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Development of Simulation Models For Predicting Heavy Vehicle Performance on Grade

by

Mayank Rastogi, B.Tech.(Civil)
Indian Institute of Technology, New Delhi, 1985

A thesis submitted to
The Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of
Master of Engineering

**Department of Civil Engineering
Carleton University, Ottawa
Ontario, Canada
August, 1989**

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To My Father

(Late) Dr. Mahendra K. Rastogi

Acceptance Sheet

The undersigned hereby recommend to the Faculty of Graduate Studies and Research acceptance of the thesis,

**"Development of Simulation Models
For Predicting Heavy Vehicle
Performance on Grade"**

submitted by

Mayank Rastogi, B. Tech.

in partial fulfillment of the requirements

for the degree of

Master of Engineering.

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August, 1989

Abstract

Heavy vehicles (trucks and recreational vehicles) pose a considerable problem with respect to the highway level of service, safety and operation, especially on grades where they are unable to maintain the speed acceptable to the other fast moving vehicles. Grade climbing abilities of these vehicles can be estimated by their performance characteristics.

Past and current available information was analysed and the need for new development was identified, to take into consideration the changing truck characteristics. In this thesis, the focus is on developing a detailed and analytical computer simulation model to predict the grade performance of these typical vehicles. The model incorporates changing truck technology and configuration of different truck types. It can deal with the case of recreational vehicles as well. Optional use of gear change delay is also included.

For comparison, a second model based on the Society of Automotive Engineers (SAE) recommended practice, was also developed and sensitivity runs were made for both models for different truck configurations and loading levels. Programming for both the models is done in a user-friendly atmosphere. Data were collected to get realistic inputs for the models. These model outputs were also compared to currently available sources and as well as with the field data.

It was found that the detailed model (Model I) is more sensitive to the truck type and loading level as compared to the SAE version (Model II). Representative truck should be changed to 180 kg/kw category which is being represented by 12.5 percentile of vehicle population. Also, present trucks of loading level of 180 kg/kw and 210 kg/kw cannot attain level grade highway speeds of 100 km/h and 90 km/h respectively. It is recommended that if detailed and reliable data is available Model I should be used. The final results are presented in both tabular and graphical forms. Applications of this research, conclusions and recommendations for further research are presented at the end of the thesis.

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Nomenclature

Following is the list of variables and their explanation as used in the text. Consistency has been maintained in the use of variables. To ensure clarity (especially where the units are different) there may be a case where a variable is being denoted by different notations in different contexts.

A	$\frac{3C_1}{25C_2}$ or frontal area of the vehicle
A_c, a	truck/vehicle acceleration
A_d	static rolling resistance coefficient
AF	altitude factor for engine performance correction
$AFAR$	altitude correction factor for air drag
AHP_e	air resistance horsepower at the given altitude
AHP_s	air resistance horsepower at sea level
A_i	respective frontal areas for tractor, semi-trailer and double-trailer
A_L	acceleration up/down grade
AR	total aerodynamic drag
AR_i	respective aerodynamic drags for tractor, semi-trailer and double-trailer (N)
AR_1	aerodynamic drag on tractor
AR_2	aerodynamic drag on semi-trailer
AR_3	aerodynamic drag on double-trailer
A_t	altitude factor
ATF	available tractive force from the engine
B_0	barometric pressure at standard conditions
B_a	barometric pressure at the carburetor air inlet
B_d	dynamic rolling resistance coefficient
B_v	atmospheric vapour pressure

