REPORT NO. FRA-OR&D-75-74.I

PB-244150

RAILROADS AND THE ENVIRONMENT - ESTIMATION OF FUEL CONSUMPTION IN RAIL TRANSPORTATION
Volume I - Analytical Model

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MAY 1975

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL RAILROAD ADMINISTRATION
Office of Research and Development
Washington DC 20590

Technical Report Documentation Page

1. Report No. FRA-OR&D-75-74.I	2. Government Accession No.
PB-244150	
4. Title and Subtitle RAILROADS AND THE ENVIRONMENT - ESTIMATION OF FUEL CONSUMPTION IN RAIL TRANSPORTATION Volume I - Analytical Model	5. Report Date May 1975
	6. Performing Organization Code
7. Author(s) John B. Hopkins	8. Performing Organization Report No. DOT-TSC-FRA-75-16.I
9. Performing Organization Name and Address U.S. Department of Transportation Transportation Systems Center Kendall Square Cambridge MA 02142	10. Work Unit No. (TRAIS) RR516/R5302
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Railroad Administration Office of Research and Development Washington DC 20590	13. Type of Report and Period Covered Final Report November 1973 - October 1974
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report describes an analytical approach to estimation of fuel consumption in rail transportation, and provides sample computer calculations suggesting the sensitivity of fuel usage to various parameters. The model used is based upon careful deliniation of the relevant physical mechanisms of energy dissipation under steady-state conditions - rolling and aerodynamic resistance (using the Davis equations), braking, idling, and locomotive power generation and conversion losses. Both simple and more complex formulations are applied as appropriate. Several classes of service are considered: branch line freight, intercity freight, conventional and high-speed passenger, and commuter. Numerous graphs illustrate typical results for specific fuel consumption as a function of speed, grade, power/weight, load factor, weight per seat, etc.

17. Key Words Fuel Consumption Rail Transportation Energy Usage	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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PREFACE

The work described in this report was performed in the context of an overall program at the Transportation Systems Center to provide a technical basis for the improvement of railroad transportation service sponsored by the Federal Railroad Administration Office of Research and Development.

The first volume of this study will be followed by a second volume devoted to validation of the analytical model. Emperical data obtained under controlled conditions, where possible, will be utilized in the calibration process.

This work has benefited from frequent discussions with Dr. K. Hergenrother, particularly concerning computer modeling and diesel engine characteristics. A. Newfell was most helpful in obtaining certain basic data, and M. Hazel made a major contribution in developing the basic equations used in the computations, as described in the Appendix.

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1. INTRODUCTION

1.1 OBJECTIVES AND SCOPE

Estimation of the energy consumption of various forms of rail transportation has generally been based upon calculation of overall averages from ICC and other transportation and fuel usage figures, or from very simple models of rail operations.[1,2,3,4,5,6] Although basically legitimate, these estimates are typically so general as to provide relatively little guidance for analysis of specific categories or situations. The approach followed in the study reported here is intended to complement these macroscopic calculations through theoretical computation of the energy inherently required for specific transportation operations. Application of this formulation to a wide variety of cases can then provide a good measure of both average fuel consumption and sensitivity of energy requirements to a large number of operating parameters. This analytical approach to a complex process, even when validated with empirical data, can at best achieve only limited precision. However, in addition to the utility of reasonable approximations, the determination of sensitivity to various relevant factors can be of particular value in extrapolating from actual cases and in attempting to make modal comparisons in specific situations. This of particular relevance to projections of the future, for which changes in technology and operations must be considered.

1.2 APPROACH

The approach taken here is based upon identification and quantification of the major energy consumption elements of rail transportation. A precise treatment of such problems would necessarily include many parameters of the overall system, with detailed specification of their interrelationships. Relatively elaborate computer simulations exist and are in use by many railroads to carry out train performance calculations as required. However, the more important loss mechanisms are sufficiently well understood and dependent on a small enough number of parameters to make possible a relatively simple formulation which can provide both general insight and meaningful estimation for particular cases.

Energy is inherently dissipated through several direct mechanisms: wheel-rail interaction, bearing friction, and aerodynamic drag. Normal operations typically include periodic use of brakes, which adds to energy consumption. The major portion of the energy required in transportation of cargo or passengers from one point to another is consumed in the steady-state line-haul portion of the cycle, with generally small additional components for engine idle time and energy lost in braking. These are the elements included in this analysis.

Given determination of the required expenditure of energy, it is then necessary to consider the efficiency with which fuel is converted to energy under various circumstances, including losses in power generation and transmission. The well-understood nature and relative constancy of the efficiency of diesel engines (as a function of load) makes this task comparatively simple.

1.3 TOPICS CONSIDERED

The initial motivation for this analysis was the desire to achieve a valid case-specific comparison between rail and highway transportation in situations for which abandonment of rail service might be considered. The special nature of such cases - particularly the light loads and short distance - render meaningless the utilization of gross averages. The necessary comparison requires estimation of both train and truck fuel consumption, with allowance for differences in distance, grades, speeds, vehicle idle time, etc. Section 2 of this report provides an outline of the basic energy consumption model used for all cases considered, and Section 3 details the application of the analysis to the potential abandonment case.

Rail passenger service is addressed in Section 5. The basic computational model is applied directly to conventional rail passenger service, following the same approach as for line-haul freight. In the absence of detailed readily available published system fuel consumption data for revenue operations, energy intensiveness of special high speed passenger trains has been estimated more crudely, but still with sufficient accuracy to be meaningful. (Operating data of sufficient specificity is seldom collected and rarely published.) Finally, the basic model is used to estimate comsumption in commuter rail operations.

In Section 4 the model is applied to general line-haul freight service, with emphasis upon development of a simple formulation for general use and examination of the sensitivity of fuel usage to operating parameters such as motive power (HP/gross ton), train size, speed, grades, etc.

1.4 MODAL COMPARISONS

A common use of average figures for fuel consumption is for comparison among alternative modes of transportation. A few comments are appropriate concerning possible pitfalls or errors in this application. One important element is circuity - the difference between a direct route and the one actually taken. Rail and highway milage between two points can easily differ by 10% to 20%; rail routes are often as much as 50% shorter than waterway distance, but can be longer. Similarly, in any specific case one must use care to account for the velocities, load factors, operating practices, etc. actually involved, which may differ from those upon which the "average" values are computed. Although it may often prove convenient to attempt to characterize modes by a single value for energy intensiveness, in specific cases such numbers must be used with great care to avoid serious error. Finally, the changes in fuel usage resulting from shifts in technology and operating conditions, particularly as reduction of fuel cost becomes of greater importance, can make present numbers invalid for future projections.

Rail freight operations appear to be close to optimal in terms of energy intensiveness, but changes in speeds, power-to-weight ratios, locomotive design, and rolling stock weight and aerodynamics could generate significant improvements. However, the more dramatic impact, in terms of national transportation energy usage, would be obtained through modal shifts; in 1970 railroads moved 39% of inter-city ton-miles with 15% of the fuel required in that category. (Overall, the rail mode consumes less than 4% of the energy resources devoted to transportation in the U.S.)

2. THE BASIC MODEL

2.1 INTRODUCTION

Precise calculations of transportation fuel consumption are generally based upon an iterative approach in which total power loading is determined, motive power is applied (according to some specified criterion), and movement, speed, and acceleration calculated, at time t, and assumed to apply for some small time interval, t_o. The computations are then repeated for a time $t + t_o$, with appropriately modified "initial" conditions, providing new values for the period $t + t_o$ to $t + 2t_o$. This process is repeated for the entire time period of interest. For specified operating equipment and conditions, accuracy is limited only by the precision and completeness of the physical model. This method has generally been applied to obtain highly specific information concerning particular rail and highway operations - train performance over a given route, or optimization of truck transmission ratios. However, the purpose of the present analysis does not warrant a model of this degree of elaboration. Instead, a much simpler course has been chosen. Transportation operations are separated into steady state segments, constant speed, constant grade, etc. - and the fuel consumption for the various elements is summed. The energy acquired by the vehicle during acceleration is accounted for when dissipated during brake application. This approach would be quite unsatisfactory for an urban motor-vehicle driving cycle, which involves more transient than steady state operation. However, for line-haul operations in general, and rail transportation in particular, a summation of steady-state consumption is quite adequate. (A more precise treatment of the acceleration situation is given in the appendix. However, it has not been deemed necessary to use this refinement in the following chapters.)

In the following sections, the basic framework and assumptions of the model will be described. Details of the equations used, and certain derivations, have been included as an Appendix. The resulting basic fuel consumption equation is given at the end of this chapter. Calculations and results shown in Chapters III - V are obtained through application of this equation, embodied in several specific computer programs which facilitate examination of various implications of numerous cases. The analysis which follows includes considerations relevant to trucks (and readily applied to buses), as this was necessary for the abandonment study. These equations are usable for line-haul freight and passenger comparisons. However, due to the relatively precise knowledge and models which already exist for truck and bus operations, it has not been judged appropriate to address that topic here.

2.2 LINE HAUL ENERGY

The fuel consumed under steady-state level-terrain conditions is dissipated primarily through resistive forces (energy expenditure rate proportional to velocity); these may be calculated from the Davis equation for rail and similar expressions for motor carriers. A large number of relevant parameters must be specified: locomotive, freight car, caboose, and motor vehicle weight; velocity for each mode; distance; load factors; and details of the size and characteristics of the engines and vehicles. This determines the basic minimum energy required. To this must be added contributions associated with grades, braking, and idling, and appropriate engine fuel efficiency factors must be included for each circumstance.

2.3 GRADES

It is difficult to accommodate the effect of grades without requiring such specific route knowledge as to destroy any generality. However, the subject can be approached with sufficient accuracy for most cases through assumption of one of two alternatives:

(1) Constant Energy. For this case it is assumed that the freight carrier, initially traveling at velocity v, ascends a grade with no increase in engine output power, climbing through conversion of kinetic energy ($mv^2/2$) into gravitational potential energy (mgp), with concomitant decrease in speed. Upon descent, the potential energy is reconverted into kinetic energy (increasing the speed), and (if there is no net change in elevation) no excess energy is consumed. Indeed, the reduction of speed will reduce aerodynamic losses.

(2) Constant Velocity. An alternative mode of operation is application of sufficient additional power on the upgrade, and braking on descent, to maintain constant velocity. In this case, the added potential energy is totally dissipated by the brakes on descent, and thereby lost.

Case (1) is commonly the situation for large trucks, particularly on interstate highways, where the vehicle may be operated at full throttle constantly; slowing down on upgrades and regaining speed on descent. Case (2) is more likely to apply for rail transport, particularly for trains for which a substantial reserve of power is available and operating speeds (often limited by track conditions) are low. For Case (1), grades have no major effect on specific energy consumption, and can be omitted here. Case (2), on the other hand, is included with relative ease. Note that the factor of interest is only the decrease in elevation for which there is descent under braking. This energy loss can be incorporated through determination of the potential energy (per ton of cargo) lost during such a constant velocity descent. Care must be taken to determine the locomotive fuel consumption separately for both ascending and descending, as the overall fuel-to-tractive effort efficiency will vary considerably for the differing load conditions. This effect is incorporated in the formulation described here.

The situation in which part of the train is ascending while another part is descending is not specifically included. It has no major impact for the Case (1) mode, and tends to reduce the total energy consumption in Case (2). For this latter circumstance, the effect can be accommodated by considering the changes in elevation to be the variations for the center of mass of the train, rather than the values associated with the actual topography.

2.4 CURVES

Inclusion of the effect of track curvature is somewhat more complex than is the case for grades, and detailed integration of the loss mechanisms over the entire route would be necessary for an accurate measure. However, approximation is again possible.

The primary effect of curved track is an increase in rolling resistance, which simply implies different coefficients in the expression for line-haul losses. In normal railroad engineering practice, this is included in terms of an "equivalent grade" - i.e., a slope of sufficient incline to require the additional force necessitated by the curvature in question. This is the course followed here.

2.5 ENGINE

Diesel engines of the type used in large trucks, buses, and locomotives operate over a very wide range of output power at nearly constant basic efficiency. (The diesel-electric energy transmission process is somewhat less efficient than the mechanical truck transmission.) For the situations of interest in Chapter III of this study, the locomotive may be operating at a few percent of rated power. In this case, the power associated with tractive efforts dips to a level comparable to the normal losses in the engine - those present under idle conditions, which, in fact, absorb the power generated at idle. A simple but reasonably accurate model for this situation leads to a direct expression for overall fuel efficiency f, as a function of x, the required horsepower (expressed as a percentage of the rated horsepower of the locomotive in use):

$$f = x/(g_i + g_o x), \quad \text{with } x = \frac{\text{required power}}{\text{rated locomotive power}}$$

where g_i is the fuel consumption rate at idle (normalized to rated horsepower), and g_o is the consumption per horsepower-hour. Thus, to obtain the appropriate value of fuel efficiency f (hp-hr/lb of fuel), one must first evaluate the steady-state power requirement for the train in question and divide that number by the rated horsepower of the locomotive(s) in use.

This factor, which is a function of the percentage of rated power required, will be different for the various operating conditions which have been discussed: steady operation on level terrain, hills, curves, stops, etc. (Note that the energy lost in braking is imparted to the train during acceleration or grade-climbing, and the appropriate f-factor must be used.)

An additional element must be considered. The generator/motor transmission of power from the diesel engine to the wheels involves a significant loss of energy. For the region of operation typically encountered, an efficiency of 80% is a reasonable estimate.

This low-load situation does not occur for trucks, permitting use of a constant factor. For the purposes of this treatment, f = 2.5 hp-hr/lb is an adequately accurate value. The mechanical transmission used represents a near-neglible energy loss; the efficiency is 95-97%. However, trucks also must be charged with additional loss of 15-25 HP typically, for operation of accessories - fan, water pumps, air conditioning, etc. For the calculations in this report, this latter factor is approximated by including an additional consumption during operation equal to twice the idle consumption rates.

2.6 IDLE CONDITIONS

It is common practice, for a number of reasons, to operate diesel locomotives continuously, which may imply idling for a large portion of the time. (A typical line-haul cycle includes 43% idle, and a common switcher cycle assumes 77%.) In order to add this term to the fuel calculation, the fuel consumption at idle, f_i, is simply multiplied by the hours of idle time per run, t_i. If f_i is not known specifically, a reasonable approximation is f_i(lbs/hr) = .0150 x (rated horsepower) for the locomotive in use.

This term is also included for trucks. However, because of the relatively short idle periods they normally undergo, as well as the low ratio of idle fuel consumption to over-the-road consumption common to this case (unlike the situation for lightly loaded trains), it is generally a small contribution.

2.7 TERMINAL AREA STOPS

The terminal area is here taken as that portion of the route subject to congestion, stops, accelerations, and other manuevers associated with final delivery of the cargo. For rail movements, this includes all train assembly operations. However, the distances and speeds involved in switching moves, especially for short trains, requires so little energy that they are best considered equivalent to idling for the same time period and added into that factor. (Deceleration of the train from line-haul velocity - a relatively unimportant factor in normal operations - can be of special significance for short, low-payload runs.) It is readily shown that normal stops involve dissipation of nearly all kinetic energy ($mv^2/2$) through braking, with very little lost in rolling friction or aerodynamic drag. Thus, the means chosen here for inclusion of this factor is consideration of the total terminal and stopping energy expenditure as equal to $mv^2/2$ for each stop, including those in the line-haul portion of the run. (The appropriate fuel efficiency term is that associated with the initial acceleration period - normally assumed to occur at full power.)

This approach is equally valid for trucks. However, one must account for the sequence of stops normally associated with entering or leaving a town or city by highway. The methodology suggested here is that this component of the trip be taken as a set of n_b decelerations from some terminal-area velocity v_{bt}, with subsequent acceleration to full speed.

2.8 ROUND-TRIP CONSIDERATIONS

Transport of freight from point A to point B may require that the vehicle involved return empty. This is rather less likely in the case of trucks, which have greater flexibility in picking up a return load, but it will often be the case that there is not an equal distribution of cargo in both directions. It can readily be shown that this can generally be accommodated with good accuracy simply through multiplying the basic equation for fuel consumption by two, utilizing as load factor the average for both directions. (When detailed information as to route topography and driving cycle is available, it is appropriate to calculate consumption separately for the various segments, summing them to obtain a final result.) Grades, however, are best treated separately.

