overall run time, even for a segment, by no means guarantees that a TPC is accurate in estimating fuel consumption. Considerations of this type were responsible for elimination of a number of test runs from the comparisons described in Section 4. In these cases information concerning speed profile, and particularly stop times, was so ambiguous (or totally lacking) that meaningful simulation would not have been possible.

5.3 Fuel Consumed in Stopping

A related topic is the impact on fuel consumption of full stops from running speed. Aside from the inherent delay, a stop dissipates the train's kinetic energy; this loss represents fuel which must subsequently be used to bring the train back up to speed. In order to provide a meaningful measure of the significance of this factor, the stopping loss can be expressed in terms of the distance which the vehicle could have travelled (at the nominal speed) for the same energy expenditure. Approximate results for a simplified analysis* are plotted in Figure 5-5 for a 75-ton car (CN resistance equation) and a 85-ton loaded TTX car (CN-EL equation).

5.4 Effects of Wind

As indicated previously, it would be extremely difficult to simulate wind conditions accurately, in view of the requirements that this would impose on knowledge of actual (compass) direction of the train at all points. Further, it would be rare that adequate data would be available. Finally, freight train aerodynamics are not sufficiently well understood to provide train resistance equations in which one can confidently and accurately specify a true "aerodynamic" term. On the other hand, it is possible to consider the approximate effect of wind under the assumption of relatively constant wind and train direction. This may be a reasonable approximation in cases such as operations across the western plains. The TPS

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*This calculation is based on the equation
Change in Kinetic Energy = Work Done = Force*Distance, or (MV**2)/2 = R(V)*D, or D = (MV**2)/(2*R(V)), where D is the distance; M, the mass of the train or car; V, the velocity; and R(V), the resistance force.