C_1	$N_e R_r \pi$
C_2	$g_a g_g$ or overall gear ratio
C_D	drag coefficient
C_{di}	respective drag coefficient for tractor, semi-trailer and double-trailer
d_1	distance between hitch and drive axle
d_2	distance between semi-trailer C.G. and hitch
D_L	deceleration up grade
E	altitude of vehicle operation, above the sea level
E_0	equilibrium point, representing steady state speed
F	total tractive effort
F_f	tractive effort at the front axle
FHP	chassis friction horsepower
F_r	tractive effort at the rear axle
F_{hi}	horizontal reaction at hitch due to semi-trailer and/or double trailer
$F_{net,a}$	net force available for vehicle acceleration
$F_{net,b}$	net force causing vehicle deceleration on up grade
FR	frictional resistance of chassis
F_T	truck factor
g	gravitational constant
G	gear ratio with respect to drive wheel ($g_a g_g$)
g_a	drive axle ratio
GHP	grade resistance horsepower
g_g	particular gear ratio
GP	percentage of grade
GR	grade resistance or total gear reduction
GTE	tractive effort
GVW	gross vehicle mass

<i>GVWR</i>	manufacturer maximum gross vehicle mass rating of powered unit
<i>GW</i>	total gross weight, <i>lb</i>
<i>GWR</i>	manufacturer's maximum gross vehicle weight rating of powered unit, <i>lb</i>
<i>HT</i>	height of the vehicle
<i>i</i>	percent slip of vehicle running gear
<i>I</i>	moment of inertia of rotating components
<i>I_n</i>	particular gear number
<i>I_w</i>	moment of inertia of wheel
<i>j</i>	denotes the <i>jth</i> speed interval
<i>K</i>	tire growth factor
<i>L₁</i>	truck/tractor wheelbase
<i>L₂</i>	distance between hitch and rear axle of semi-trailer
<i>L₃</i>	distance between front axle and C.G. of the truck/tractor
<i>mph</i>	road speed
<i>M</i>	vehicle mass
<i>M₁</i>	mass of the tractor
<i>M₂</i>	mass of the semi-trailer
<i>M₃</i>	mass of the double-trailer
<i>M_e</i>	engine output torque
<i>ME</i>	equivalent mass of the whole vehicle
<i>M_v</i>	gross mass of the vehicle
<i>n</i>	number of vehicle components, viz. tractor, semi-trailer and double-trailer
<i>N_e</i>	engine speed
<i>NG</i>	total number of gears
<i>NHP</i>	certified net engine horsepower at sea level
<i>NHP_e</i>	net engine horsepower corrected for altitude
<i>NTE</i>	net tractive effort

OR	total resistance to vehicle motion
p	percent grade
P	engine power under given atmospheric conditions
P_0	engine power under standard atmospheric conditions
P_T	percent trucks in the traffic stream
r	rolling radius of the tire
R_a	aerodynamic resistance
R_d, R_{d1}	drawbar pull in case of double-trailer and recreational vehicle respectively
ΣR_g	summation of all resisting forces at a given grade
R_g	grade resistance
RHP	rolling resistance horsepower
ΣR_0	summation of all the resisting forces at level grade
rpm	engine speed
R_r	static rolling radius of drive axle wheel
R_{rf}	rolling resistance at the front axle
R_{rr}	rolling resistance at the rear axle
R_{rs}	rolling resistance at the rear of semi-trailer
R_{rv}	dynamic rolling radius of drive axle wheel
RR	rolling resistance
S_L	distance covered in acceleration during particular speed interval
$SLIP$	percent slip of vehicle running gear
$SLIPF$	slippage factor
t	ambient temperature
t_0	standard condition temperature
T	engine torque
TE	available tractive force
$TE(1)$	tractive force available as per road-tire adhesion

$TE(2)$	tractive force available as per engine characteristics with altitude correction
$TE(2)'$	tractive force available as per engine characteristics without altitude correction
TF	tire factor, tire rpm at 1mph
T_L	distance covered in deceleration during particular speed interval
TN	total number of wheels in the truck assembly
TND	total number of wheels in the drive axle
V	vehicle speed
V_0	equilibrium speed at any given grade
V_f	maximum attainable speed at the level grade
V_{max}	maximum allowable highway speed
V_w	wind speed
W	vehicle weight
W_1	tractor weight
W_2	semi-trailer weight
WD	width of the vehicle
W_{drive1}	normal reaction at the drive axle, in case of straight truck and recreational vehicle
W_{drive2}	normal reaction at the drive axle, in case of semi-trailer and double-trailer
W_{hi}	vertical reaction at hitch due to semi-trailer and or double-trailer
W_r	normal reaction at the drive axle
W_s	normal reaction at rear axle (or group of axles) of semi-trailer
X	$(A_d + B_d V)$
Z	$0.5\rho(V + V_w)$
α	engine utilization factor