As shown in the Appendix, the formulation described above can be expressed as a general equation for carrier fuel consumption. F, the total required diesel fuel, is given below, for both rail and highway modes, followed by a list of the parameters required. A brief discussion of the source of each term is included as an Appendix. Total rail fuel use is then calculated as $F_{R1} + F_{R2}$, and highway as $(F_{H1} + F_{H2}) \times N_t$, where the subscripts indicate Rail or Highway, and outgoing (1) or return (2). N_t is the number of trucks required.

$$F = \sum_{\substack{\text{All} \\ \text{Level} \\ \text{Elements} \\ i}}^{n} \frac{d_{1i}}{V_{1i}} \left[R_I + \frac{r_o V_{1i}}{375 r_e} R_o(V_{1i}) \right] \qquad \text{Line Haul Component}$$

$$+ \sum_{\substack{\text{All} \\ \text{Grade} \\ \text{Sections} \\ i}}^{n} \frac{d_{gi}}{V_{gi}} \left\{ R_I + \frac{r_o V_{gi}}{375 r_e} \left[R_o(V_{gi}) + 20 W_t S_i \right] \right\} \qquad \text{Grade Component}$$

$$+ \sum_{\substack{\text{All} \\ \text{Braking} \\ \text{Elements} \\ i}}^{n} 3.37 \times 10^{-5} \frac{N_{bi} W_t V_{bi}^{2}}{r_e} \left[\frac{R_I}{P_m} + r_e \right] \qquad \text{Stopping Component}$$

$$+ t_I f_I \qquad \text{Idling Component}$$

$$\text{With } R_o(V) = \sum_{\substack{\text{All Loco} \\ \text{\& Cars} \\ i}}^{n} P_i(V) \quad (n = 1 \text{ for trucks})$$

$$R_I = \left[1 + r_a\right] f_i$$

In the grade component term if, on descent

$$S_i < - \frac{R_o(V_{gi})}{20W_t}$$

Then the second term becomes:

$$\sum_{\substack{\text{All} \\ \text{Grade} \\ \text{Sections} \\ i}}^{n} \frac{d_{gi} R_I}{V_{gi}}$$

Parameters used in the equation for F are as follows:

Parameter	Physical Meaning	Units
d_{li}	distance on i^{th} level terrain	miles
V_{li}	velocity on i^{th} level terrain	miles/hour
d_{gi}	distance on i^{th} grade section	miles
V_{gi}	velocity on i^{th} grade section	miles/hour
f_i	fuel consumption at idle	lbs/hour
N_{bi}	i^{th} brake applications	miles/hour
V_{bi}	velocity change of i^{th} brake application	miles/hour
P_m	rated engine power (gross)	hp
r_a	ratio of power absorbed by accessories to power generated at idle*	
r_e	transmission efficiency**	
r_o	basic fuel/energy conversion efficiency***	

*Generally taken as 0 for trains, 2 for trucks.
**Generally taken as .95 for trucks, .8 for locomotives
***Generally taken as .34 lbs/hp-hr (diesel fuel)

Parameter	Physical Meaning	Units
s_i	slope (grade of i^{th} grade section)	percent
t_I	time at idle	hours
W_t	total weight	tons
W_v	weight of vehicle	tons
( )	function of	

For each vehicle (locomotive, car, truck),

$$P_i(V_i) = A + BW_v + CV_iW_v + DV_i + EV_i^2$$

A,B,C,D, and E are functions of vehicle characteristics and (for rail) location in train. The high-speed values used here, summarized in Table 2-1, are based upon numerical approximation to the experimental curves of Totten,[7] as presented in Hay.[8] Those developed by Davis[9] from Schmidt's data[10] are used for low speeds. The source of these coefficients, with comments upon their accuracy, will be found in the Appendix.

TABLE 2-1. COEFFICIENTS FOR VEHICLE RESISTANCE EQUATION

Vehicle	A	B	C	D	E
Freight car, caboose (low speed)	116	1.3	.045	0	.045
Freight car, caboose (high speed)	195	3.48	0.	-14.9	.362
Passenger Car	139	1.56	.023	0	.056
First locomotive	116	1.3	.03	0	.264
Additional Locomotives	116	1.3	.03	0	.045
Truck	0	13.5	.15	0	.21

In the previous full expression for F, note that R_I term adds a fixed component of fuel consumption for both level and grade operation. Thus, the net efficiency is determined by this fixed amount and by the fuel requirement for moving the train. The latter quantity is determined by the speed and train resistance, which in turn is a function of numerous train and operating parameters. Thus, the net efficiency is also determined by those variables.

2.9 ESTIMATED ACCURACY

The analytical approach taken in this study depends for accuracy upon the precision and completeness of the model and on the validity of the data used. For cases in which the summation of steady-state elements is a good approximation to the actual operating cycle, accuracy should be reasonably good. In general, the greatest errors are likely to arise from uncertainty in train resistance and failure to include minor energy-dissipation mechanisms. As described in the Appendix, even rolling resistance is imperfectly known under various conditions.

The approach taken in this formulation has been to use the highest reasonable estimates of train resistance, in order to err on the high side in prediction of fuel consumption. This aids in compensating for normal variations in operating technique and conditions, wind, diesel condition, etc.

For speeds above 40 to 50 MPH, (when aerodynamic losses become a significant part of energy consumption) knowledge of train resistance becomes still less precise. This arises largely from limitations of existing experimental and theoretical data on the subject. In any event, the great variation possible in train consists would seriously limit the applicability of more accurate characterization of aerodynamic losses. For example, one would expect the drag of twenty empty flat cars coupled to twenty box cars to be substantially different from one-by-one alteration of the same number of the two types of car.

This potential error is not of major significance in much of freight service, which typically involves relatively low speed operation - under 50 to 60 MPH. However, for some freight transportation, and much passenger service, aerodynamic losses are a significant factor. The Appendix describes modifications to the Davis equation which are intended to minimize these and other uncertainties, but a potential fuel consumption ambiguity of the order of 5% at low speeds and 10% at higher speeds must be recognized as easily possible.

Other input data and parameters should generally contribute less than a 5% uncertainty, except when a complex terrain profile or driving cycle is involved. Individual operator influence on the fuel consumption represents a variable which cannot be accurately quantified. Experience from the automotive field indicates a potential 10% variability from this factor. Since the analytical formulation represents a somewhat idealized model and an optimized power use, it is not unreasonable to assume, prior to experimental validation, that on average it will understate actual consumption, expected uncertainty between -10% and +15%.

3. BRANCH-LINE SERVICE: RAIL VS. HIGHWAY FUEL CONSUMPTION

3.1 INTRODUCTION

It is the purpose of this section to provide guidelines for estimation of the relative energy efficiency of motor trucks and railroad trains for movement of relatively small quantities of freight over short distances. The particular focus of this study is the energy implications of abandonment of rail service and equivalent diversion to motor carrier.

This study is concerned only with energy considerations, and explicitly refrains from assessment of questions of overall economic relationships or impact upon environmental quality, public convenience, local economies, land use, etc. The intent of this analysis is merely to provide useful, if approximate, guidelines concerning energy consumption of the two modes under relevant conditions.

Insofar as fuel consumption is concerned, there are several key elements which characterize cases typically considered as candidates for abandonment of rail service. Trains are generally very short by normal railroad standards - often ten cars or less, sometimes only one. The light usage of such lines warrants only minimal track maintenance, limiting speed (according to FRA track standards) to a maximum of ten miles per hour. In spite of the very low motive power requirements necessitated by this type of service, locomotives available are generally in the range of 1500 to 2000 HP. These elements imply high specific fuel consumption in two principal ways:

1. The locomotive operates at only a few percent of rated power, a condition under which fuel efficiency is far lower than normal, and
2. Fuel consumption under "load" is not markedly greater than at idle, so that the idle fuel becomes a major (and unproductive) energy expenditure to be charged to the transportation service provided.

3.2 GENERAL SUMMARY OF CONCLUSIONS

The basic model of Chapter II has been applied to this case. Results for a large number of cases have been calculated on a digital computer, with the objective of determining the conditions which mark the boundary between rail and highway as the energy-preferred mode. Parameters considered in these test cases include circuity, grades, number of stops, velocities, and details of vehicles and rolling stock, load factors, distance, and load. (Many of these are often different for the two modes.)

A relatively clear pattern emerges. The situation can best be understood through consideration of the energy consumption associated with basic line-haul movements, temporarily omitting effects of stops, grades, idle time, etc. Figure 3-1 shows the specific fuel consumption (pounds of fuel per ton-mile) for rail and highway cases, averaged over a round trip, as a function of load. The quantity calculated is the fuel consumed per ton moved (from point A to point B, with the carrier returning empty to its origin) divided by the distance between origin and destination. The highway results are basically independent of load (but not load factor), since additional freight is carried simply by addition of more trucks of equal efficiency. In Figure 3-1, speeds of 8 MPH (rail) and 30 MPH (highway) are assumed. The break-even point between highway and rail is approximately 100 tons for the idealized case considered.

For long distances, the total specific fuel consumption will approximate the values shown in Figure 3-1. However, several other factors are important for shorter hauls. Principal among these are the locomotive fuel consumption at idle and during switching moves, and truck energy dissipation during possibly-frequent terminal area decelerations and stops under braking. Under conditions of substantial rail idle, the rail advantage of Figure 3-1 occurs only for the longer hauls, for which the idle energy per mile is relatively small. Conversely, a significant number of terminal area stops, in traffic and at intersections, can diminish the basic <u>highway</u> advantage normally found for very light loads.

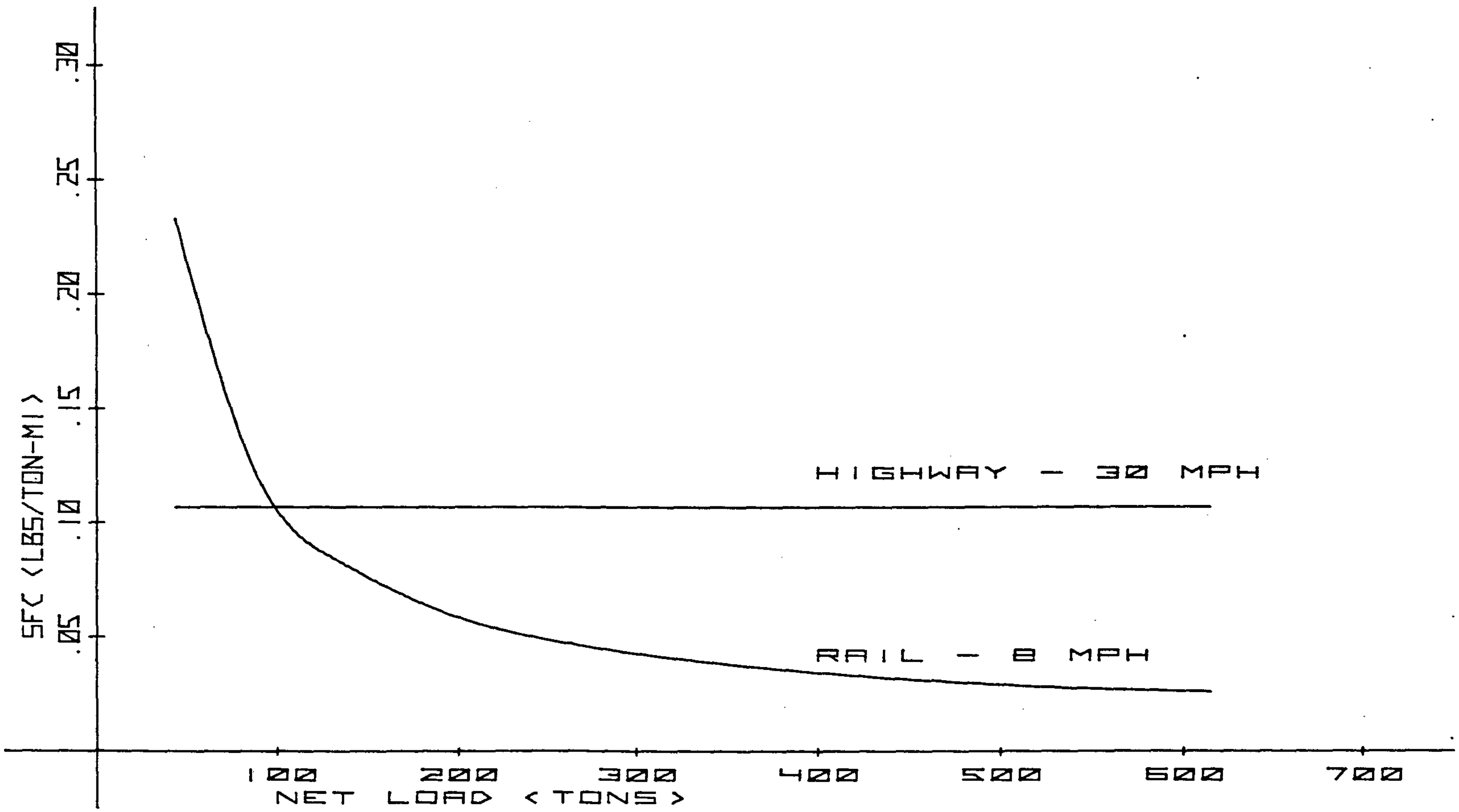

Figure 3-1. Specific Fuel Consumption as a Function of Load. Calculated values are for round-trip, fully loaded outgoing, empty return. Zero grade

In most cases it is found that these two effects tend to cancel one another. This compensation effect, combined with the steep slope of the locomotive specific fuel consumption curve for lightly loaded cases, leads to the result in most instances that the break-even load is quite insensitive to distance of haul, and often not a function of it at all. It is generally a load fairly close to that determined on the basis of line-haul constant velocity operation only (Figure 3-1, for example).

The trade-off does vary significantly with velocity and grade. Figure 3-2 repeats Figure 3-1 for a variety of rail and highway speeds, and it is seen that the marked improvement in net locomotive efficiency when under increased load significantly shifts the crossover. Again, detailed calculations for a variety of situations cluster about the break-even loads apparent from Figure 3-1 (line-haul only), and show little dependence upon distance. The results are very similar for grades, which are shown in Figure 3-3 for the 8 MPH (rail), 30 MPH (highway), assuming a route consisting of one-half ascending grade and one-half descending grade, with no net change in elevation. Constant-velocity (case 2) operation is assumed. It is immediately apparent that rail fuel efficiency suffers far more severely than highway, primarily due to the low ratio of loaded to empty train weight. Although trucks are typically exposed to greater grades, these results (in addition to the prevalence of a constant power (zero loss) driving cycle, rather than constant velocity) indicate that the fuel consumption values shown in Figure 3-1 represent a good measure of the actual situation, and the energy-optimal choice will typically be highway up to at least 100 tons for the common (low rail-velocity) situations, and substantially higher if significant grades are involved. Unusually large values of other variables (idle, stops, etc.) can, of course, significantly alter this conclusion.

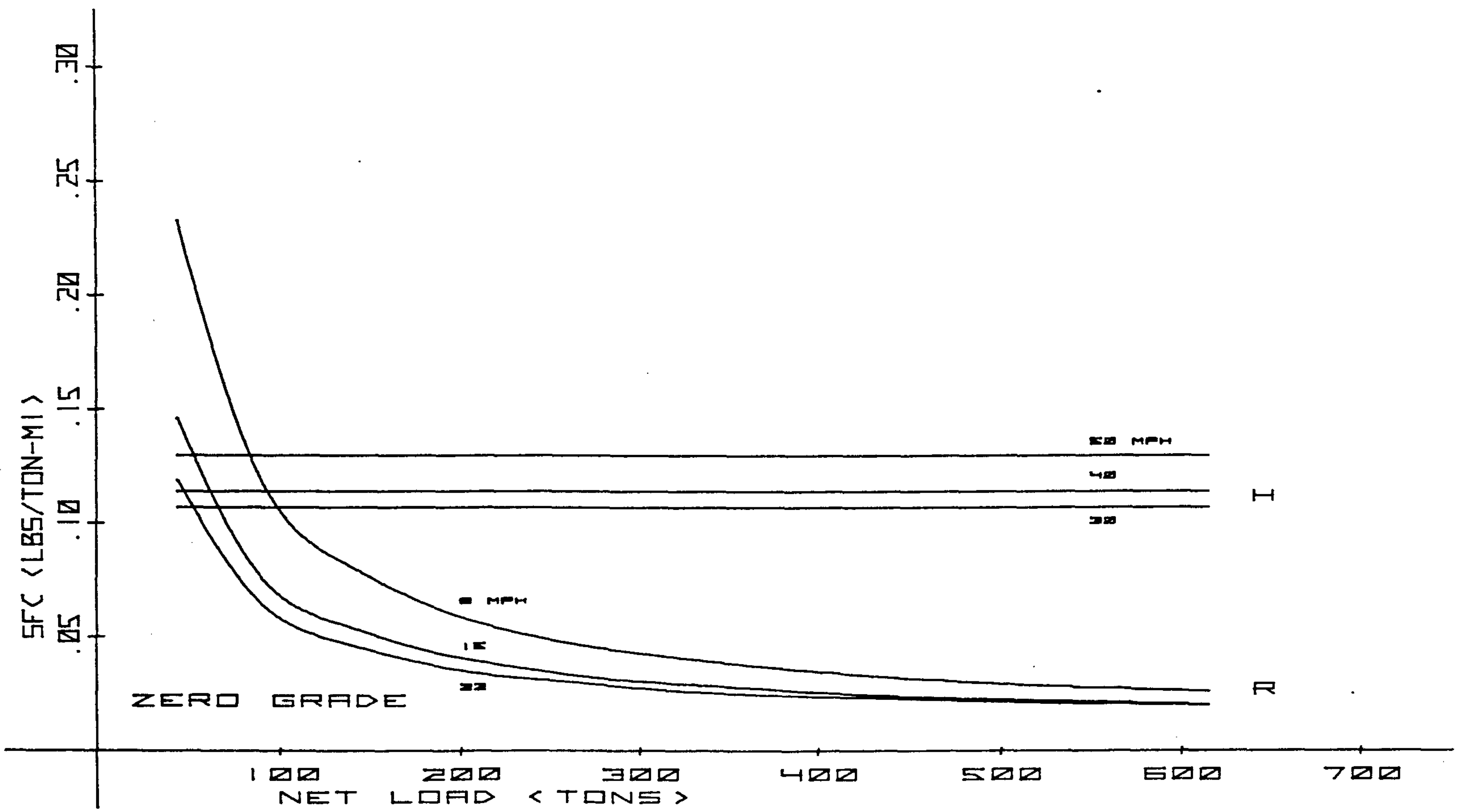

Figure 3-2. Specific Fuel Consumption as a Function of Net Load, for Various Rail and Highway Speeds