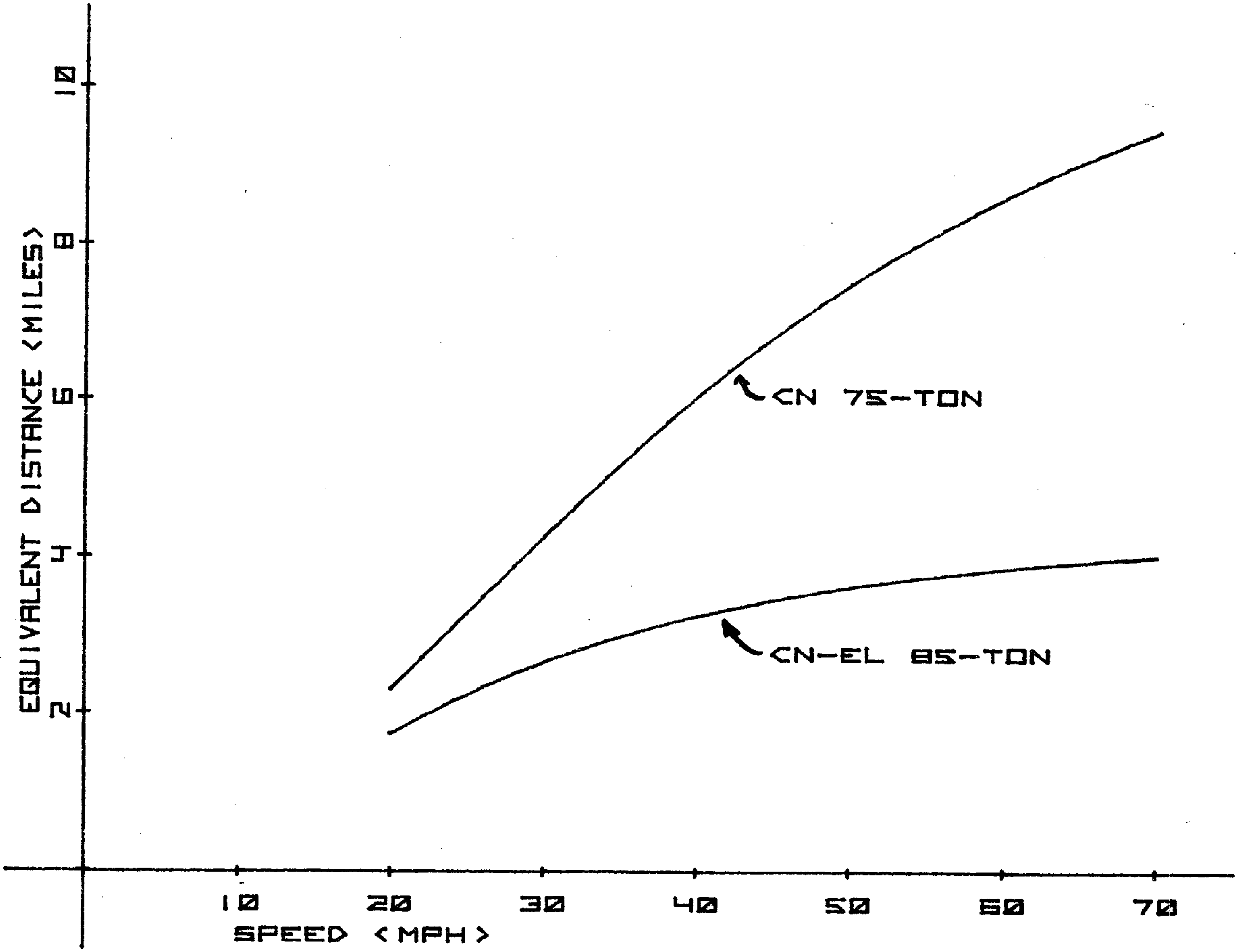

FIGURE 5-5. DISTANCE EQUIVALENT TO ENERGY LOST IN STOPPING, AS A FUNCTION OF RUNNING SPEED

treats wind by modifying the velocity used in the V-square term of the train resistance equation. Specifically, V is replaced by V+V'[sine(A)+cosine(A)], where V' is the wind velocity and A is the angle between the wind and the direction of movement of the train. Note that the additional term is thus a function of both longitudinal and lateral wind force. While far from precise, this appears to be a reasonable model for purposes of analysis, and is not in serious disagreement with more sophisticated research(10).

In the course of TSC/FRA fuel measurements, one TOFC train operating at high speed between North Platte, Nebraska and Los Angeles was monitored. High winds were encountered through much of the run, particularly in the half from North Platte to Salt Lake City. TPS simulations were performed under a variety of assumptions concerning wind; these are presented in Table 5-1. These results do not bear meaningfully upon the question of TPS accuracy; clearly one could, with judicious choice of theoretical wind, achieve almost any desired fuel usage computation. They do illustrate, if imprecisely, the magnitude of the impact which wind can have on fuel consumption. For example, an assumed 5 MPH, 30-degree wind for the entire route increases calculated consumption by almost 20%. Thus, this effect should always be considered in interpreting both measured and predicted (computed) fuel usage.

TABLE 5-1. EFFECTS OF WIND ON SIMULATED FUEL USAGE [UNION PACIFIC TEST SERIES (2)]

Assumed Wind	Actual Fuel	TPS Fuel	Difference (percent)
Westbound:			
None	13679	11952	-13
20 MPH, 30-degree North Platte to Salt Lake City	13679	14540	-6
40 MPH, 30-degree North Platte to Salt Lake City	13679	17632	28
10 MPH, 30-degree Entire Route	13679	14303	4
5 MPH, 30-degree Entire Route	13679	13083	-5
Eastbound:			
None	12888	14669	14
20 MPH, 150-degree Entire Route	12888	13178	2

5.5 Locomotive Variability

Detailed data recorded during the Santa Fe test reveal some departure from conventional TPC assumptions. Four nominally identical SD-45 locomotives were used. Yet, the fuel consumption among them varied significantly. Table 5-2 shows the total gallons for the two round trips in which all four locomotives were used, along with the percentage deviation for each one from the average of all four. Note that the highest-fuel locomotive required 14% more than that which was consumed by the lowest. It is quite possible that this corresponds not so much to differences in efficiency, as to variations in actual horsepower among the units.