γ_m	mass factor
μ	coefficient of road-tire adhesion
ν	truck equivalence kernel
ξ_0	overall gear ratio
η_e	engine speed
η_T	engine transmission efficiency
θ	grade slope with respect to horizontal
ρ	air density

All other variables like h , h_1 , h_2 , h_3 , h_a , h_{a_1} , h_{a_2} , h_d , l_1 , l_2 , and l_3 etc. are quite evident as shown in the respective figures.

Chapter 1

Problem Definition

1.1 Problem Background

The vast majority of Canadian intercity highways are made of two-lane roads. Besides various other reasons, significant up grades can also pose operational and safety problems at some places (as discussed later). These problems can often be attributed to three basic causes:

- 1) Inadequate road geometry (e.g. roadwidth, grades, alignment and sight distances), either at specific locations or over long sections;
- 2) Lack of passing opportunity either due to limited sight distances, heavy oncoming traffic volumes or grades unnegotiable at reasonable speeds by heavy vehicles; and
- 3) Traffic conflicts due to turns at intersections and driveways.

Many of these operational and safety problems (as seen later) can be overcome by extensive highway realignment, construction of four-lane divided highways, provision of access control and major intersection improvements. An alternative approach is to provide low-cost improvements on existing two-lane rural roads. Such improvements include provision of passing lanes, turning lanes and localized alignment improvements. On two-lane highway up grades, a number of problems are being posed by slow moving heavy vehicles, in terms of increased travel time, reduction in level of service, increase in accident rates, driver frustration, and limited or no passing opportunities for the following traffic. Evidence of these problems are discussed in the following sections.

1.2 Evidence of Need

The effect of grades on speed of heavy vehicles has been one of the major problems for the smooth flow of traffic. Heavy or low performance vehicles pose safety problems (i.e. accident involvement), delays due to slower speeds on grades, discomfort, driver frustration, and inconvenience for the following traffic. Realistic design of highway grade sections, should therefore make use of the grade performance curves for these heavy vehicles.

The gravity of the problem is illustrated by the increasing use of highways for goods transportation, increase in commercial and heavy vehicle population, increased accident involvement of heavy vehicles and various cost and monetary implications arising from the above causes.

1.2.1 Usage

The increasing use of highways by trucks is documented in Figure 1.1. It is observed that truck volume on Ontario highways has increased by 19.8% during the period of 1983 to 1987 (1). Usage of road network by trucks as compared to total vehicles can be inferred from a usage index 'registered vehicles per kilometer of road'. In 1970 there were 2.2 registered trucks per kilometer of road. The corresponding 1985 figure was 4.3 registered trucks per kilometer of road. The respective figures for total vehicles for 1970 and 1985, are 10.6 and 18.7 registered vehicles per kilometer of road. This shows an increase in percentage usage of highways by trucks over the time as compared to total highway usage, from 20.75% in 1970 to 23.0% in 1985 (2).