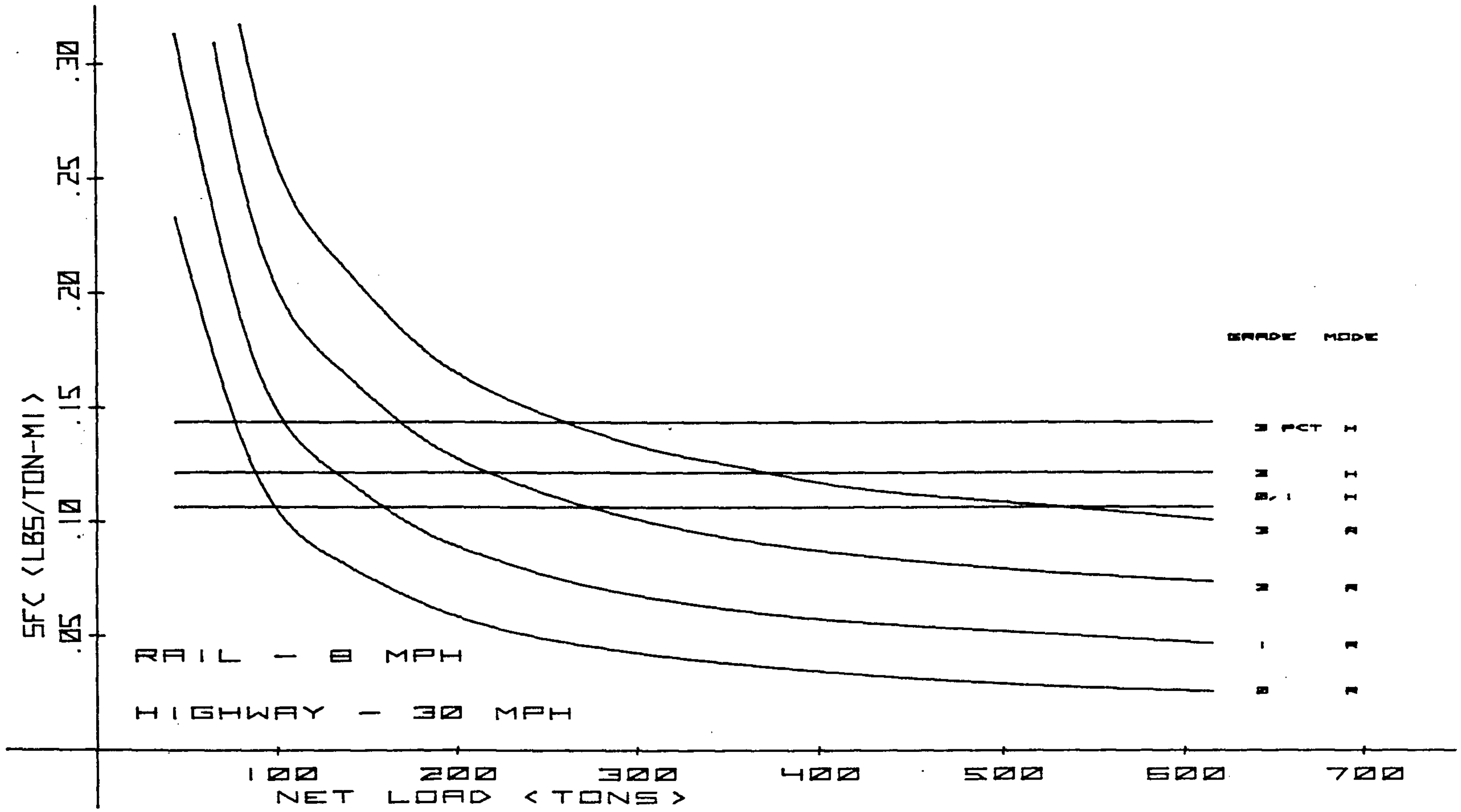

Figure 3-3. Specific Fuel Consumption as a Function of Net Load, for Various Grades

As indicated above, the primary factor reducing rail fuel efficiency for light loads is the typical necessity of utilizing a locomotive of far greater power capacity than is required in this type of service - the required line-haul power is generally less than 500 HP, and can be under 100 HP for a few cars hauled at low speeds on level terrain. For example, to maintain 10 MPH for a gross weight of 500 tons, approximately 70 HP is necessary. The effect of locomotive power on specific fuel consumption is suggested in Figure 3-4, which shows several cases for 1000, 1500, and 2000 HP locomotives, and can be extrapolated to lower values.

Although this suggests significant potential benefits from use of special-purpose, low-power locomotives, operation of such units would be highly impractical. The "excess" horsepower of locomotives now in use may be required only occasionally, but at those times it is a necessity. Also, too small a locomotive may have inadequate starting traction.

All of the curves referred to in the preceding discussion represent fuel consumption under steady-state line-haul conditions, without inclusion of the effects of braking and idling (which includes switching moves). As an illustration of the consequences of these factors, Figure 3-5 shows a comparison of line-haul to overall specific fuel consumption for several cases, under the assumption of a 10-mile run (each way), with two stops, and a period of idling or switching equal to the running time.

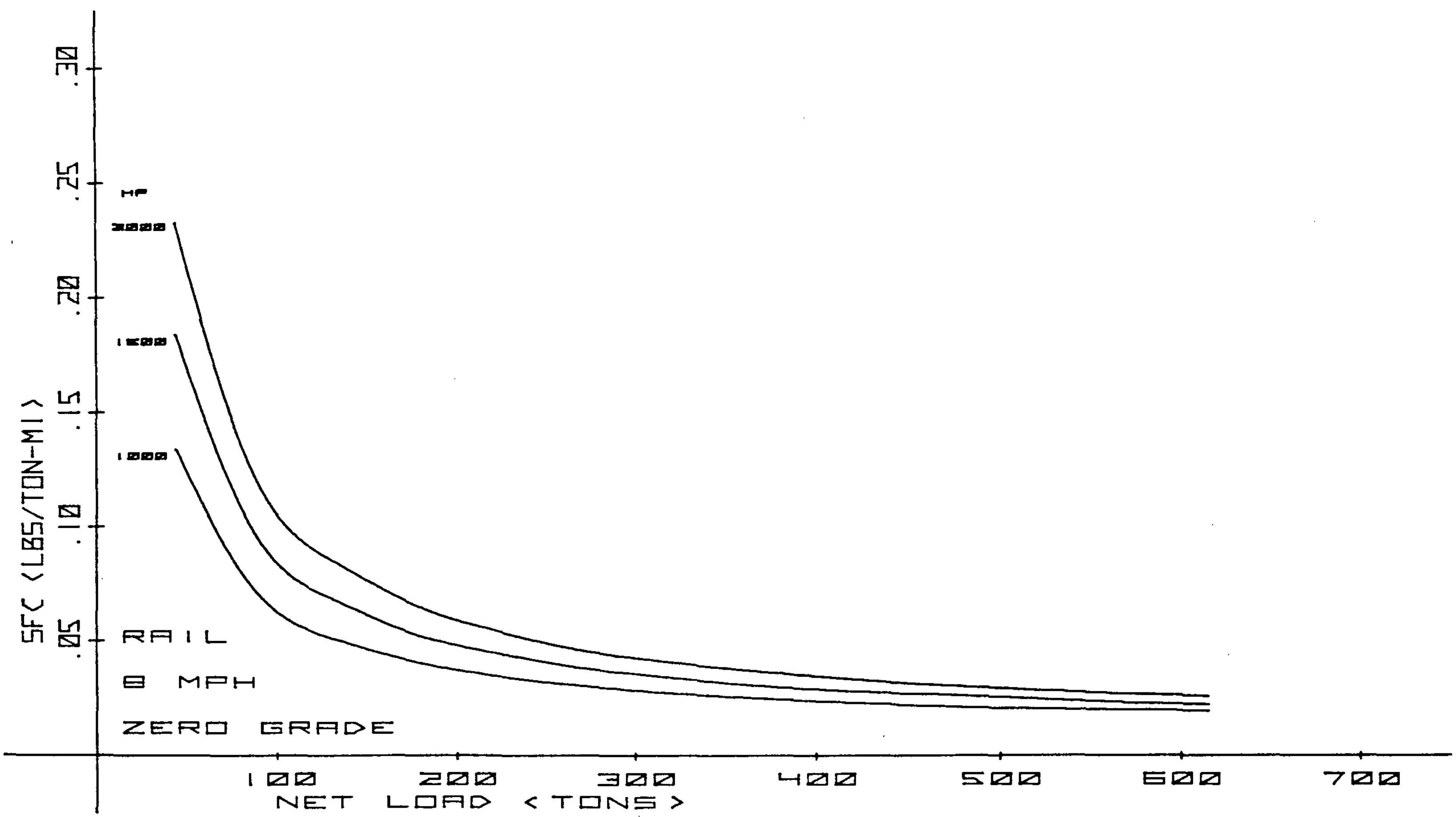

Figure 3-4. Specific Fuel Consumption as a Function of Net Load, for Various Values of Locomotive Rated Horsepower

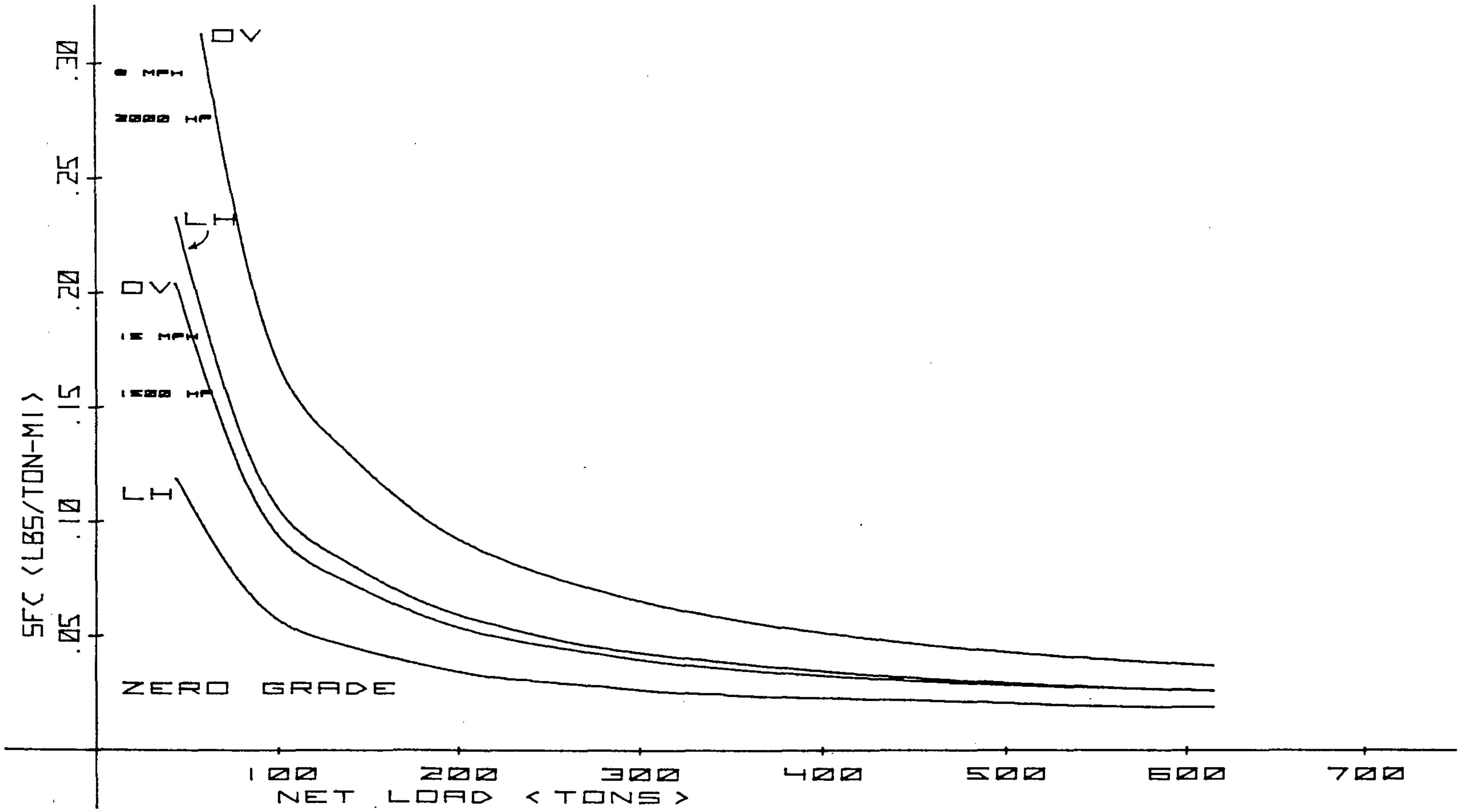

Figure 3-5. Line-Haul (LH) and Overall (OV) Specific Fuel Consumption as a Function of Net Load for Two Cases

4. INTERCITY FREIGHT SERVICE

4.1 A SIMPLE MODEL

The detailed formulation previously presented and applied to branch line operations can also be utilized for line-haul service, characterized by far greater loads and longer distances. However, it is both instructive and potentially useful first to consider a much-simplified formulation. In essence, this requires replacement of the basic train-resistance equation, normally of the form $A + W(B + Cv) + Ev^2$, by a velocity term only, so that the train may be treated as a unit. The power required to move a train at velocity v on level terrain can be expressed as

$$P_t = \frac{v}{375\eta} R_t \cdot W_t$$

where R_t is the train resistance coefficient (lbs/ton) and W_t is the train weight, and η is the overall locomotive power-transmission efficiency.

There will then be P_t/v horsepower-hours of energy consumed per mile. For a basic fuel/energy conversion rate of .34 lbs/hp-hr, and a weight of 7.1 lbs per gallon, the fuel consumed (gal/mile), F, can be written as

$$F = \frac{.34}{7.1} \frac{P_t}{v\eta},$$

$$= \frac{.34}{7.1} \frac{1}{v} \frac{v}{375\eta} R_t W_t$$

and the overall specific fuel efficiency f_e (ton-miles/gal) is

$$f_e = \frac{L}{F} = \frac{7830\eta}{R_t W_t} L$$

For an overall efficiency η of .75,

$$f_e = 5.87 \times 10^3 \frac{L}{W_t R_t} = \frac{5.87 \times 10^3}{R_t} \cdot \frac{L}{W_t}$$

The train weight may be written as

$$W_t = n_c W_c + L + W_\ell ,$$

where n_c is the number of cars,

W_c is the average empty car weight (tons)

L is the total load weight (tons)

and W_ℓ is the locomotive weight

The number of cars is readily determined in terms of the overall load factor f_ℓ and average car capacity c_c:

$$n_c = \frac{L}{c_c f_\ell}$$

Typical values of locomotive weight and power, and train power/weight ratios, imply that the locomotive weight will be of the order of 10% of the empty train weight, so that

$$W_t \approx \left(1.1 \frac{W_c}{c_c f_\ell} + 1\right) L$$

The ratio of car capacity to empty car weight (c_c/W_c) can vary from approximately unity to greater than 3. For box cars, 2.2 is a reasonable average value, so that

$$\frac{L}{W_t} \approx \frac{1}{(1 + \frac{1}{2f_\ell})} = \frac{2f_\ell}{(1 + 2f_\ell)}$$

Examination of the traditional measured train resistance curves (see Appendix) shows that in the range of 35 to 60 MPH R_t may be expressed with fair accuracy by

$$R_t \approx .162v$$

(This includes a recommended 8% addition for normal variations.)