Data recording the time spent in each throttle notch were also collected, and are summarized in Table 5-3 for each run. If one multiplies these values by the nominal (published) fuel rates in each notch for that model of locomotive, actual fuel consumption is found to be approximately 18% less than the throttle notch times and fuel rates would suggest. This may, at least in part, represent some limitation of the data collection process. Review of a brief portion of the measured results (1-1/4 hours continuously at eighth notch) showed a

TABLE 5-2. VARIABILITY IN LOCOMOTIVE FUEL USE [SANTA FE TEST SERIES (2)]

Locomotive Number:	1	2	3	4	Average
Fuel Used (Gallons)					
Run 1EB	3796	3701	3864	3998	3833
Run 1WB	3411	3042	3432	3565	3362
Run 3EB	3063	2782	3034	3221	3025
Run 3WB	4019	3645	4008	4189	3965
Total	14288	13169	14338	14972	14191
Deviation from Average	1%	-7%	1%	6%	

TABLE 5-3. PERCENTAGE OF TIME IN EACH THROTTLE POSITION [SANTA FE TEST SERIES (2)]

Run:	1WB	1EB	2WB	2EB	3WB	3EB
Throttle Notch						
Idle	16.5	18.1	25.0	23.8	19.1	17.6
1	2.8	5.8	3.0	4.1	3.5	4.4
2	3.4	5.5	4.6	5.2	3.5	4.8
3	2.6	4.8	4.5	6.3	3.4	5.3
4	3.0	4.2	4.5	5.8	3.5	5.9
5	3.2	3.7	4.8	6.2	2.9	4.6
6	4.1	4.3	5.7	6.8	2.9	6.1
7	2.8	3.8	4.1	6.9	2.3	5.3
8	47.5	39.4	31.4	28.0	43.2	27.2
Dyn. Brake	14.1	10.4	12.5	6.9	15.1	18.8

consumption of 177 gallons per hour per locomotive, compared to the nominal value of 194 gallons, a difference of approximately 10%. No full explanation has been sought for this effect, which is well outside the scope of this study. It is true, however, that load cell tests of nominally identical locomotives often show substantial variation of horsepower. It appears highly likely that these differences are associated more with horsepower than with fuel efficiency.

5.6 Moderate Descending Grades: A Special Case

For level terrain and normal speeds, fuel usage is approximately proportional to total train resistance. An uncertainty in only one coefficient in the equation, such as the aerodynamic (V-square) term, will produce a less than proportional change in consumption. On ascending grades, the gravity component will tend to be the dominant effect, so that a moderately inaccurate train resistance equation will have little impact on overall precision. For typical speeds and trains, the gravity term becomes comparable to the other components at .2% to .3% grade. For steep downgrades, train resistance is irrelevant, since brakes will be required in any event. However, on moderate descending grades a special situation arises which renders fuel usage calculations highly sensitive to grade. In this case, for which the gravity term is negative, the net train resistance will become negative for a grade of .2% to .3%. This net resistance is determined by the difference of two reasonably large numbers: (1) the sum of the level-terrain resistance terms, and (2) the gravity term. The relative or percentage change in net nominal (level) resistance which arises from a small error in the nominal resistance can thus be very large. This is illustrated in Figure 5-6, prepared for a loaded 85-ton TTX car at 55 MPH, for two different assumed values of CN-EL aerodynamic coefficient (representing changes of 10% and 25%); the base case assumes the conventional value of k=.16, rather than the .20 generally used for simulations in this study. Due to the fuel usage of the idling engine, consumption does not become zero for zero train resistance, so the impact on relative energy use is not so dramatic as suggested in Figure 5-6, but nonetheless a major discrepancy can arise.