1.2.2 Truck Population

Besides increased usage of highways by trucks, an absolute increase in the number of registered commercial vehicles (typically low performance vehicles) in Ontario also occurred from 1983 to 1987. In percentage terms, it has increased by 28.8% from 1983 to 1987. Figure 1.2 depicts this trend (1). Looking at figures from 1966

LEGEND: Freeways
 Other King's Hwys
 All Highways (NOTE: This total includes Secondary and Tertiary roads)

Type of Road	1983	1984	1985	1986	1987
Freeways	2,707	2,793	3,031	3,242	3,464
Other King's Hwys	1,929	1,940	1,918	1,961	2,108
All Hwys	4,736	4,835	5,049	5,305	5,676

Source: (1)

Figure 1.1 Annual Truck Travel Experience (Ontario)

Registered Type of Vehicle	1983	1984	1985	1986	1987
Commercial	775,479	858,213	904,111	946,145	998,473

Source: (1)

Figure 1.2 Commercial Vehicle Registration (Ontario)

to 1986, trucks showed a population increase of 143% as compared to automobiles which showed an increase amounting to only 121%. Also percentage of trucks in total vehicle population increased from 21.4% in 1966 to about 25% in 1988 (2).

1.2.3 Safety

With the overall increase in accident rates (1), it becomes quite imperative to observe the extent of heavy vehicle (truck) involvement in highway accidents.

After recognizing the trends in the highway usage and truck population, the safety studies show a remarkable increase of 40% in truck accidents on Ontario highways from 1983 to 1987 (1). Figure 1.3 shows the increasing trend of truck accidents on freeways and other highways as well.

This observation about accidents highlights the safety issue being posed by truck operation. One of the major factors influencing accidents is the speed differential of heavy vehicles (especially on steep grades with limited or no passing) from the normal highway operating speed.

Figure 1.4 also illustrates the accident involvement rate of truck, depending on the various allowable speed reductions. It is observed that speed reduction of 15 *km/h* is critical, after which accident rates tend to increase very fast. At such locations, where speed reductions are greater than 15 *km/h*, alternative solutions to segregate the trucks (or low performance vehicles) from the main traffic stream should be investigated.

1.2.4 Delays and Discomfort

Delays and inconvenience are encountered by other highway users due to slow moving vehicles on grades. Specifically, on a two-lane highway up grade, where passing opportunities are restricted or absent, considerable amount of driver frustration occurs due to the low performance of these heavy vehicles. It can be seen in the Highway Capacity Manual (30) that highway speeds and associated delays are major concerns in the provision of adequate level of service (LOS).

LEGEND: ● Freeways
 ■ Other King's Hwys
 ⊖ All Highways (NOTE: This total includes Secondary and Tertiary roads)

Type of Road	1983	1984	1985	1986	1987
Freeways	1,724	2,134	2,484	2,552	2,680
Other King's Hwys	1,856	2,046	2,254	2,234	2,339
All Highways	3,666	4,274	4,837	4,875	5,132

Source: (1)

Figure 1.3 Trends in Truck Accidents on Ontario Highways

Figure 1.4 *Accident Involvement Rate for Trucks on Two-lane Roads*

1.2.5 Cost Implications

Due to accidents, personal injuries and property losses occur. Studies show that in the period of 1983 to 1987, personal injuries on provincial highways have increased by 46.6% and property damage costs have markedly increased by 77.3%. Trucks due to their size, performance characteristics and associated monetary value, may be responsible for much of these personal injuries and monetary costs. Increased fuel consumption in cases where faster traffic is trapped due to slow moving vehicle or vehicles, also adds to the cost. Using dollar value for the loss of time occurring due to slower speeds, delays also contribute to the cost implications.

Given these above observations and findings regarding safety, delays, inconvenience, cost implications, driver frustration and overall level of service, it is necessary to investigate the performance characteristics of these impeding vehicles. These vehicles can be trucks and commercial vehicles or recreational vehicles.

1.3 Problem Definition

Following the above identification of the problem, the problem definition can be structured as given below.

1.3.1 Objective

The objective is to predict the performance characteristics (speed-distance curves) of heavy vehicles on grades, knowing that speed reductions of these vehicles on grades cause considerable loss of level of service, and cause accidents, driver frustration, and personal and property damage. These performance curves form a basis for the decision making process in the provision of alternate facilities that alleviate the problem.