As a result,

$$f_e \approx \frac{3.625 \times 10^3}{v} \frac{2f_\ell}{1 + 2\ f_\ell} \quad .$$

The f_ℓ expression can be simplified by means of a Taylor-series expansion about $f_\ell = .5$;

$$\frac{2f_\ell}{1 + 2f_\ell} = .25 + .5f_\ell$$

(This is accurate within 3% for $.35 < f_\ell < .7$.)

Finally, then,

$$f_e \approx .91 \frac{1 + 2f_\ell}{v} \times 10^4$$

For example, if $f_\ell = .5$, $v = 45$ MPH,

$$f_e \approx 400 \text{ ton-miles/gal}$$

(Note that this includes no idling, stops, grades, etc.)

As shown in the Appendix, the effect of grades may be included by replacing "$R_t \approx .162v$" by "$R_t \approx .162v + 20s$", where s is the grade (in percent). The final equation then becomes

$$f_e = .91 \frac{1 + f_e}{v + 123s} \times 10^4 \quad .$$

In order to obtain a measure of the validity of this result, particularly in view of the many approximations involved, fuel efficiency has been calculated for a large number of load factors, speeds, and train configurations. Results are graphed (ton-MPG vs. load factor) in Figure 4-1. As indicated in the figure, the least-squares fit to the points for two assumed forms are

$$(1)\quad f_e = 717\, f_\ell$$

and

$$(2)\quad f_e = 179(1 + 2\, f_\ell).$$

(These correspond to the previous equation for the case in which $v = 51$ MPH). Although the spread between cases is fairly great, this suggests that a relatively simple estimate is possible in cases not requiring great precision.

4.2 SAMPLE CASES

Calculated fuel efficiency as a function of speed is plotted in Figure 4-2, with grade and power/weight ratio as parameters. These calculations were made for the case of a 2800-ton payload, carried at a 45% load factor in cars of 80-ton capacity. (This implies a 79-car train.) Other calculations show f_e to be nearly independent of load (except for very light loads) when load factor and power/weight ratio are held constant. The low f_e-values at low speed (in Figure 4-2) are caused by the reduced locomotive efficiency when under light loading. The rolling-resistance energy dissipation term is nearly independent of speed, so it is only at speeds above 30 to 40 MPH (for which aerodynamic losses become significant) that specific fuel efficiency decreases.

The calculated variation of fuel efficiency with load factor and grade is shown in Figures 4-3 and 4-4, respectively, for a variety of cases. The curves show the expected qualitative variation. The assumed train is as for Figure 4-2. The operational characteristics of different values of power/weight, for trains of the size used above, are shown in Figure 4-5. The maximum grade which can be ascended at a specified velocity is plotted as a function of speed. (This also provides a measure of the maximum

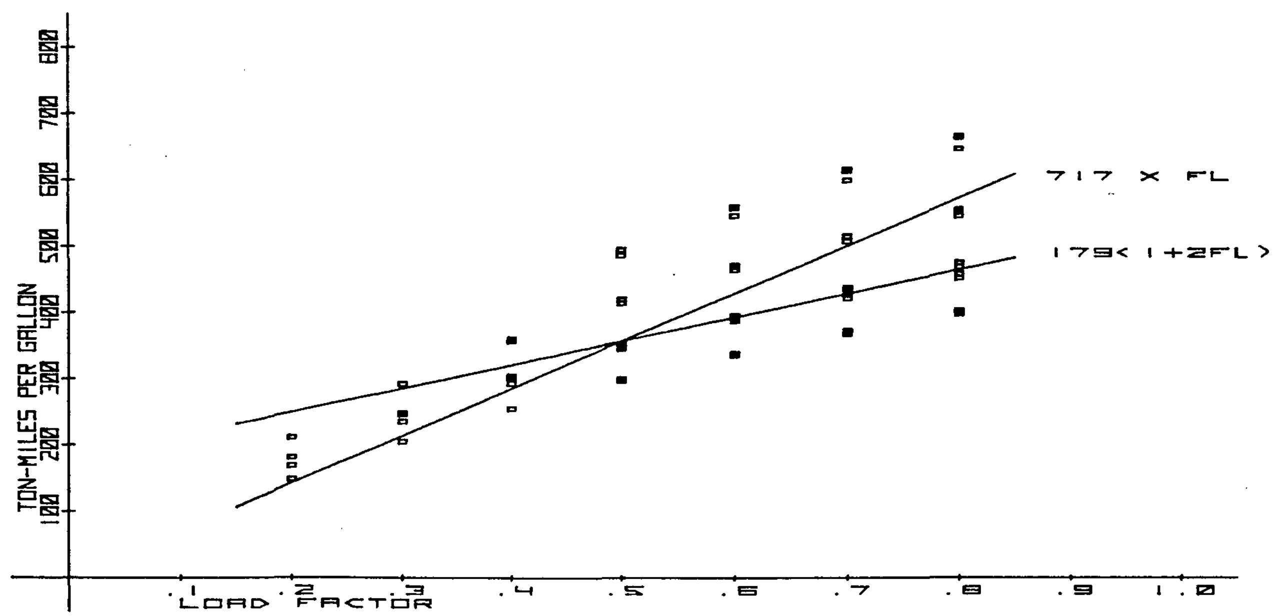

Figure 4-1. Fuel Efficiency as a Function of Load Factor for a Variety of Specific Cases

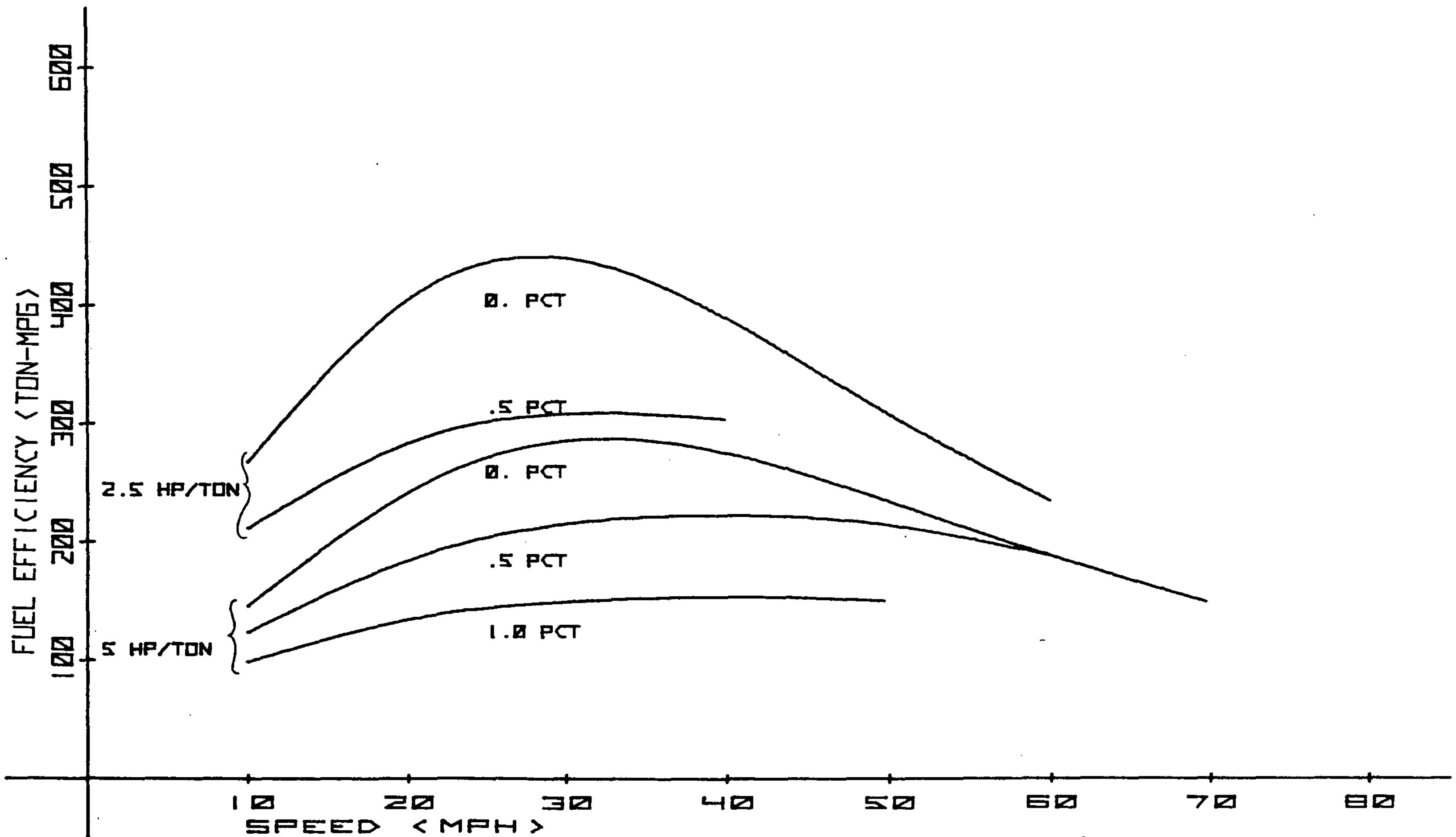

Figure 4-2. Fuel Efficiency as a Function of Speed, for Various Grades and Power-to-Weight Ratios