The situation is more than an academic anomaly. The Santa Fe route segment from Gallup to Winslow (segment 8) is a relatively constant descent (westbound) for 128 miles; the average grade is .24%. For the third run in the TSC test series -- the only Santa Fe run involving a boxcar consist -- CN and Davis equation simulations were compared. For the overall run, the Davis version resulted in calculated fuel usage 24% greater than that for the the CN case -- a difference

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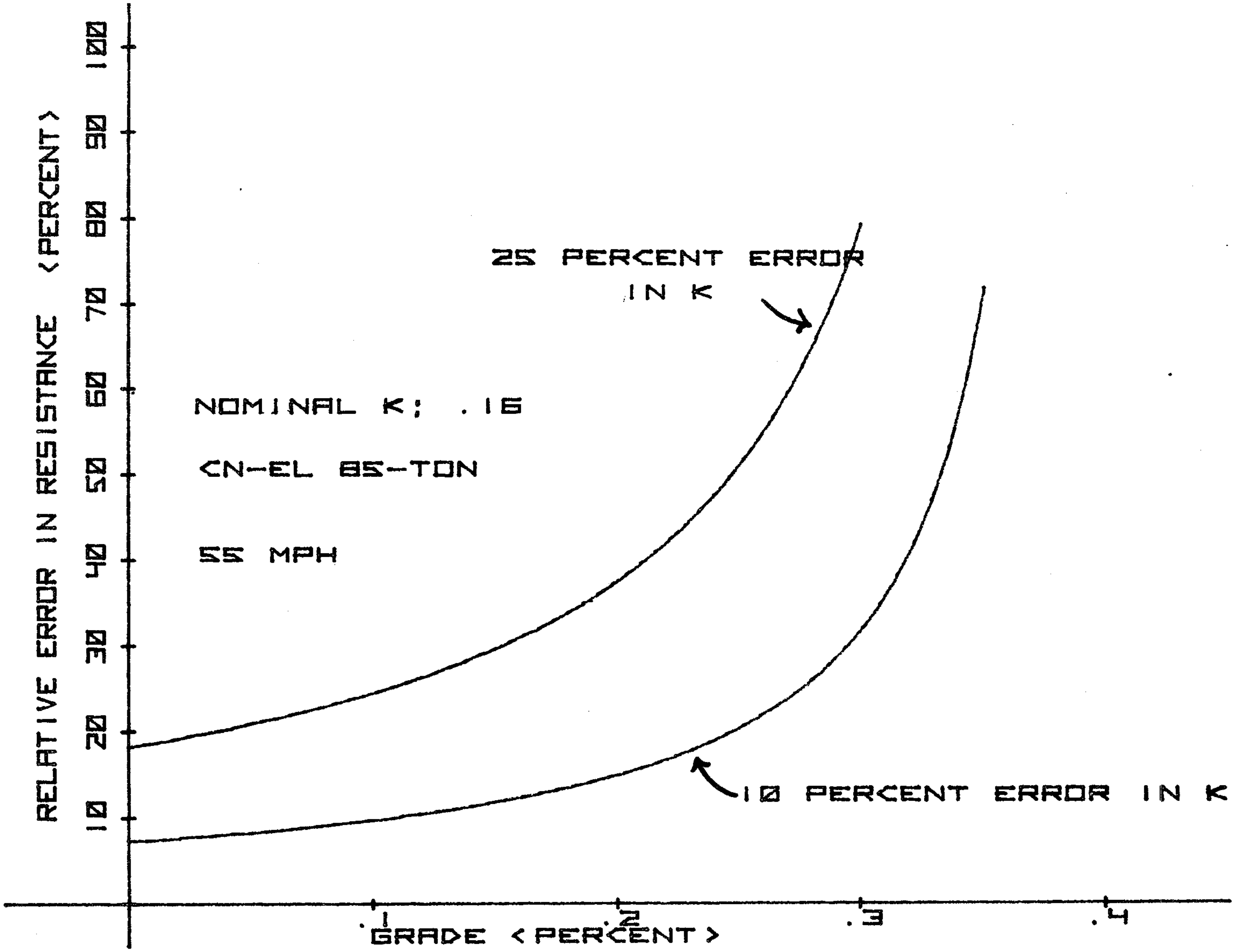

FIGURE 5-6. SENSITIVITY OF TOTAL TRAIN RESISTANCE TO ERROR IN K-VALUE, AS A FUNCTION OF GRADE

of more than 300%. The value actually measured was 405 gallons. A dynamic brake fuel usage correction would add approximately 25 gallons to the TPS CN result. The throttle-notch summary confirmed what was happening; the train simulated according to the Davis equation was predominantly in sixth through eighth notch (72% of the time), while the CN calculation showed primarily second and third notch (60%). When the CN resistance equation was modified by increasing the aerodynamic coefficient from .07 to .08, the calculated fuel usage increased by 16%, to 382 gallons.