Thus a basic and detailed computer simulation model for the heavy vehicle performance should be developed. Also, to check the model's validity, a second

model based on Society of Automotive Engineers' (SAE) recommended procedure, which was used by some previous researchers, should also be developed.

1.3.2 Inputs and Outputs

Inputs in this particular problem context deal with the information on truck or recreational vehicle weight/power ratio and various other input parameters required for the simulation process. Outputs are sought in the form of speed-distance curves at various grades for different weight/power ratios and truck configurations. These outputs in turn give us the idea of vehicle gradability, crawl speeds on grades and critical lengths for different grades (critical length is defined in a later section).

1.3.3 Constraints

Possible constraints affecting the problem can be :

- inadequate information on vehicle weight/power ratio for establishing a representative truck or recreational vehicle
- time and fiscal limitations to gather information on vehicle characteristics and loading practices
- limited response rate for surveys (if any)

1.3.4 Value Functions and Decision Criteria

As for the product of this research, value functions are not required. Decision criteria for assessing the product are the reasonableness and accuracy of the speed-distance functions. Apriori, it is required that the output of this research should compare reasonably with the field data and other speed-distance functions. However, the exact level of closeness cannot be specified at the outset of this research.

As for the application of the product of this research, as outlined earlier, proper and accurate solution approach would result in appropriate provision (design, location and length) of the alternate facility (climbing lane, as defined in a later section). This will further result in:

1. reduction in accidents and hence increase in highway safety
2. reduced driver frustration
3. less delays and inconvenience for the traffic
4. savings in fuel and property damage costs, and less personal injuries
5. improvement in the level of service for the highway section

Aesthetics of highway with and without the provision of climbing lane would normally be of minor significance if it is being warranted by one or more of the above discussed safety or operational considerations. Through well established highway design practices, the addition of climbing lanes should not result in highway aesthetics issues.

1.4 Context Within Transportation Engineering

Development of a performance simulation model would aid the decision on climbing lane planning, design and location. Presently there is no vehicle performance simulation package commercially available which can be used to *generate* the performance curves for the desired weight to power ratio and vehicle configuration. All what is available, is in the form of speed-distance curves in various sources.

The importance of climbing lanes and the magnitude of benefits achieved, can very well be imagined in the light of previous discussions and also by the following observations.

In Canada, climbing lane locations total 1,688 with about 176 in the province of Ontario and in U.S. there are 1,529 installations. Eight provinces in Canada and 34 states in U.S. intend to install climbing lanes in next 5 years (3). It shows the amount of attention which climbing lanes should receive with respect to planning, design and operation. A realistic decision framework for climbing lane design and

location advocates the need for accurate performance curves for heavy vehicles, besides other design and cost-effectiveness procedures.

In Canada, warrants for the climbing lanes include various speed reductions, level of service and traffic volume criteria. Various operational and safety benefits which occur due to climbing (and passing) lanes can be summarized as follows (3):

1. Climbing lane installations have shown to decrease accident rates by 25% as compared to untreated two-lane sections. Safety benefits also occur downstream of climbing lanes, which closely relate to the platooning benefits. Figure 1.5 (4) shows accident rate reduction due to provision of climbing lanes, for a Swedish study.
2. Climbing lanes are effective means of overcoming delays caused by slow moving vehicles, on steep grades. These facilities also improve traffic operation by breaking up platoons caused by inadequate passing opportunities.