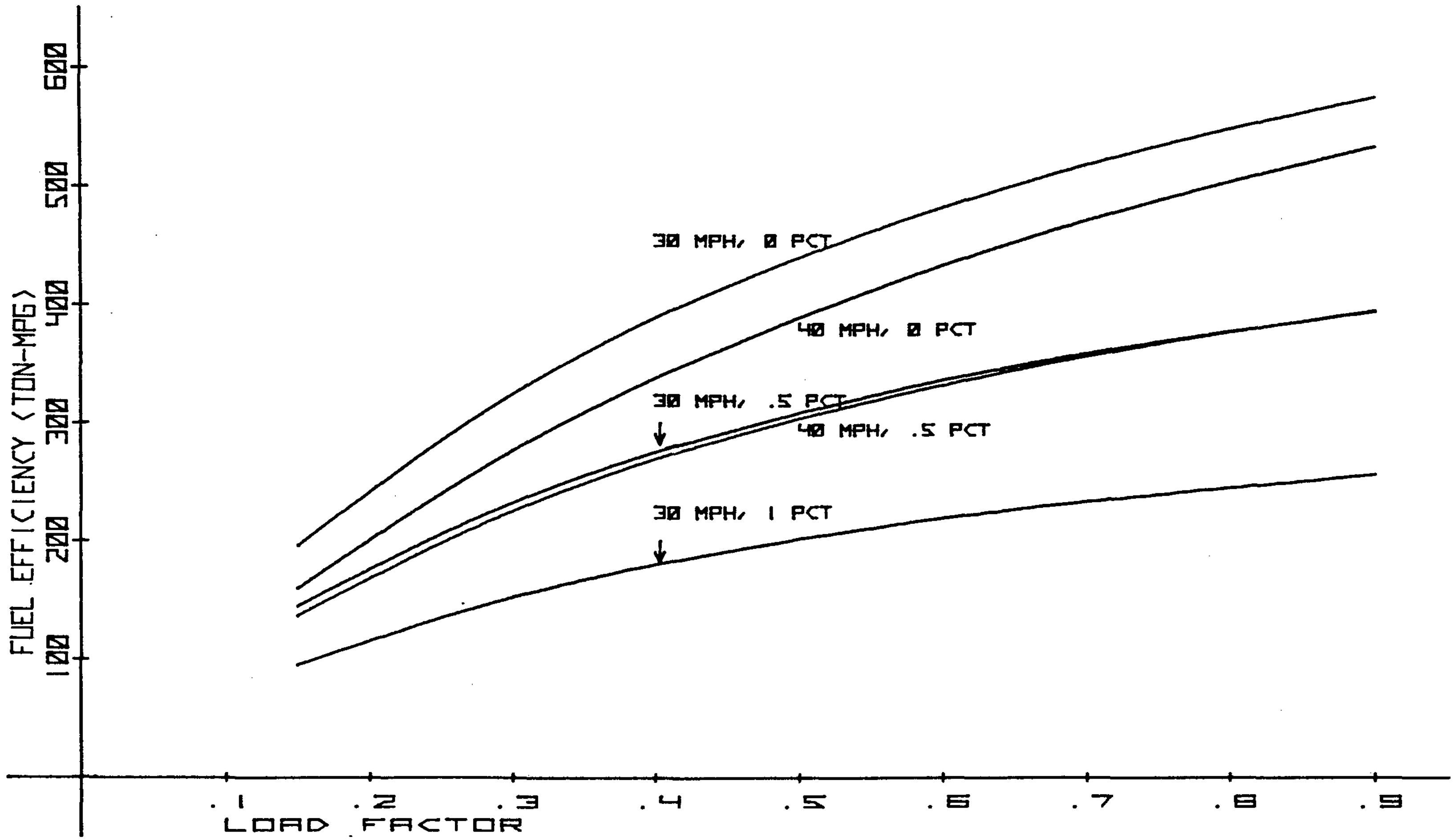

Figure 4-3. Fuel Efficiency as a Function of Load Factor

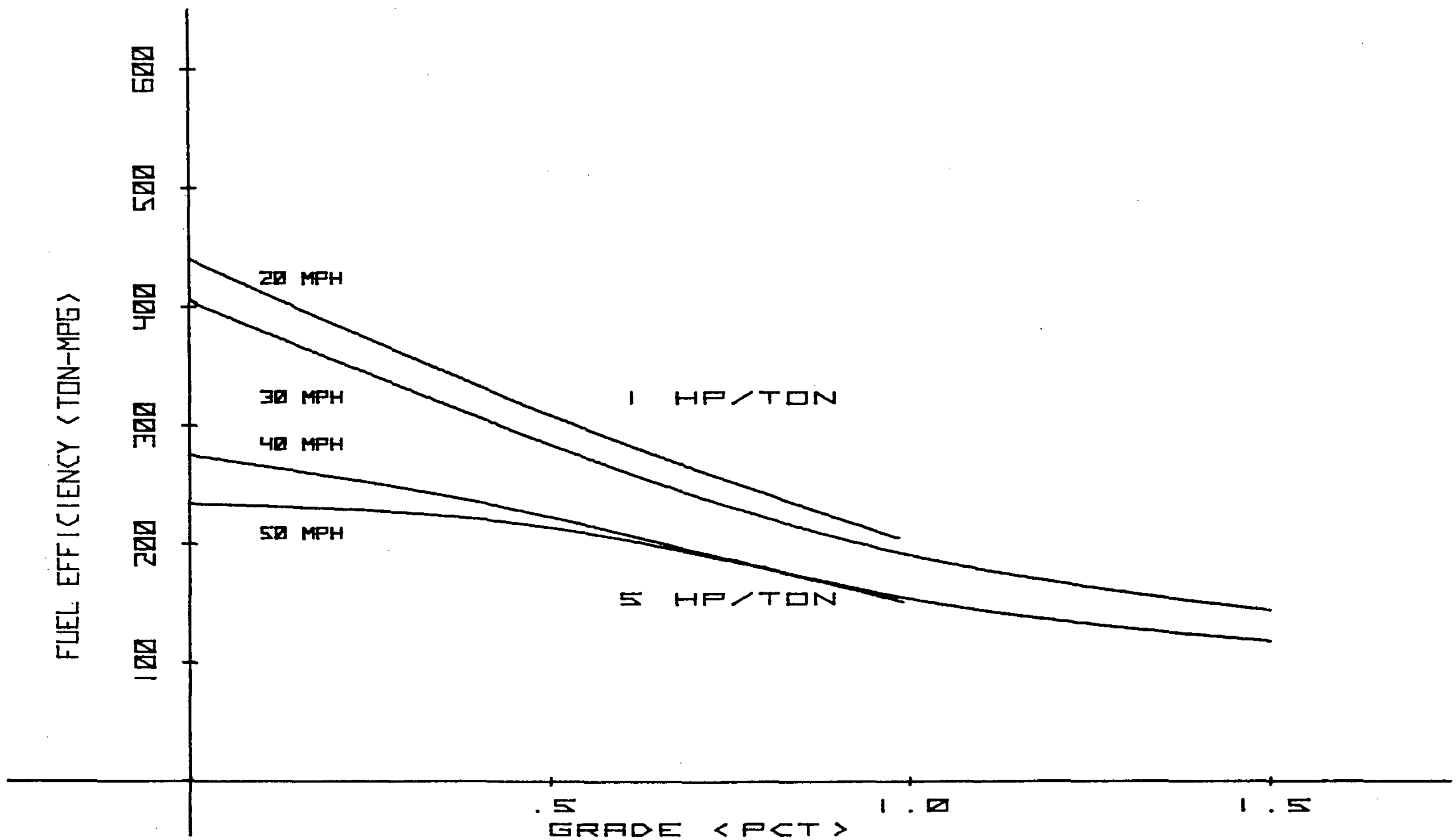

Figure 4-4. Fuel Efficiency as a Function of Grade

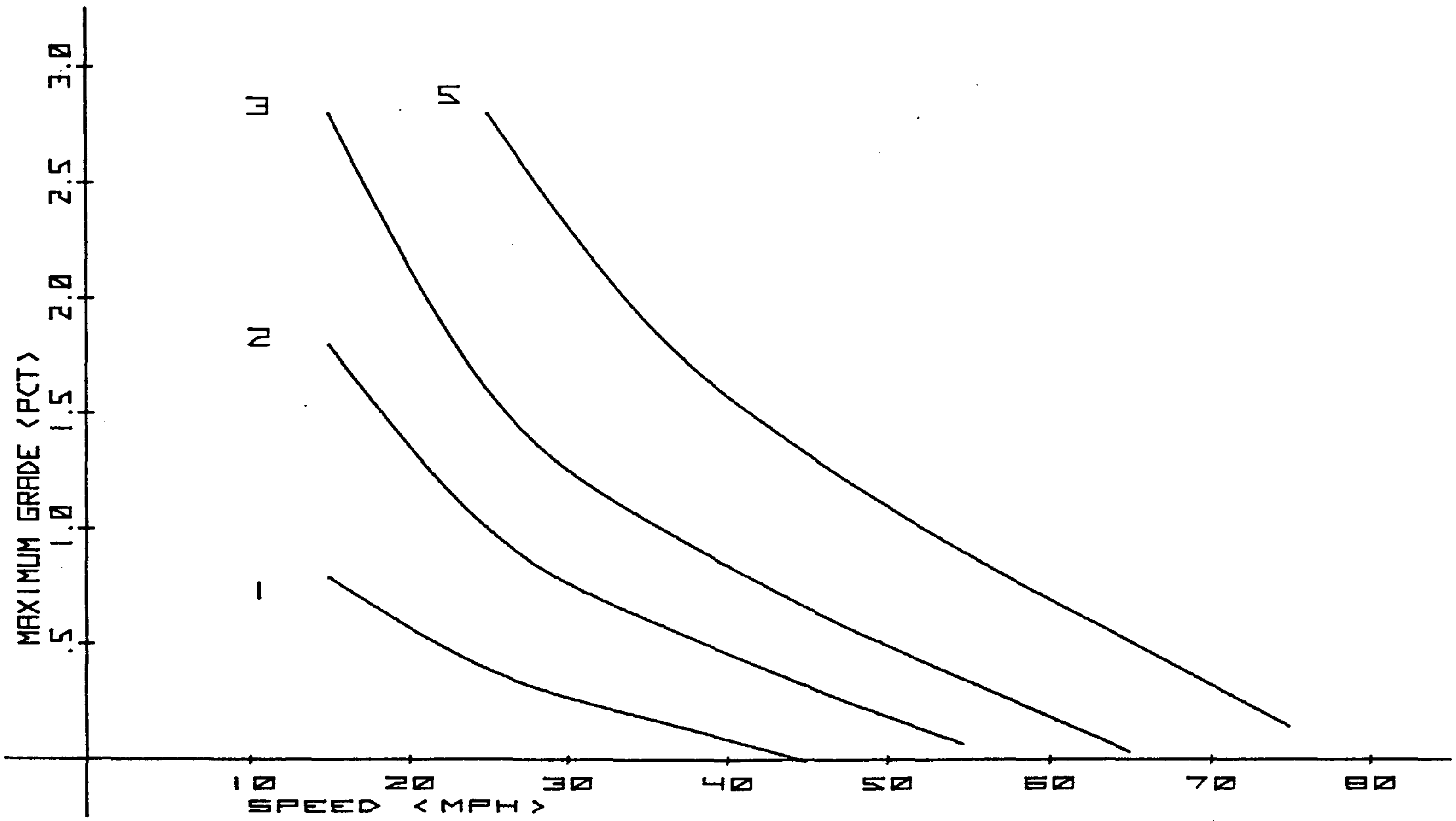

Figure 4-5. Maximum Grade Which can be Ascended at Specified Speed, as a Function of Speed, for Various Power-to-Weight Ratios

acceleration possible at a given speed.) The fuel-consumption implications of power/weight ratios are shown in Figure 4-6, in which ton-MPG is plotted as a function of HP/ton. It is to be noted that for higher speeds and/or grades fuel efficiency is relatively insensitive to this variable.

Neither fuel consumption at idle nor energy dissipated in stopping has been included above; all figures are for steady state operation. A measure of the relative importance of these factors can be obtained by examination of a variety of specific cases. The percentage of total fuel consumed in braking and idling, for several speeds and grades, is indicated in Table 4-1. Two basic cases are considered: 25% idle time, with a stop every 50 miles; and 50% idle time, with a stop every 20 miles. The same train as used previously is assumed; a value of 5 HP/ton is used to maximize both percentages. (It should be noted that substantial slowing, with acceleration back to cruising speed, can be nearly equivalent to a stop insofar as fuel consumption is concerned. For example, slowing from 45 MPH to 15 MPH dissipates nearly 90% of the kinetic energy of the train.)

It is not the purpose of this study to examine changes - either minor or major - which would significantly improve fuel efficiency. However, a number of brief comments are appropriate. All-electric is generally characterized as having an overall fuel efficiency somewhat less than that for diesel electrics. The gas turbine can do slightly better than electric in principle, but is not currently available for freight service and realization would pose several major technological challenges. Many considerations other than fuel consumption bear upon the value of such alternatives, including life-cycle costs, use of non-petroleum fuels, operational requirements, etc. Modest but significant improvements in overall diesel-electric efficiency should not be ruled out, as increasing attention is focused upon this characteristic. Technological innovations such as energy storage techniques are unlikely to have had major effect on line haul freight operations, although they could be beneficial in other classes of service. Lighter weight rolling stock, and

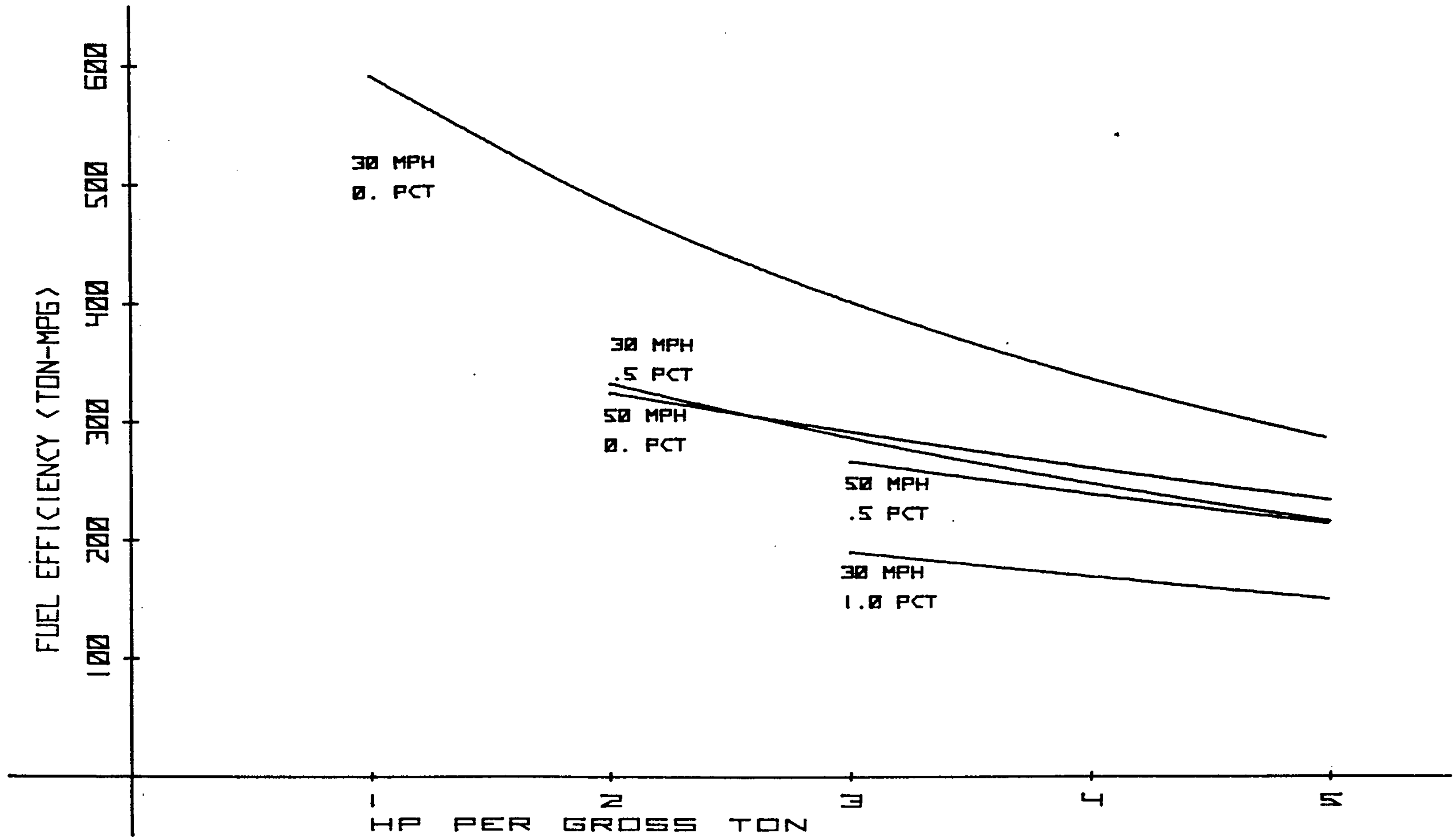

Figure 4-6. Fuel Efficiency as a Function of Power-to-Weight Ratio

improved aerodynamics of certain consists - TOFC, for example - could contribute significantly. In summary, significant gains are possible, but nothing currently anticipated offers dramatic improvement.

TABLE 4-1. PERCENTAGE OF FUEL USED IN IDLING AND BRAKING FOR A VARIETY OF CASES. 5 HP/GROSS TON

Case	Speed	Grade	% of Fuel Used in Idling	% of Fuel Used in Braking
25% Idle Time 50 Miles Between Stops	40 MPH	0 %	6.6	4.1
	50	0	4.3	5.1
	60	0	2.8	5.7
	40	.5*	5.9	3.6
	50	.5	4.1	4.9
	60	.5	2.8	5.7
50% Idle Time 20 Miles Between Stops	40	0	16.7	8.5
	50	0	11.0	11.0
	60	0	7.3	12.5
	40	.5	15.1	7.7
	50	.5	10.6	10.6
	60	.5	7.3	12.5

*50% of trip level; 25% ascending grade; 25% descending.

5. PASSENGER SERVICE

5.1 CONVENTIONAL INTERCITY PASSENGER TRAINS

The simplified approach followed in the analysis of rail freight transportation is also of value with appropriate modifications in considering passenger operations. For the passenger case, the fuel consumption is nearly independent of load, since the load weight is generally in the range of 5% to 10% of the train weight. Thus, load factor is important only in conversion from seat-miles per gallon to passenger-miles per gallon, and the analysis is best carried out in terms of the former quantity.

In terms of train weight per seat w_s (lbs), the horsepower P_t required to maintain a velocity v on level terrain is

$$P_t = \frac{v}{375\eta} \cdot R_t \cdot W_s \cdot n_s,$$

where R_t is the train resistance coefficient (lbs/ton), n_s is the number of seats, and η is the overall locomotive power transmission efficiency. The energy expended per seat-mile is $P_t/vn_s = R_t/375\eta W_s$, and the fuel, F, (gal.), consumed per seat mile is given by $F = R_t W_s/375\eta\ r_o$ where r_o is the energy released (hp-hr) per gallon of fuel, typically taken as (.34/7.1) hp-hr/gal. Assuming (for the purposes of this approximate analysis) $\eta = .75$,

$$F \approx 1.7 \times 10^{-4}\ R_t W_s$$

and the normalized fuel **efficiency** S_{mpg} (seat-miles per gallon) is

$$S_{mpg} \approx \frac{5.87}{R_t W_s} \times 10^3$$

As in the freight-service treatment, examination of standard train resistance curves indicates that in the speed range from 40 to 80 MPH R_t can be approximated relatively accurately by

$$R_t = \frac{v}{15,000} \quad ; \text{ (lbs per lb)}$$

with an additional 8% increase recommended to allow for typical variations. The result is the simple expression

$$S_{mpg} = \frac{8.16}{vW_s} \times 10^7$$

Grades are easily included in the simplified formulation, under the assumption of constant velocity. As developed in the appendix, the additional (grade-related) energy consumption is obtained by replacing the previous value of R_t $(\frac{v}{1.5} \times 10^{-4})$ by $R_t = (\frac{v + 150\ s}{15,000})$, where s is the grade, expressed in percent.

S_{mpg} as calculated from the above equation was compared to the results of computations based upon the detailed formulation described in Chapter II and in the Appendix. Detailed-calculation values for the zero-grade, 60 MPH case, for a variety of loads, load factors, power/weight, etc, are plotted in Figure 5-1. The ratio of S_{mpg}(simple) to S_{mpg}(detailed form) for these 74 cases has a mean of 1.14; the solid curve in Figure 5-1 represents the equation $S_{mpg} = ((8.16 \times 1.14)/vW_s) \times 10^7$. For 1188 cases including various grades and speeds, the corresponding ratio is 1.05, with a standard deviation of .11. Thus, the simple form appears sufficiently accurate for use in cases not requiring high precision.

5.2 SAMPLE CASES

In order to provide insight into the specific fuel consumption for typical intercity rail passenger operations, variation of

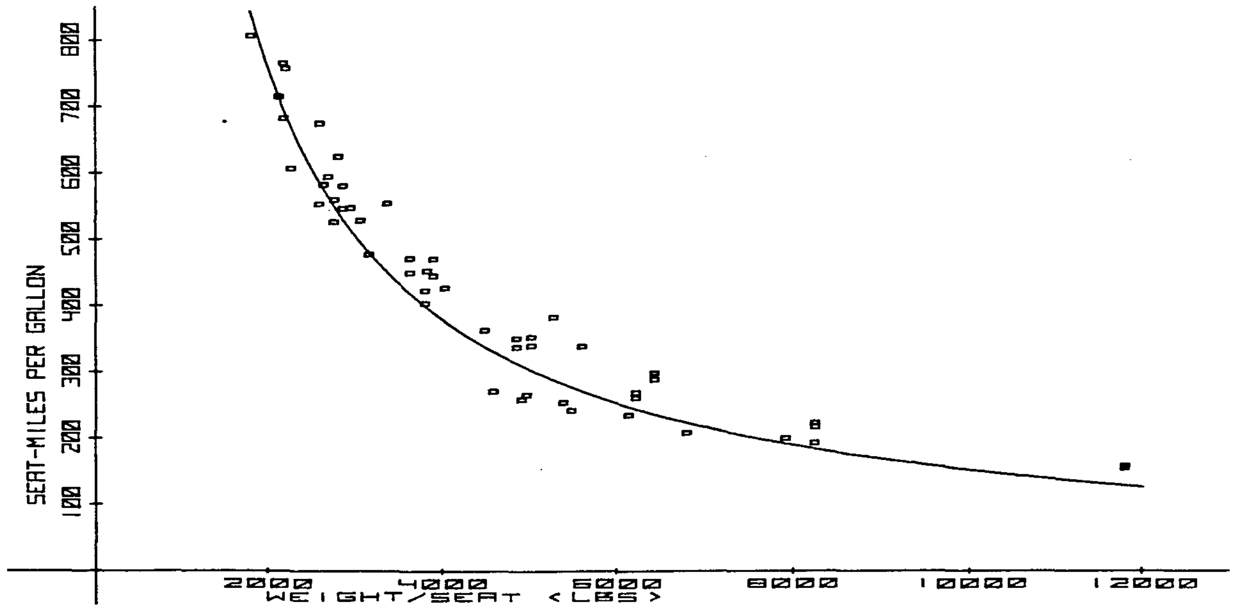

Figure 5-1. Fuel Efficiency as a Function of Weight per Seat, for a Variety of Specific Cases, 60 MPH. Modern High Speed Passenger Trains Fall in the Range of 1500 - 3000 lbs/seat, with Conventional Equipment Typically at 5000 - 10,000 lbs/seat

energy usage with relevant parameters has been computed and plotted in a number of graphs (following). Two routes are considered: (1) level operation; and (2) 60% level, 40% of the trip at a .5% grade. Grades are equally divided between ascending and descending. As indicated previously, the most significant variable is the weight per seat. Although this is readily calculated for specific cases, it is useful to express this quantity in terms of operational variables. W_s, total train weight per seat (in lbs), can be written as

$$W_s = \frac{W_c}{C_c} \left(1 + \frac{n_s}{n_c}\right) \left(1 + \frac{P_t}{P_\ell - P_t}\right)$$

where W_c = weight per car (lbs)
C_c = seats per car
n_s = number of service cars
n_c = number of passenger cars (characterized by C_c)
P_t = train horsepower/total train weight (tons)
P_ℓ = train horsepower/total locomotive weight (tons)