It should be emphasized that this problem arises only when a major portion of a route consists of moderate downgrade. Otherwise, the high relative error is diminished in importance by the fact that a small absolute quantity of fuel is consumed in descending movements. In the Santa Fe example, that segment represented about 7% of the route mileage, but required only 3% of the total measured fuel used on the run.

The dynamic brake question discussed in Section 3.2.4. is relevant here, as for any segment which is largely descent. The additional fuel used during dynamic braking can be a substantial portion of the total required under these circumstances.

5.7 Coasting vs. Constant Speed in Rolling Terrain

In rolling terrain, yet another problem arises. A train could be operated, power permitting, at a constant velocity (such as the speed limit) down a descent (requiring substantial braking) and up the following ascent (with power applied). Alternatively, the train could be allowed to accelerate under gravity on the downgrade, and then coast part or all of the way up the subsequent hill. Insight into the implications of this situation can be gained through analysis of two simplified scenarios. The first is that of constant velocity, with brakes applied on the downgrade and sufficient power to maintain speed for the ascent. The energy per ton necessary to overcome total train resistance (including gravity) is the ascending train resistance multiplied by the ascent distance, since no energy need be supplied on the descent. If both grades are of distance D and gradient S, with train velocity V, the energy (per ton) is given by*:

$$[R(V) + 20*S]*D$$

One can think of the coasting mode as requiring sufficient power to overcome train resistance at all times on both segments (both down and up), while the gravitational energy is merely transformed through acceleration and deceleration from

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*For simplicity of expression, R is here normalized to represent the resistance force, without gravity, per ton of vehicle weight, rather than the total force as in Section 2.

potential energy at the top to kinetic energy at the bottom and back to potential energy again. For this symmetric case the gravity component cancels out insofar as the power requirements are concerned. In a more realistic model no power would be applied on the descent, with some potential energy going not into increased kinetic energy, but rather into overcoming train resistance. However, an equal amount of energy would then have to be supplied on the ascent, so the situation is nearly equivalent. Thus for the coasting scenario, the energy provided per ton is

$$\int_0^D R(v)*dx + \int_0^D R(v)*dx$$

Since acceleration is constant the average velocity V is well approximated by

$$V=(V' + V'')/2,$$

where V" and V' are the speeds at the top and bottom of the grades. R(V) is nearly linear in this range, so that R(v) can be removed from the integral as the constant R(V), and the ratio of the energy required for constant velocity to energy for coasting can be expressed as

$$[R(V) + 20*S]/[2*R(V)],$$

or

$$.5 + 10*S/R(V),$$

with S in percent and R(V) in pounds per ton. (Note that the distance D cancels out.) The difference between the two cases is basically the energy lost in downgrade braking in the constant-velocity mode. R(V) is typically in the range of 4 to 8 pounds per ton, so for a 1% grade the constant-velocity case will require about 1.7 to 3 times as much energy. For a .5% grade the differential is a factor of 1.1 to 2.

This simple analysis does not include the idling fuel consumed on the downgrade for the second scenario, which would produce a fuel ratio lower (closer to unity) than the energy ratio determined above. On the other hand, the constant-velocity case may utilize dynamic brake, which also entails a significant fuel penalty. Also, if average speeds are to be equal, there is an implication of significant operation above the nominal speed limit for the coasting mode. Nevertheless, it is clear that for route segments which are suitable to this possibility, the choice made by the engineer will have substantial impact upon fuel usage.

Use of the coasting mode is limited by the acceptable minimum and maximum speeds V' and V". Simple recourse to the law of conservation of energy [change of kinetic energy equals change of potential energy (mgh = mgD*S)] plus necessary conversion of units yields the result that

(V"**2 - V'**2) = 1627*D*S,

with speeds in miles per hour and distance D in miles. This permits calculation of the maximum distance over which coasting can be applied without violating the speed constraints. For example, if V" = 50 and V' = 60, D*S = .55, and D will be 1.1 miles for a .5% grade. In a more extreme case, if V" is allowed to drop to 35 MPH and V' to reach 65 MPH, D would be 3.7 miles for a .5% grade or 1.84 miles for a 1% grade. (Recall that D is half the total descent-ascent distance.)