Swedish experience (3) shows reduction in accident rates of 31% for hills with climbing lanes. These observations are:

Hills with climbing lanes	$0.44a/mapk \pm .04$
Hills without climbing lanes	$0.64a/mapk \pm .05$
National average on 90 km/h road	$0.44a/mapk$

where:

$a/mapk$ = accidents per million axle pair kilometer

Also several studies on overtaking (passing and climbing) lanes showed accident rate reduction (3). These are:

Voorhees (1968) U.K.	- 13% reduction
Rinde (1977) California	- 25% – 27% reduction
Harwood and St. John (1985) U.S.	- 38% reduction for all accidents
	- 29% reduction in fatal and injury accidents (76 sites)

Source: (4)

Figure 1.5 *Accident Rate Reduction Due To Climbing Lanes on Two-lane Roads in Sweden*

Thus, climbing lanes or passing lanes prove to be an asset for improving traffic operation, reduce delays and avoid accidents on up grades. Climbing lanes involve huge sums of money and as such, the decision regarding their planning, design and location should be governed by accurate and realistic inputs. One of the major inputs is the grade performance characteristics of a typical heavy vehicle.

1.5 Problem Solution

In light of previous discussions on improving the speed of traffic on up grades, the possible solutions, seem to be:

- (a) provision of facilities (e.g. climbing lanes) for slow-moving vehicles to avoid main traffic stream (which requires accurate prediction of vehicle performance characteristics), and
- (b) improving the speed of slow moving vehicles.

Option (a) seems to be more reasonable and practicable. In option (b), the way to achieve the objective would be either to reduce the payload or to increase the engine power (1), both of which will likely be uneconomical in the long run, because most of the time the vehicle will be under-utilized e.g. on the level or quite low up grades. Unless and until the speed of the vehicle falls below some predetermined minimum speed, climbing lanes are not generally warranted. Particular length of the grade beyond which the vehicle speed will drop below the desired speed level is called the "critical length".

Critical Length of the Grade:

Critical length of a grade is the length which will cause a representative vehicle to decelerate from entry speed to an acceptable minimum speed on the grade. Speed which is lower than the minimum designated speed, is considered to be unsafe and operationally inefficient (12,18,29).

Climbing Lane:

Climbing lane is an auxiliary lane adjacent to the main up grade travel lane, on which the slow moving vehicles can operate without hindering the main traffic.

Generally, climbing lanes extend from the point on the up grade where the heavy vehicle speed falls below the minimum allowed up grade speed, and upto the point where once again the speed becomes the same as it would be at the start of the climbing lane. Typical configuration for a climbing lane is shown in Figure 1.6.

Other factors which may determine the location and provision of climbing lanes are economic efficiency, safe sight distances, passing opportunities, adjacent terrain and traffic volume. A treatment of these factors and methodology for their incorporation in analysis and evaluation tasks is beyond the scope of this thesis research.

1.6 Thesis Organization

Chapter 2 examines the past works related to the performance characteristics of the heavy vehicles and comments on their deficiencies. Further, the research framework and methodology, adopted for this study are covered.

Chapter 3 contains some basics of the vehicle characteristics in general, drag forces acting on the vehicle and a description of power plant and transmission characteristics. Also, various approaches for studying vehicle performance are identified and explained, and the simulation approach defended as the one.

Chapter 4 outlines the data requirements for cases of truck and recreational vehicle simulation. Various surveys along with the information collected are reported. As a result, design (representative) truck and recreational vehicle were

Figure 1.6 *A Typical Climbing Lane Section*

identified for use in computer simulations. Details of field study on truck and recreational vehicle speed and data collected, are also reported in this chapter.

Chapter 5 describes the simulation model (Model I) in detail. A complete explanation of different modules of the simulation is provided. Model structure and logic are also shown for complete understanding. Application of the model in the case of recreational vehicle and its prominent features are also outlined.

Chapter 6 describes Model II, based on SAE recommended practice, and includes the simulation model framework with its various sub-modules.

In Chapter 7, outputs from the two models are compared with each other, with similar results from other sources and agencies, and with field data available from them.

Chapter 8 deals with the applications of performance curves (i.e. the model outputs) in case of climbing lane decisions and determination of truck equivalency factors.

Finally, conclusions and recommendations are given in Chapter 9.