For the purpose of general estimation, one can assume $W_c \approx$ 150,000 lbs and P_ℓ = 20 hp/ton (3500 HP for a 175 ton locomotive). Using these values, and a simplified expression (Taylor series expansion about P_t = 7.5) for the power term,

$$W_s \approx \frac{W_c}{C_c} \left(1 + \frac{n_s}{n_c}\right) (1 + P_t)$$

The horsepower/ton value for a passenger train is of relevance to two important aspects of operational performance: grade-climbing and acceleration. The two characteristics are related by simple physical laws; the acceleration (expressed in g's) possible for specified power, at a given speed, is equivalent to the

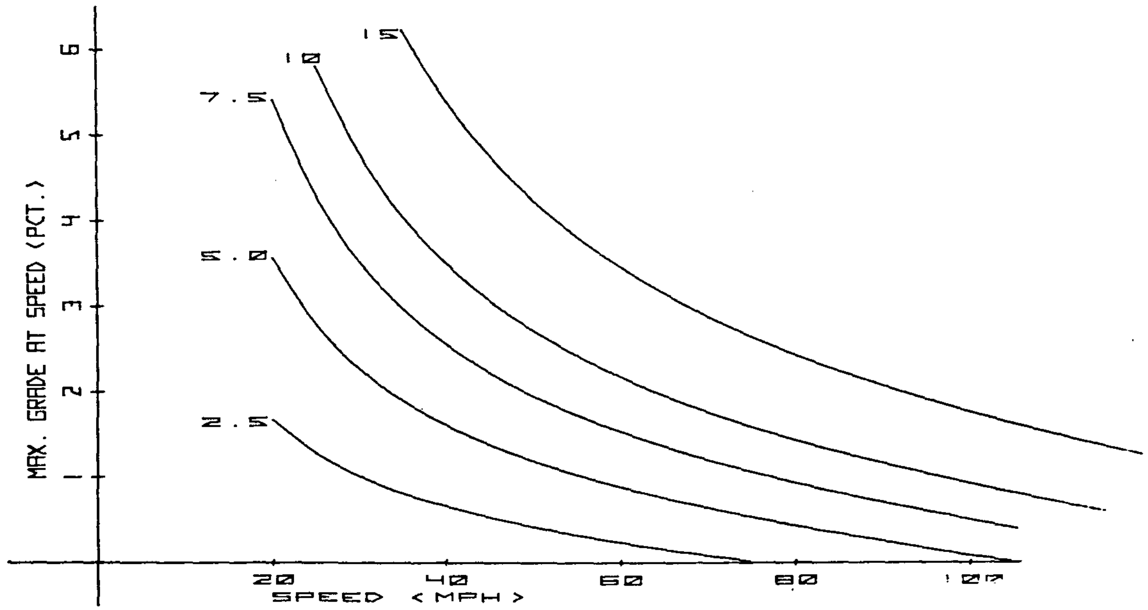

Figure 5-2. Maximum Grade Which can be Ascended at a Specified Speed, as a Function of Speed

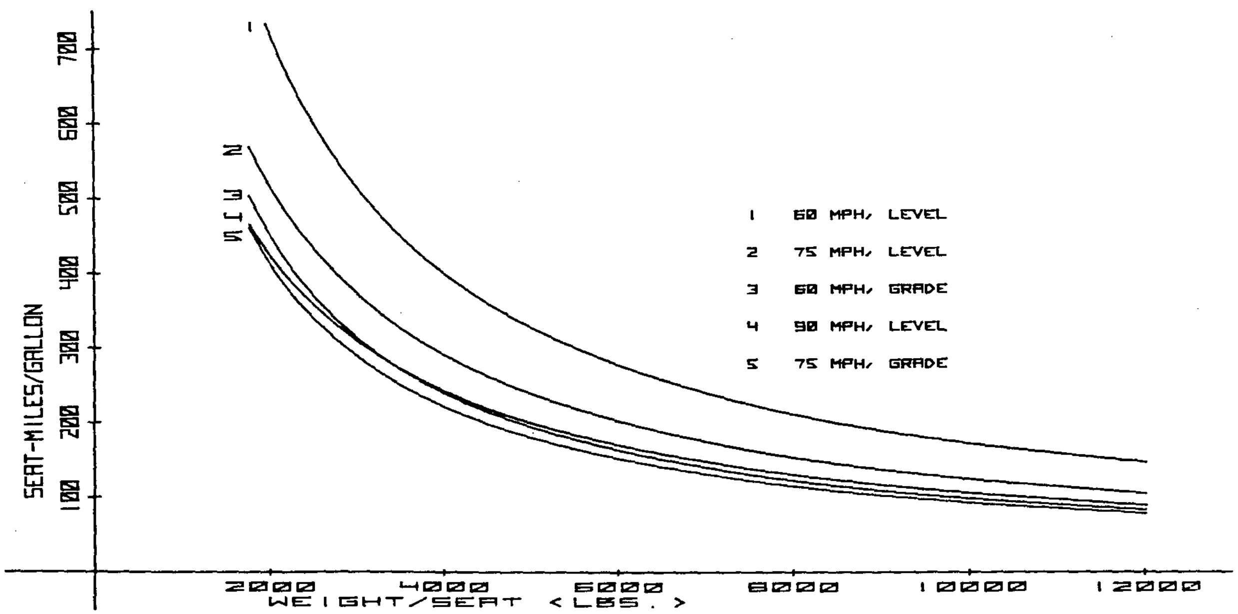

Figure 5-3. Fuel Efficiency as a Function of Weight per Seat. ("Grade" indicates calculations for 20% of trip at .5% Ascending, 20% at .5% Descending Grade.)

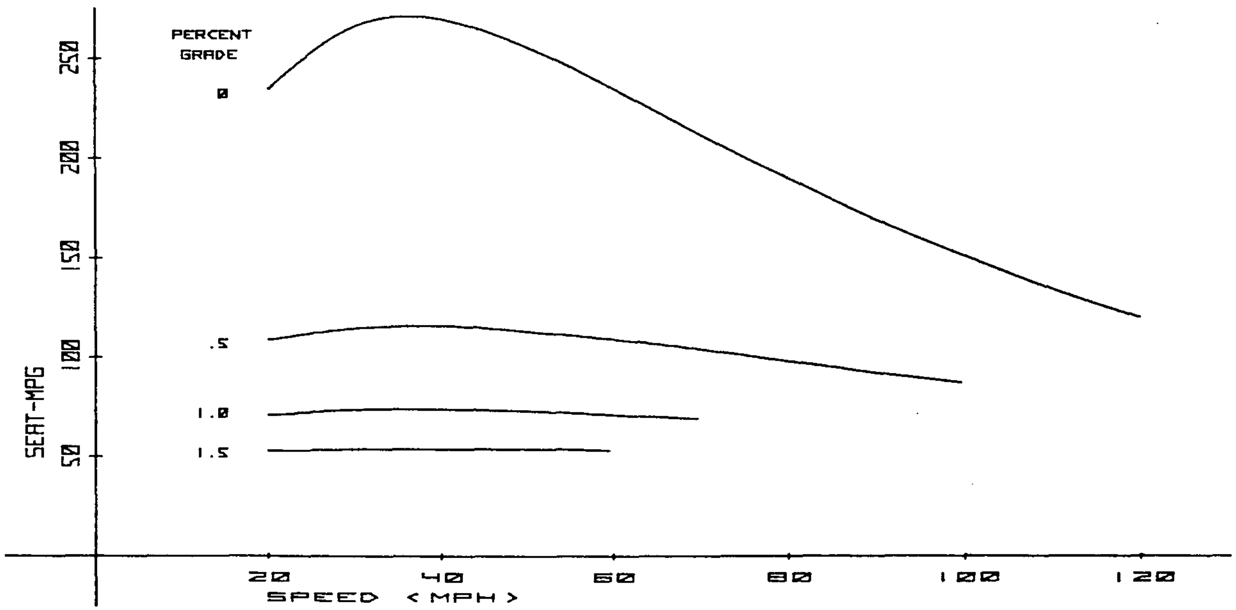

Figure 5-4. Fuel Efficiency as a Function of Speed. 12-Car Train, 40 Seats per Car

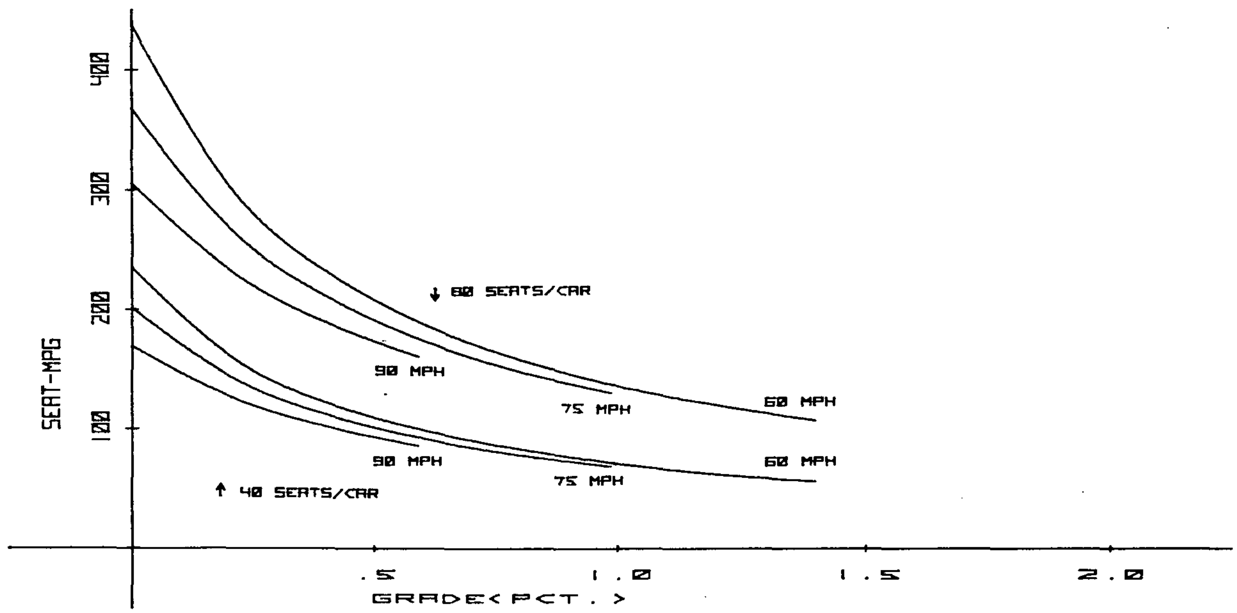

Figure 5-5. Fuel Efficiency as a Function of Grade

TABLE 5-1. PERCENTAGE OF FUEL USED IN IDLING AND BRAKING FOR A VARIETY OF CASES. 7.5 HP/GROSS TON; 6000 LBS/SEAT

Case	Speed	Grade	% of Fuel Used in Idling	% of Fuel Used in Braking
25% Idle Time 100 Miles Between Stops	60 MPH	0 %	5.8	4.0
	75	0	4.0	5.3
	90	0	2.8	6.8
	60	1*	4.1	2.8
	75	1	3.0	4.1
	90	1	2.6	6.0
50% Idle Time 50 Miles Between Stops	60	0	15.0	6.9
	75	0	10.5	9.4
	90	0	7.4	11.5
	60	1	11.1	5.1
	75	1	8.3	7.4
	90	1	7.0	10.8

*60% of trip level; 20% ascending grade; 20% descending.

grade which can be ascended at that speed. For example, the power necessary to climb a 1% grade will provide an instantaneous acceleration of .01 x g (.22 MPH/sec, or 13 MPH/min) at the same speed on level terrain. Figure 5-2 is a graph of the maximum grade which can be ascended for a specified velocity, for several values of horsepower/gross ton. The values were obtained with the detailed train performance model, for the case of a 20-car passenger train.

In Figure 5-3 the fuel usage, in terms of seat-miles per gallon, is plotted as a function of weight per seat, for three speeds (60, 75, and 90 MPH) and the two terrains referred to previously. (Note that if both seat-mpg and weight/seat are multiplied by the number of seats, these become curves of train-mpg vs. train weight.)

Variation of seat-mpg with velocity and grade are shown in Figures 5-4 and 5-5, respectively. In each case a 12-car train, with 40 seats/car, is assumed; the seat-mpg figures are readily converted for other seat/car values. (At a load-factor of .5, this would imply 240 passengers.) The effect of train length is - for constant load factor, etc - very small; a typical calculation shows less than 10% increase in efficiency as train length is varied from 8 to 32 cars for constant power-to-weight ratio. This is because the rolling and aerodynamic resistance increase in proportion to the number of cars, except for the fixed drag of the lead locomotive, which must be "amortized" over all the cars.

Additional fuel consumption associated with idling and stops can readily be determined as indicated in Chapter 2 and the Appendix. However, an indication of the magnitude of the correction necessary can be seen in Table 5-1, which shows the percentage of fuel consumed in those aspects for a 20-car 7.5 HP/ton train at three cruising speeds and terrains. In essence, both factors are proportional to train weight, and thus will not be significantly different for other consists; fuel consumption at idle will also be proportional to HP/ton.

5.3 COMMUTER OPERATIONS

Rail commuter service is governed by the same parameters as for the intercity case. However, certain parameters are typically somewhat different - particularly average distance between stops, idle time, and seats/car. In addition, the assumed locomotive power/ton can be quite different for MU cars than for intercity rolling stock. In order to illustrate some of these differences, seat-mpg is plotted in Figure 5-6 as a function of lbs/seat, for 40 and 60 MPH zero-grade operations, assuming a stop every 10 miles or every 25 miles, and 50% idle time. The impact of interval between stops as a variable is seen in Figure 5-7, for which speed and weight/seat are taken as parameters.

5.4 HIGH-SPEED TRAINS

In recent years trains designed for cruising speeds between 90 and 160 MPH have been placed in service or planned in a large number of countries.[11,12,13,14,15] In general, fuel consumption has not been a primary design constraint, and specific figures for this characteristic are generally not available. The analytical approach followed elsewhere in this study is not applicable here because of the inadequate information concerning aerodynamic drag, the major energy-consuming element at high speeds. In addition, numerous train configurations, sources of motive power, and passenger-comfort energy requirements are involved, further compromising any attempt at a general analysis.

Rather, the approach followed here is the use of a very simple model to estimate, from published data, specific fuel consumption for a large number of existing or planned high-speed passenger trains. The main source of information utilized here is trade-press articles, supplemented in some cases by information from manufacturers. Train weight, installed power, speed, and seating capacity are the basic data used. If one were to assume that full rated horsepower is required for operation at the specified cruise velocity, the steady energy expenditure would simply be power/velocity (horsepower-hours/mile). Dividing by the number of seats, and converting HP-hours to gallons of diesel fuel (as done previously in this chapter) would

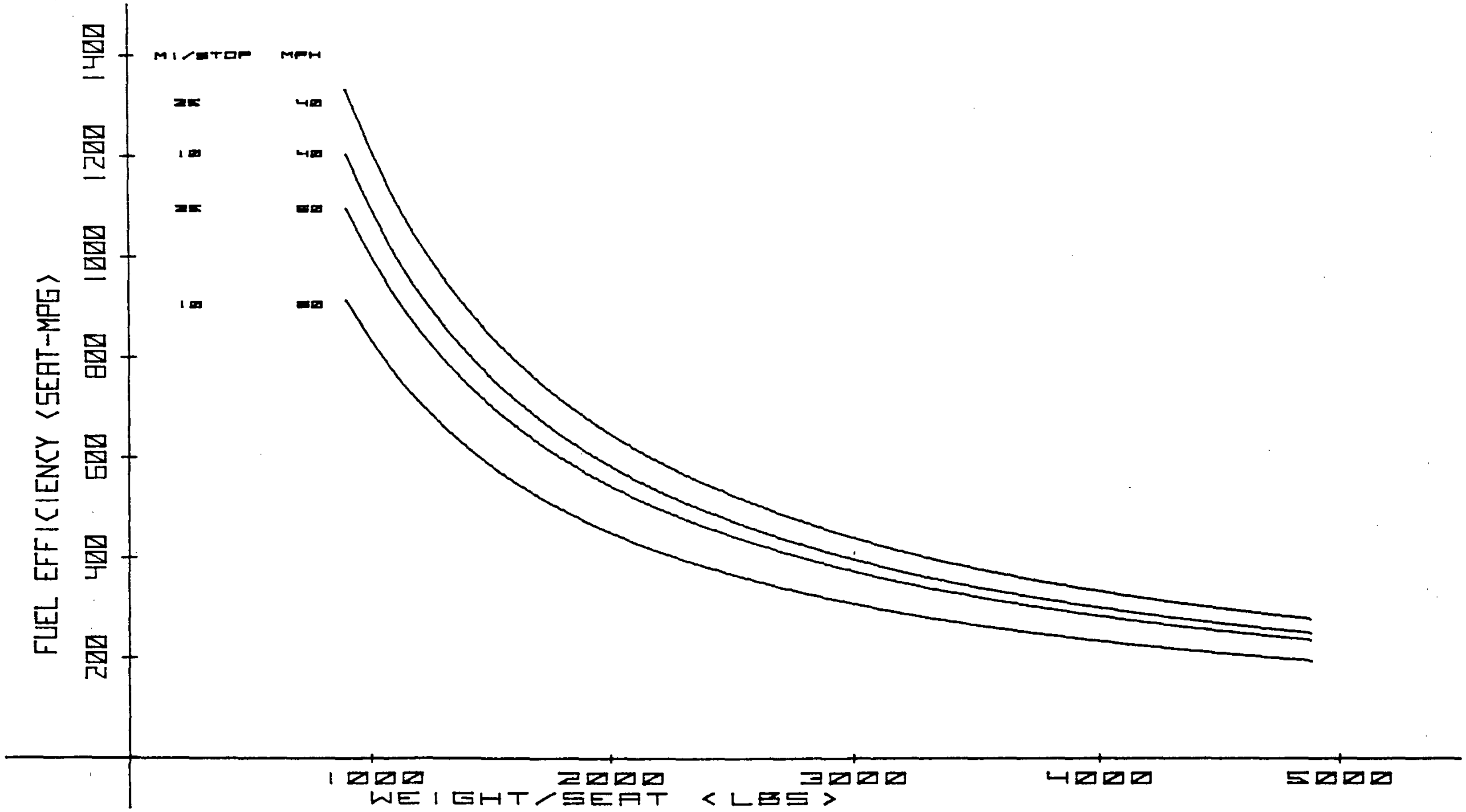

Figure 5-6. Fuel Efficiency as a Function of Weight per Seat.
10 Miles/Stop; 50% Idle Time