Some experimental confirmation of the effect of coasting is available. In the Santa Fe tests (Section 4.6), distinctly different operating modes were used on Runs 1 and 2. On the first run, a velocity of 70 MPH was maintained wherever permitted by speed limits and available power. On the second run, power was not applied above 55 MPH, but gravity-assisted "drifting" to 70 MPH was allowed where possible. This latter case showed a 9% lower average velocity, accompanied by a 14% reduction in fuel used per gross trailing ton mile.

A similar ambiguity exists for general replacement of level-terrain braking by coasting for stops or severe speed reductions, but this is a relatively minor situation in rail freight operations, primarily because of schedule implications. To the degree that it does occur for moderate decelerations, the impact on fuel usage will normally be quite small.

5.8 Effect of Curves

Many of the simulations described in this report did not include the effect of track curvature on train resistance. The magnitude of the error which this introduces should therefore be assessed. The commonly accepted value for curve-related train resistance is .8 pounds per ton per degree of curvature. A 1-degree curve, for normal speeds and consists, thus increases the total resistance force by approximately 10% to 20% over the level-terrain value. On grades, where curves are common, the gravity component (20 pounds per ton per percent grade) dominates, so that the relative error introduced is quite small. For the primarily tangent track which characterized most of the TSC tests omission of curves from the simulation can produce a limited but detectable effect. Examination of track charts for relevant routes indicates that curves are commonly of the order of 1 degree, occurring for from 5% to over 50% of a route segment. If one allows for the reduced impact in grade territory, and assumes an overall effective occurrence for 10% to 15% of the route, the average contribution to train resistance (and hence to fuel usage) will be approximately 2%. For lower speeds or a route with many curves, the impact could rise to 5% to 10%, and might explain some of the discrepancies for particular run segments in the Santa Fe tests.

6. CONCLUSIONS

6.1 Summary of Findings

Overall results for each test series and each consist type are presented in Table 6-1. For the overall project, on a fuel-weighted basis, the TPS calculations are only 2.2% below measured consumption; if one weights each test series equally, the overall average error is -3.0%. In addition to the many uncontrolled or unknown elements of the test situations, which contributed a variability of approximately plus-or-minus 10% to 15% within each test series, several systematic errors have been identified in the preceding sections for which an estimated correction is possible. For the Santa Fe runs only, regular use of dynamic brake is estimated to increase fuel usage approximately 2% above that calculated by the TPS in its present form. For all runs except Southern Pacific, absence of track curvature data is assumed to produce an underestimation of fuel consumption of approximately 2% also. For branchline operations, TPS estimates tend to be low by approximately 30%. This is judged to result from the higher mechanical train resistance associated with track structures common to branchlines and the special short-haul nature of such operations.

TABLE 6-1. SUMMARY OF MEASUREMENT/TPS COMPARISON RESULTS

Test Series	Fuel Used (Actual Gallons)	Fuel Used (TPS Gallons)	Deviation (%)
Burlington Northern	146505	143925	-1.8
Southern Pacific	15916	15136	-4.9
Santa Fe	70887	69184	-2.4
All TOFC	195130	194202	-.5
All Boxcar	34198	30339	-11.3
Overall Total	233308	228245	-2.2

These comparisons indicate that a small modification to the commonly used train resistance equations may be appropriate for fuel usage simulation purposes. This is discussed in section 6.2.2. The suggested changes would reduce the CN-EL (TOFC) aerodynamics term by 12% (compared to the TPS version of the CN-EL form) and increase the boxcar aerodynamic term by 29%. At a nominal speed of 45 MPH, for an 85-ton loaded TTX car this implies an 8% lower train resistance force on level terrain. For a 75-ton box car, the increase is 14%. At lower speeds and for grades, one finds that there is generally a change in calculated fuel use of about 5% to 6% for both TOFC and boxcar trains. The combined effect of corrections for curvature, dynamic braking, and the modified train resistance equations is to produce only a small change in the difference between TPS calculations and measurements, since the corrections tend to balance one another.