Five Appendices are included at the end of this thesis. *Appendix A* contains input variables and program listing for the two models. *Appendix B* presents details of input data and output curves for both the models. Rationale for vehicle mass and dimensions used in the work, is given in *Appendix C*. Technical data and details for representative trucks and recreational vehicles are included in *Appendix D*. Finally, *Appendix E* contains a copy of questionnaire which was used for gathering information on truck power, weight and dimensions.

Chapter 2

Previous Studies and Research Framework

2.1 Overview

One of the major impedances to the flow of traffic on a two-lane roadway is the ever-increasing population of vehicles having non-uniform performance (1,2). As volumes on two-lane highways grow, the variance in vehicle performance also grows. The differences in performance characteristics between heavy vehicles and other normal traffic are more pronounced on grades and are responsible for much of the traffic instability, accidents and loss of highway capacity and therefore reduce the level of service offered by the roadway (1,2,3,4,5).

The vehicles which generally pose these kinds of problems are heavy commercial vehicles like trucks and combination vehicles, recreational vehicles including campers and travel homes, passenger cars of low performance and other typically low performance vehicles found on highways.

2.2 Past Studies

Various truck gradability procedures have been developed and used to predict the performance of trucks and longer combination vehicles on grades, in an effort to establish a design procedure that will enable all the vehicles to operate safely on highways.

Extensive study on truck performance was done by Saal (5) taking into consideration gross mass, tractive effort and grade. This was further used by Taragin

(6) to evaluate the grade length effect on heavy vehicles and to develop speed-distance curves. This formed the basis of American Association of State Highway Officials (AASHO) manual for geometric design in 1954 (7). Later on, Willey (8) also documented truck performance on grade and classified them into four main categories.

Further, Glennon (12) examined and compared various available prediction procedures used by Willey (8), Huff and Scrivner (9) and Firey and Peterson (10). Considerable disparity was evident among various prediction methods. Huff and Scrivner values were considerably higher than others. Also, various methods and assumptions were adopted by each in developing the performance model.

In Huff and Scrivner (9) a simple analytical formulation was used in conjunction with vehicle tests to describe the acceleration and deceleration of a heavy truck on grade. In Firey and Peterson (10), coasting test results were used in an analytical model to produce performance curves for a range of weight/power ratios and grades. This work incorporates gear shift delays but does not identify separate power losses.

At that time, however, Huff and Scrivner values were the only values verified by the actual field tests of a heavily loaded truck, and as such they were adopted by ASSHO (11) policy in 1965. The entry speed of 47 mph (75 km/h) used at that time, (where the normal highway speed these days is 90 to 100 km/h) and the representative vehicle identified as 400 lb/hp category, are no longer valid. Smith (13) also investigated and developed a computer program to estimate the vehicle performance.

The procedure given by the Society for Automotive Engineers (SAE) (15,16), describes steady-speed power losses in detail, but is not applicable to dynamic situations in which gear-shift delays can be taken care of. Later on, John and Kobett and others (17,18), did some work on traffic flow stability and capacity for the U. S. Federal Highway Administration (FHWA), in which they based their model largely on SAE (15,16) procedure with some adjustments to rolling resistance coefficient and aerodynamic drag coefficient, as given by SAE.

Further, in order to review the American Association of State Highway and Transportation Officials (AASHTO) study on vehicle weight/power ratio (19), Hayhoe and Grundman (20) in 1978 recommended that weight/power ratio of the representative truck should be changed from 400 lb/hp which was then prevalent, to 300 lb/hp with the highway speed of 55 mph (88.5 km/h). They also used an analytical model based primarily on the SAE prediction model, which is largely empirical and aggregate in nature.

In association with the California Department of Transportation, Abbas and May (21) developed performance curves, especially for five axle trucks based solely on the model given by John and Kobett (18). The trucks were simulated for 50 and 12.5 percentile speed, as observed in the field study. In this model, they assumed changes in the rolling resistance coefficient and in the aerodynamic drag coefficient. The former was reduced to 22% of the SAE recommended value and latter to 72% of recommended value, to get a close agreement with the published and calculated performance curves. This reduction has no particular basis. Recently Safwat and Walton (22,23) made the same assumption with respect to these coefficients. This happens to be the latest work (1986) related to performance characteristics of heavy vehicles.