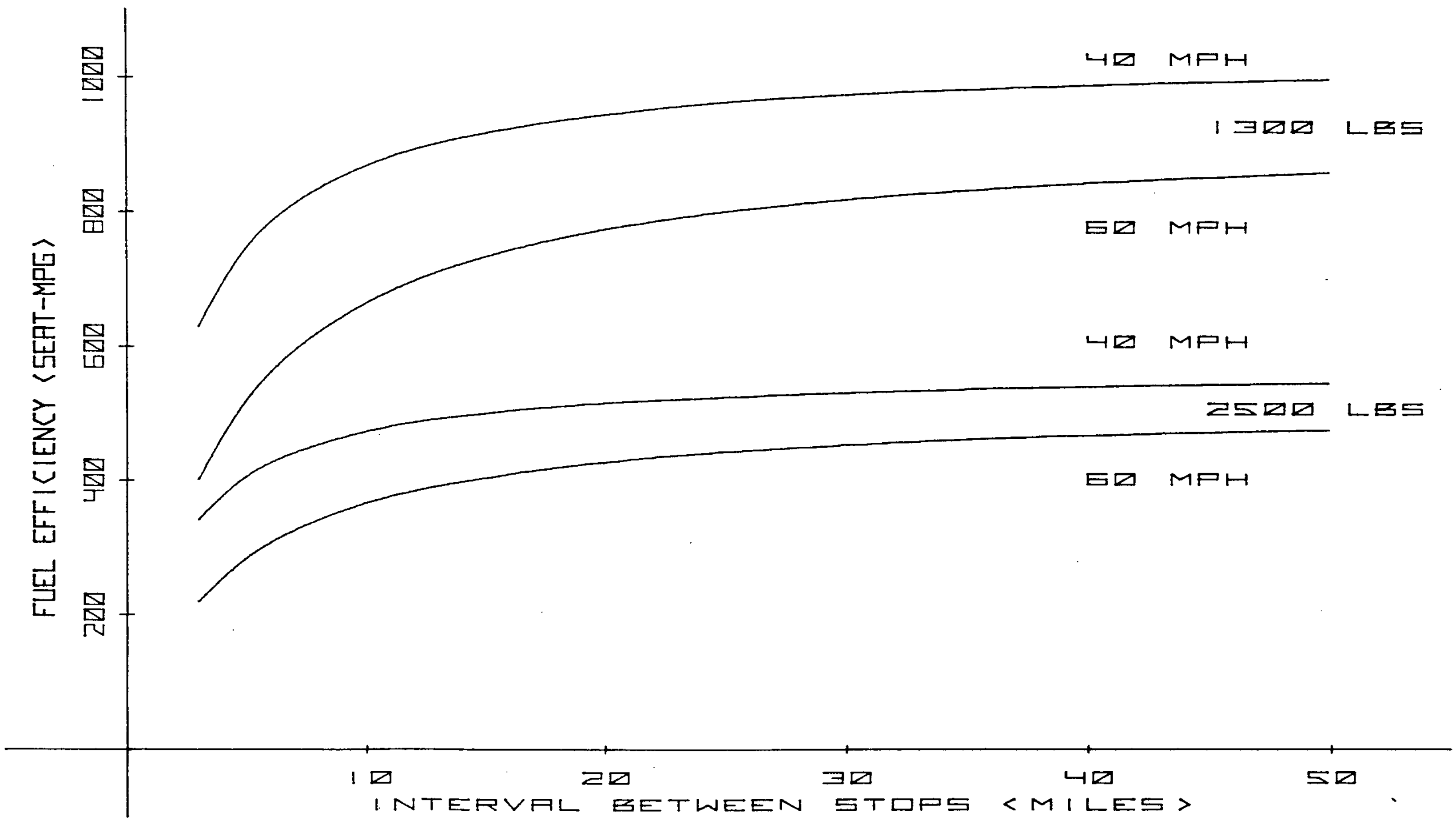

Figure 5-7. Fuel Efficiency as a Function of Distance Between Stops. (Various Weight/Seat)

provide an estimate of specific fuel consumption. However, one modification is desirable to retain some degree of realism in this highly-simplified approach. It must be assumed that the rated power provides an excess above that required to achieve the cruise speed on level terrain; both grades and acceleration to the desired speed must be considered. The methodology used here is to assume (in most cases) that the specified installed power will permit climbing of a .5% grade at undiminished speed; this is equivalent to a .005 g acceleration (6.5 MPH/min) at the cruise speed. For trains characterized by a power/weight of less than 10, a .33% grade criterion is applied, and in one case of high power/weight (31 HP/ton for 125 MPH cruise speed), 1% grade is used. With the further assumption of an 80% internal efficiency, one can then calculate the cruise power, and proceed as above. One additional factor which must be considered is efficiency of the power system. In view of the extremely approximate nature of this entire procedure, this element is accommodated by simply asserting an overall efficiency relative to that of the basic diesel prime mover of 80% for diesel-electric motive power, 75% for all-electric, and 35% for turbine. (The inherent fuel-to-available-power fuel-conversion efficiency of a large diesel engine is approximately 38%.) Table 5-2 presents the assumed train statistics; these figures should be valid, but are subject to error or change. In Table 5-3 resultant estimated operational characteristics are given; the inferential and highly approximate nature of these numbers is to be emphasized. The range of values for seat-MPG is ±10% from the calculated value, although significantly greater inaccuracies are possible.

It is to be emphasized that these results merely suggest the range of fuel efficiencies now obtained, and do not indicate the performance obtainable if equipment is optimized. All existing rolling stock was designed at a time when fuel consumption was a much less significant factor than is now the case, and major improvement should be possible.

TABLE 5-2. SUMMARY OF PUBLISHED DATA FOR EXISTING AND PLANNED HIGH-SPEED TRAINS. (Data May Contain Inaccuracies. Where Several Consists Are Possible, Typical Cases Have Been Assumed.)

TRAIN/NATION	STATUS[1]	MOTIVE POWER[2]	CRUISE SPEED (MPH)	INSTALLED POWER (HP)	SEATS	WEIGHT (TONS)
Metroliner/US	S	E	110	5900	246	360
TurboTrain/US	S	T	120	2000	144	128
TurboTrain/CN	S	T	95	1600	326	199
LRC/Canada	Ex	DE	118	5800	288	452
Tokaido/Japan	S	E	130	11900	987	820
951/Japan	Ex	E	160	2700	150	83
961/Japan	Ex	E	160	8800	490	240
HST/UK	S	DE	125	4500	372	600
APT/UK	Ex	T	155	4000	120	120
RTG/France	S	T	125	2300	280	280
RTG/(US Version)	S	T	90	2060	280	275
TVG001/France	Ex	T	185	5000	146	223
ETR/Italy	P	E	155	2400	175	167
ET403/Germany	Ex	E	125	4900	159	261
ER200/USSR	Ex	E	125	13800	872	1010

NOTES: [1]S = In Service; Ex = Experimental; P = Planned.
[2]DE = Diesel-Electric; T = Turbine; E = Electric

TABLE 5-3. CALCULATED INDICES AND ESTIMATED FUEL EFFICIENCY OF EXISTING AND PLANNED HIGH-SPEED TRAINS, DERIVED FROM PUBLISHED TRAIN SPECIFICATIONS, WHICH ARE SUBJECT TO ERROR AND CHANGE (These Values Are For Level Operation At Cruising Speed, And Do Not Include Stops, Slowing, Or Idling.)

TRAIN	HP/TON	HP/SEAT	LBS/SEAT	CRUISE SEAT-MPG (ESTIMATED)
Metroliner	16.3	23.9	2930	65 - 95
TurboTrain	15.6	13.9	1780	70 - 100
Turbo(CN)	7.7	4.9	1280	160 - 230
LRC	12.8	20.1	3140	115 - 170
Tokaido	13.7	11.4	1670	180 - 270
951	32.3	17.9	1110	120 - 175
961	36.8	18.0	980	115 - 170
HST	7.5	12.1	3220	220 - 330
APT	31.3	33.3	2130	75 - 110
RTG	18.1	8.1	2000	135 - 235
RTG(US)	7.5	7.4	1960	100 - 145
TVG001	22.5	34.5	3060	45 - 65
ETR	14.1	13.5	1910	75 - 115
ET403	18.9	31.0	3280	75 - 115
ER200	13.7	15.8	2320	120 - 180

APPENDIX

FUEL CONSUMPTION EQUATIONS

M. HAZEL

NOTATION

a	Acceleration in g's	----
d_a	Fuel-equivalent distance for acceleration	miles
d_g	Fuel-equivalent distance for grades	miles
e_a	Net energy per unit load for acceleration	hp-hr/ton
e_f	Total energy requirement per unit load for task	hp-hr/ton
e_g	Total energy rate required for grades at constant speed	hp-hr/ton-mile
e_h	Energy rate required for constant speed without grades	hp-hr/ton-mile
f_c	Vehicle capacity factor	----
f_e	Net engine energy conversion	hp-hr/lb
f_i	Idle fuel consumption rate	lb/hour
f_ℓ	Vehicle load factor	----
f_o	Total fuel consumption rate, including idle, accessory, and useful loading	lb/hour
F_a	Net fuel per unit load used for acceleration	lb/ton
F_f	Total fuel per unit load required for task	lb/ton
F_g	Total fuel rate required for grades at constant speed	lb/ton-mile
F_h	Fuel rate required for constant speeds without grades	lb/ton-mile
g	Acceleration due to gravity ($g = 79036$)	mile/hour^2
g_r	Grade, or slope ratio	----
L	Weight of cargo in a truck or rail car	tons
L_t	Total cargo weight (truck or entire train)	tons
m	Mass of vehicle	pound
N_c	Number of freight cars in train	----
N_ℓ	Number of locomotives in train	
P_a	Aerodynamic resistance	pounds
P_g	Resistance due to grades	pounds
P_i	Inertial resistance, due to acceleration	pounds

p_r	Rolling and other mechanical resistance	pounds
p_t	Total vehicle resistance at specified velocity, acceleration, and grade	pounds
P	Power required to move truck or train at velocity v (applied at wheels)	horsepower
P_a	Power required for accessories	horsepower
P_f	Power required to maintain (constant) velocity v_f	horsepower
P_i	Power consumed at idle	horsepower
P_m	Rated, or maximum power of engine	horsepower
P_o	Power output of engine (applied to input of transmission)	horsepower
r_a	Ratio of accessory to idle power	----
r_e	Efficiency of power transmission to wheels	----
r_i	Characteristic idle consumption rate	lb/hr/hp
r_o	Fuel energy-weight conversion factor	lb/hp/hr
v	Velocity	miles
s	Length of a grade	miles
W_c	Caboose weight	tons
W_ℓ	Locomotive weight	tons
W_t	Total vehicle weight (truck or entire train), including cargo	tons
W_v	Empty vehicle weight (truck or freight car)	tons
x_a	Energy-equivalent distance for acceleration	miles
x_f	Distance required for task	miles
x_g	Energy-equivalent distance for grades	miles

Note: Two constants which appear frequently are:

2000 is the number of pounds per ton

375 is the number of mile-lb per hp-hr.

Throughout this text the following definitions apply. The term "car" shall mean a rail vehicle which carries freight, principally a box car, but shall exclude locomotives and cabooses. The term "truck" shall mean any highway vehicle which has as its primary function the carrying of freight, and shall include the whole vehicle, whether it be a single unit, or made up of a tractor and one or more trailers or semi-trailers.

LOAD FACTOR AND CAPACITY FACTOR

Let the car or truck cargo weight, L, be some fraction of the maximum allowable cargo weight, L_{max}. That fraction is called the Load Factor, f_ℓ

$$f_\ell = \frac{L}{L_{max}}$$

Let the empty vehicle weight (car or truck) be W_v. A Capacity Factor, f_c, can then be defined as the ratio of maximum load to empty weight

$$f_c = \frac{L_{max}}{W_v}$$

The commonly used weights of vehicle-plus-load can then be expressed in terms of these factors.

$$\text{Maximum GVW} = W_v + L_{max} = W_v\ (f_c + 1)$$

$$\text{Actual GVW} = W_v + L = W_v\ (f_c\ f_\ell + 1)$$

And the load,

$$L = W_v\ f_c\ f_\ell$$

The gross weight of a complete train is

$$W_t = N_c W_v (f_c f_\ell + 1) + N_\ell W_\ell + W_c$$

and the total load is

$$L_t = N_c W_v f_c f_\ell$$

These equations for W_t and L_t apply equally for trucks as well as for trains if,

$$\text{for trucks} \begin{cases} N_c = 1 \\ W_\ell = W_c = 0 \end{cases}$$

FUEL CONSUMPTION

At idle, a Diesel engine consumes fuel at a rate

$$f_i = r_i P_m$$

where r_i is a characteristic rate independent of engine size,
and P_m is the maximum rated horsepower of the engine.

The effective power consumed by idle is

$$P_i = \frac{f_i}{r_o} = \frac{r_i}{r_o} P_m$$

where r_o is the energy-to-weight conversion factor for Diesel fuel.

When delivering engine output power P_o, additional fuel is consumed. Also additional load is placed upon the engine for accessories, such as fans and pumps. A reasonable approximation for this accessory power is

$$P_a = r_a \, P_i = r_a \, \frac{r_i}{r_o} \, P_m$$

where r_a is an accessory power ratio.

The power train (transmission, or generator-motor) driven by the engine will have some losses associated with it. Let that efficiency be called r_e. If the mechanical power required to move the truck or train under specified conditions is called P, then the engine output power required will be larger than P:

$$P_o = \frac{P}{r_e}$$

The total power developed is $P_i + P_a + P_o$ and the total fuel required is

$$f_o = f_i + r_o \, P_a + r_o \, P_o$$

The power available to pull the vehicle divided by the total fuel rate gives the net power plant energy conversion factor

$$f_e = \frac{P}{f_o} = \frac{r_e \, P}{(1 + r_a) \, r_e \, r_i \, P_m + r_o \, P}$$

which is valid for the range $0 < (P_o + P_a) \leq P_m$, or for

$$0 < P \leq (1 - r_a \, \frac{r_i}{r_o}) \, r_e \, P_m.$$

Note that the maximum energy conversion occurs when $P_o + P_a = P_m$, or

$$f_{e\ max} = \frac{(r_o - r_a r_i)\ r_e}{(r_i + r_o)\ r_o}$$

TRAIN RESISTANCE

The resistance force associated with a train moving on level, tangent track consists of a rolling component, P_r, (due primarily to bearing and wheel-rail energy dissipation), and aerodynamic drag, P_a. At present, neither term can be characterized precisely, either experimentally or analytically. However, a conventional formulation of long standing is widely used. This is the Davis[9] equation, which may be written as:

$$P_r = A + (B + Cv)W, \text{ and}$$

$$P_a = Ev^2,$$

with P_r and P_a in lbs, W the gross vehicle weight in tons, and v the velocity. Experimental findings by Schmidt[10] below 40 MPH basically were in agreement with coefficient values (A,B,C,E) given by Davis. These are suitable for use at low speeds. However, later measurements by Tuthill, at speeds up to 70 MPH, indicated a need for revision. Professor Tuthill fit the data with a set of equations for $P_i = P_r + P_a$ as a function of velocity only, with different coefficients for different weights. For simplicity, in the present application the Tuthill curves, as presented in Hay,[8] were fitted to an equation of the form

$$P_i = A + Bv + CWv + Dv + Ev^2$$

over a range from 35 MPH to 65 MPH to provide a satisfactory formula for higher speed freight car rolling resistance. In absence of other data, the Davis values for locomotives are used at all speeds.