6.2 Basic Validity of the Simulation

6.2.1 General Comments

The TPS simulations, when aggregated over a series of runs, show a high degree of accuracy -- deviations are typically less than a few percent. Thus, the fundamental validity of the model appears to be well established. Since the major sources of uncertainty -- speed profiles and power braking -- are likely to increase fuel usage, the general TPS underestimation, based on an idealized model, is not unreasonable. It is also possible that the 2% correction for curvature should be slightly larger. Finally, a systematic offset could occur through a small underestimate of locomotive mechanical or energy conversion efficiency, or in the constant and linear terms in the resistance equations.

The substantial variability found when specific runs or run segments are considered (deviations can be greater than 15%) can be assigned to a combination of real-world variability, ambiguities in the manner in which a train may be operated, and limited data concerning the equipment (i.e, aerodynamic drag) or operations (i.e, speed profiles). In general, the physical and human variability appears to have at least as great an impact upon measured results as on simulations. Deviations (in gross trailing ton miles per gallon) were even greater within sets of measured data than for TPS/actual comparisons. In other words, even a series of measurements will generally provide no greater precision in prediction of fuel usage (or running schedule) than will a simulation. In essence, the most critical uncertainties are associated with speed profiles and how they are produced. The simple analyses in Section 5 show the potential for introduction of substantial discepancies into results through

(1) cycling of speed (when the simulation uses average values), (2) uncertainties in dwell time at stops, and (3) use of coasting in rolling terrain. Dynamic and power braking can also introduce effects of significant magnitude that require exceedingly detailed information for successful modeling. Indeed, in view of these many pitfalls, it is almost surprising to find the high degree of success obtained with the TPS. It is particularly noteworthy that essentially equivalent results were found in the Santa Fe and Southern Pacific tests for the boxcar trains, in spite of the great difference in terrain, speeds, and power-to-weight ratios.

Most of these comments apply to general routes and scenarios. A specific case may have special features associated with it which will affect the validity of the simulation. For a route consisting primarily of a steep ascending grade, the major work done is the addition of gravitational potential energy to the train which completely dominates other aspects of train resistance. In this case, accuracy should be particularly good. On the other hand, simulations for steady moderate downgrades are highly sensitive to the resistance equation coefficients. Strong winds, especially for TOFC trains, can be a major factor. Predominantly rolling terrain injects the uncertainties of dynamic and power braking, coasting, and the problems associated with moderate grades. Frequent stops or other speed variations can be difficult to accommodate in a precise manner.

Some refinements to the TPS could increase accuracy somewhat. One is the use of specific aerodynamic characteristics for each car, taking car order into consideration. However, it is not clear at the present time whether existing data are adequate to warrant this level of detail. Other possible modifications, such as provision for dynamic braking, draw one into the problem of determining an algorithm that represents the manner in which a train may actually be operated. In sum, it appears that significant improvements are possible through this approach only for the treatment of special applications.

6.2.2 Train Resistance Equations -

To the degree that a pattern can be discerned in the comparison results, one finds that the simulation has a distinct tendency to overestimate fuel usage for TOFC trains and to underestimate fuel usage for boxcar trains. This effect is particularly evident in the Southern Pacific tests, where mixed-consist trains were simulated with an accuracy intermediate to that for the other two types. However, a similar effect is observed for the Santa Fe tests. Fuel usage was underestimated for every segment of the boxcar operations simulations may be preferable for resolution of a particular problem.

Similarly, certain applications may require less precision in train performance matters, but even greater sophistication concerning special aspects. For example, precise simulation of electrified railroads would require a substantially more complex locomotive model (including attention to thermal ratings and time constants) and raises questions concerning substation locations, line voltage drops, etc. Highly accurate simulation of the dynamic response of the train to braking, grades, etc, is more properly accomplished with the Train Operation Simulation developed by the Association of American Railroads. However, for the wide range of problems and questions for which a train performance calculator is appropriate, the TPS has been found to be an effective and accurate tool.

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