For passenger trains, the curves of Totten[16] have been used, treated over the range 45 MPH to 75 MPH as were the Tuthill curves for freight cars. The coefficients resulting from all of these sources are presented in Table A-1. Note that the curve-fitting approach, applied over a restricted range, does not necessarily support a particular physical interpretation for each term; the negative D-value and high value for E (for freight cars at higher speeds) should not be surprising.

An alternative formulation could have been used. More recent tests by the Canadian National Railways, using modern rolling stock, imply somewhat smaller coefficients (lower train resistance) than for the original Davis equation.[17] However, in view of the widespread use of the Davis, Schmidt, and Tuthill values, and the desire that this analysis be a conservative one (erring, if necessary, on the side of over-estimation of fuel consumption), the CNR variation was not used.

When used in later sections of this text, p_a and p_r shall mean the total p_a or p_r for the entire train, calculated as

$$p_a = \sum_{i=1}^{N} (p_a)_i \quad \text{or} \quad p_r \sum_{i=1}^{N} (p_r)_i, \text{ respectively,}$$

where $(p_a)_i$ is p_a for the ith vehicle in the train of N vehicles, and similarly for p_r. N includes locomotives and caboose.

$$N = N_c + N_\ell + 1$$

TABLE A-1. COEFFICIENTS FOR TRAIN RESISTANCE

Coefficient

Vehicle	A	B	C	D	E
Freight car, caboose (low speed)	116	1.3	.045	0	.015
Freight car, caboose (high speed)	195	3.48	0.	-14.9	.362
Passenger Car	139	1.56	.023	0	.056
First locomotive	116	1.3	.03	0	.264
Additional Locomotives	116	1.3	.03	0	.045

$$P_i(v) = A + BW + CWv + Dv + Ev^2$$

TRUCK RESISTANCE

The equation for rolling (mechanical) resistance of large trucks has been determined as [18,19]

$$P_r = (A + B\ v)\ W_t$$

The road surface conditions (composition, roughness, wetness, etc.) and tire inflation play a role in determining values for A and B. Some typical values are given in Table A-2.

TABLE A-2. TRUCK RESISTANCE EQUATION PARAMETERS
(APPROXIMATE VALUES)

		A	B
Dry, Class I pavement	SAE HS-82[18]	15.2	.18
	Detroit Diesel[19]	13.5	.148

	Truck Width	Truck height	C
	8 feet	15 feet	.24
	8 feet	14 feet	.22
	8 feet	13 feet	.21

The aerodynamic resistance is difficult to generalize because it is dependent upon size and shape of the truck and number of trailers. A reasonable approach states

$$p_a = C\, v^2$$

where C is a parameter determined by the frontal area of the truck.

$$C = K\, w\, (h - \tfrac{3}{4})$$

where K is a constant determined to be approximately .0021,

w is width in feet, and

h is height in feet.

CONSTANT SPEEDS

In general, the power required to move a truck or train is

$$P = \frac{v}{375}\left[p_a + p_r + p_i + p_g\right]$$

where p_a and p_r are already defined,

p_i is the resistance force due to inertia, and

p_g is the resistance force due to grades and curves.

For level road or track and constant speeds, $p_i = p_g = 0$.

The energy rate required to maintain velocity v without acceleration or grades is

$$e_h = \frac{P}{v\ L_t} = \frac{1}{375\ L_t}\left[p_a + p_r\right]$$

The engine must provide output power

$$P_o = \frac{v\ L_t}{r_e}\ e_h$$

The specific fuel rate required is

$$F_h = \frac{e_h}{f_e} = \frac{1}{v\ L_t}\left[(1 + r_a)\ r_i\ P_m + \frac{r_o}{r_e}\ P\right]$$

provided that $P \le (1 - r_a\ \frac{r_i}{r_o})\ r_e\ P_m$

CONSTANT ACCELERATION

The additional resistance caused by constant acceleration, A, while increasing velocity from zero to the final, or line-haul, velocity, v_f, is

$$p_i = 2000\ \frac{W_t}{g}\ A$$

where A is the acceleration in miles per hour^2, and

g is the acceleration due to gravity, 79036 miles per hour^2.

However, acceleration is more conveniently expressed in "g's"

$$a = \frac{A}{g}$$

$$p_i = 2000\ a\ W_t$$

The power required at any intermediate velocity, v, is

$$P = \frac{v}{375}\left[p_a + p_r + p_i\right]$$

Note that both p_a and p_r are functions of velocity and that P increases (non-linearly) as the velocity increases.

The energy rate at any specific velocity is, as before,

$$e_h = \frac{P}{v\ L_t}$$

and the total energy per unit load required to accelerate to that velocity is

$$e_f = \int_0^x e_h\ dx$$

where x is the distance traveled while accelerating. Since

$$v = \frac{dx}{dt} \quad \text{and} \quad a\ g = \frac{dv}{dt}\ ,$$

the total distance required to accelerate from zero velocity to velocity v_f can be written as

$$x_f = \frac{1}{a\ g} \int_0^{v_f} v\ dv \quad = \frac{1}{2\ a\ g} v_f^2$$

and the total energy required is

$$e_f = \frac{1}{a\ g} \int_0^{v_f} e_h\ v\ dv \quad = \frac{1}{a\ g\ L_t} \int_0^{v_f} P\ dv$$

The total fuel required to accelerate from zero velocity to velocity v_f is

$$F_f = \frac{1}{a\ g} \int_0^{v_f} \frac{e_h}{f}\ v\ dv$$

$$F_f = \frac{1}{a\ g\ L_t} \left[(1 + r_a)\ r_i\ P_m\ v_f + \frac{r_o}{r_e} \int_0^{v_f} P\ dv \right]$$

with the usual restriction that $P \leq \left(1 - \frac{r_a\ r_i}{r_o} \right) r_e\ P_m$.

If the vehicle had traveled the entire distance x_f at constant final velocity v_f, it would have required power P_f to do so

$$P_f = \frac{v_f}{375} \left[p_a + p_r \right]_f$$

where the subscript f indicates evaluation of the bracketed terms at velocity v_f. The energy that would have been used is

$$x_f \left[e_h \right]_f = \frac{1}{2\ a\ g\ L_t}\ v_f\ P_f$$

and the fuel that would have been used is

$$x_f \left[F_h \right]_f = \frac{v_f}{2\ a\ g\ L_t} \left[(1 + r_a)\ r_i\ P_m + \frac{r_o}{r_e} P_f \right]$$

The net energy required for the acceleration is then

$$e_a = e_f - x_f \left[e_h \right]_f$$

and the net fuel used for the acceleration is

$$F_a = F_f - x_f \left[F_h \right]_f$$

$$e_a = \frac{1}{a\ g\ L_t} \left[\int_0^{v_f} P\ dv = \frac{1}{2} v_f\ P_f \right]$$

$$F_a = \frac{1}{a\ g\ L_t} \left[\left[(1 + r_a)\ r_i\ P_m - \frac{r_o}{r_e} P_f \right] \frac{v_f}{2} + \frac{r_o}{r_e} \int_0^{v_f} P\ dv \right]$$

Both valid only for

$$P \leq \left(1 - \frac{r_a r_i}{r_o}\right) r_e\ P_m$$

The vehicle, in accelerating, required additional energy e_a, and additional fuel, F_a, over that which it would have required had it traveled the same distance at constant velocity v_f. It is interesting to find out how much farther that energy, or fuel, would have taken the vehicle at velocity v_f if no acceleration were involved.

The energy-equivalent distance for acceleration, x_a, is defined

$$x_a \left[e_h\right]_f = e_a$$

$$x_a = \frac{v_f}{ag} \left[\frac{1}{P_f} \int_0^{v_f} P \, dv - \frac{1}{2} v_f \right]$$

The fuel-equivalent distance for acceleration, d_a, is defined

$$d_a \quad F_{h\ f} = F_a$$

$$d_a = \frac{{v_f}^2}{2\ a\ g} \left\{ 1 - \frac{2\ r_o}{(1 + r_a)\ r_i r_e P_m + r_o P_f} \left[P_f = \frac{1}{v_f} \int_0^{v_f} P \, dv \right] \right\}$$

GRADES (AT CONSTANT VELOCITY)

The additional resistance, p_g, caused by changing elevation is merely the component of the vehicle weight parallel to the slope. The slope ratio g_r is usually multiplied by 100 and called the "percent of grade". The resistance is

$$p_g = 200\, g_r W_t$$

Note that p_g can be either positive or negative, depending upon whether travel is uphill or downhill, respectively. The sum of resisting forces on grades is

$$p_t = p_a + p_r + p_g$$

For downhill travel ($p_g < 0$), the sum p_t could be negative, which would result in the engine attempting to supply negative power. So a restriction must be made that the brakes will be applied sufficiently to keep the required power from going negative. (The engine cannot run slower than at idle.) The usual restriction that the output power cannot exceed maximum rated power also applies. The power required to maintain velocity on grades is, then

$$P = 0, \; p_t \leq 0$$

$$P = \frac{v}{375} p_t, \quad \begin{array}{l} p_t > 0 \\ P \leq \left[1 - \dfrac{r_a r_i}{r_o}\right] r_e P_m \end{array}$$

The total energy rate required to negotiate the grade is

$$e_g = \frac{P}{v\, L_t}$$

and the total fuel rate is

$$F_g = \frac{e_g}{f_e} = \frac{1}{v\, L_t} \left[(1 + r_a)\, r_i P_m + \frac{r_o}{r_e} P\right]$$

The vehicle, in negotiating an upward grade of length s required additional energy, and therefore fuel, over that which it would have required had it traveled the same distance without grades at the same constant velocity. The energy without grades is

$$s\ e_h = \frac{s\ p_f}{v\ L_t}$$

where

$$p_f = \frac{v}{375}\left[p_a + p_r\right]$$

and the fuel without grades is

$$s\ F_h = \frac{s}{v\ L_t}\left[(1 + r_a)\ r_i P_m + \frac{r_o}{r_e}\ p_f\right]$$

The energy-equivalent distance for grades, x_g, is defined as the distance without grades the vehicle could have travelled on the additional energy at the same constant speed.

$$x_g e_h = s\ e_g - s\ e_h$$

$$x_g = s\left[\frac{p}{p_f} - 1\right]$$

The fuel-equivalent distance for grades, d_g, is defined as the distance without grades the vehicle could have traveled on the additional fuel at the same constant speed.

$$d_g\ F_h = s\ F_g - s\ F_h$$

$$d_g = \frac{s\ r_o \left[P = P_f\right]}{(1 + r_a)\ r_i r_e P_m + r_o P_f}$$

POWER-LIMITED (CONSTANT-POWER) ACCELERATION

The case of constant acceleration is so commonly found, and so easily treated analytically, that other possibilities are often ignored. However, the acceleration of vehicles often involves a different situation: full power is constantly applied, and is converted into acceleration (increase in kinetic energy) and heat (dissipation into rolling and aerodynamic resistance). Under these circumstances, dynamic behavior is described by equations rather different from those for constant acceleration.

In general, if power P is applied at the wheels, the associated force is P/v, where v is the vehicle velocity. By Newton's Law,

$$\frac{P}{v} - P_t = ma,$$

where P_t is the total resistance force, m is the vehicle mass ($m = W_t/g$), and "a" is the vehicle acceleration. Thus,

$$P = mav - P_t\ (v)$$

For low velocities the power which can be utilized is limited by wheel/rail or wheel/road adhesion; if greater power is applied, wheel spin will occur, with serious detrimental effect. This consideration may be incorporated into the analysis by assuming the instantaneous acceleration to be limited to some maximum value a_m, which will be equal to $g\eta$, where η is the coefficient of adhesion. Thus, the acceleration will be constant and equal to a_m (ηg) up to the speed v_o at which (by definition of v_o) the maximum available horsepower ($r_e P_m$) can be absorbed; v_o can be determined from the relationship:

$$r_e P_m = Ma_m v_o + P_t\ (v_o)$$

For speeds between zero and v_o, then the vehicle motion is described by the conventional equations:

$$a = a_m$$

$$v = a_m t$$

$$x = \frac{a_m t^2}{2} = \frac{v^2}{2a_m}$$

For speeds above v_o, however, the situation is more complicated. In general,

$$r_e P_m = mav + P_t(v),$$

or

$$a = \frac{dv}{dt} = \frac{r_e P_m - P_t(v)}{mv}$$

This differential equation is relatively cumbersome to deal with, since P_t is of the form $a + bv + cv^2$. In most cases, it will be simpler to carry out numerical integration to determine v or x as a function of time, or time to reach a given x or v. However, at low speeds the term can be omitted with little loss of accuracy, and explicit solution is possible. (Under these circumstances virtually all of the power is going into acceleration - increasing the kinetic energy - rather than overcoming train resistance.) Under this assumption,

$$r_e P_m = m a_m v_o, \text{ or}$$

$$v_o = \frac{r_e P_m}{m a_m}$$

and, for $v \geq v_o$

$$a = \frac{dv}{dt} = \frac{r_e P_m}{m} \cdot \frac{1}{v}$$

Since $v(t_o) \equiv v_o$,

$$\int_{t_o}^{t} v(i)\ \frac{dv(t')}{dt'}\ dt' = \int_{v_o}^{v} vdv = \int_{t_o}^{t} \frac{r_e P_m}{m}\ dt$$

and integration of this equation yields

$$\frac{v^2}{2} - \frac{v_o^2}{2} = \frac{r_e P_m}{m}\ (t - t_o),$$

with t_o the time at which acceleration from velocity v_o begins. This is equivalent to the direct energy relationship,

$$\Delta KE = P \cdot t \quad \left(\frac{m\Delta(v^2)}{2} = P \cdot \Delta t\right)$$

This may be solved explicitly for v:

$$v(t) = \sqrt{\left(v_o^2 - \frac{2r_e P_m t_o}{m}\right) + \frac{2r_e P_m}{m} \cdot t}$$

which is readily integrated to obtain

$$x(t) = x_o + \frac{m}{3r_e P_m} \left[\frac{2r_e P_m}{m}\ (t - t_o)\right]^{3/2}$$

The time required to achieve maximum velocity v_m is then obtained from the equation for v(t):

$$t = t_o + \frac{m}{r_e P_m} \left(\frac{v_m^2 - v_o^2}{2}\right)$$

and

$$x(v_m) = x_o + \frac{m}{3r_e P_m} \left(v_m^2 - v_o^2\right)^{3/2}$$

Since,

$$v_o = \frac{r_e P_m}{m a_m}$$

$$t_o = \frac{r_e P_m}{m a_m^2}$$

$$x_o = \frac{r_e^2 P_m^2}{2 m^2 a_m^3}$$

In the low-speed region, for which full power cannot be utilized, fuel efficiency will increase as power level increases to P_m (at v_o). However during most of this already-small interval, the efficiency will differ only marginally from the full power case. Above v_o, the full-power value is used. The total energy supplied (under the assumption of zero train resistance) is then

$$E = \frac{m v_m^2}{2}$$

$$f_{e\ max} = \frac{(r_o - r_a r_i) r_e}{(r_i + r_o) r_o}$$

Thus,

$$\frac{1}{f_e} = \frac{(r_i + r_o) r_o}{(r_o - r_a r_i) r_e}$$

$$= \frac{r_o}{r_e} \cdot \frac{1}{r_o} \; \frac{r_i + r_o}{1 - \frac{r_a r_i}{r_o}} \doteq \frac{1}{r_e} (r_i + r_o) \left(1 + \frac{r_a r_i}{r_o}\right)$$

$$\doteq \frac{1}{r_e} \left(r_i + r_o + r_a r_i + \frac{r_a r_i^2}{r_o}\right)$$

$$= \frac{1}{r_e} \left[(1 + r_a) r_i + r_o\right] \; .$$

Since $r_i/r_o \approx .05$, and $r_a \leq 2$, the error introduced is less than 1%. So the net fuel used for acceleration to velocity v is

$$F_a = \frac{mv^2}{2} \cdot \frac{1}{r_e} \left[(1 + r_a)r_i + r_o\right]$$

Recall that m = w/g. For weight in tons, v in MPH, and r_o, r_i in lbs/hp-hr,

$$F_a = \frac{1}{2}\left(\frac{2000\ W}{79,036}\right) v^2 \frac{1}{r_e} \left[(1 + r_a) \frac{r_i}{375} + \frac{r_o}{375}\right]$$

$$= 3.37 \frac{Wv^2}{r_e} \left[(1 + r_a)r_i + r_o\right]$$

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