2.3 Deficiencies in Previous Studies

Until now, most of the models for the heavy vehicle performance were not detailed and explicit, mainly using empirical relations. The level of details varied quite a bit. It is required that a separate, basic, and detailed model be developed which can be used quite independently in the future. All the variables and coefficients used should be explicit and not built in, as in several studies like SAE, etc. The major drawbacks of the currently available works are:

- 1) Most of the models are based on empirical formulations and the values used therein may not be valid at present. A more basic and fundamental model formulation is therefore required.

- 2) Assumptions about the truck technology, especially engine and transmission, efficiency, drag coefficients, and vehicle configuration (number of axles and tires) may not be valid at present, due to improvements in truck technology and aerodynamics. These changes can affect the values of coefficients used.
- 3) All the work presently available has no capability to treat different kinds of truck configurations like straight truck, semi-trailer and double-trailer in a distinct manner, as these models are based on weight/power ratio only and do not take into account the effect of axle and wheel configurations.
- 4) Information of truck aerodynamics was limited as applied to these works. Recent and more detailed work is available, taking into consideration the aerodynamics of tractor and semi-trailer (24,25,26).
- 5) Considering the changed regulations regarding weight and dimension limits in the truck operation, details of the representative vehicle as used in the previous studies, should be investigated.
- 6) The performance model should be able to deal effectively and independently with the case of recreational vehicles.

Thus by recognizing the problem posed by heavy vehicles on grades and analysing the previous works done on this subject, it is desirable to investigate more into the performance aspects of heavy vehicles, by developing a realistic simulation model.

2.4 Research Framework

The problem of low performance vehicles moving up grade along with other traffic of relatively high speed, on a two-lane two-way highway is quite crucial, as passing and lane changing opportunities are at times is quite restricted. Determination of critical length and decision to provide climbing lanes depends a lot on the

vehicle acceleration and deceleration up and down the grade. Realistic performance curves are needed to alleviate the problem.

2.4.1 Research Needs

Current performance curves and other related information may not be relevant for the reasons discussed above. Some major ones are:

- Changing truck characteristics due to change in engine and transmission capabilities;
- New and changed sets of allowable weights and dimensions and hence change in loading and usage pattern of the heavy vehicles;
- Different truck configurations due to change in axles, tires, aerodynamics.

Canadian planning and design guidelines and policy manuals containing heavy vehicle performance information, need to be updated. The curves used by the Ministry of Transportation, Ontario (MTO) date back to the 1960s (27). In the late 1970s, as a part of a highway capacity seminar, relatively new truck speed distance curves were introduced (28). However, these curves suggest the use of a design vehicle of weight-to-power ratio of 200 kg/kw (329 lb/hp). The 'Manual of Geometric Design Standards' published by the Roads and Transportation Association of Canada (RTAC) also contains the similar curves (29).

Recent highway design policy manual of the American Association of State Highway and Transportation Officials (AASHTO) and Highway Capacity Manual of the Transportation Research Board (TRB) (19,30), contain truck performance curves that reflect decreasing weight/power ratios. The curves in the AASHTO manual (19) are also taken from reference (20), which for the reasons stated before may not be reliable, being the outcome of the aggregate SAE procedure. TRB (30) to some extent, also relied on the same source.

Since the publication of the TRB manual, not much work has been done to update the information on performance curves, especially in the wake of improved information based on truck characteristics in recent years (15,26,33,37,38).

The need for improved information is critical, given that truck fleet characteristics have changed over time and further changes are quite likely owing to the liberalized weights and dimensions regulations. Thus the main objective of this work is to develop realistic speed distance curves (performance curves) that reflect the characteristics of existing and future heavy vehicles and recreational vehicles on Canadian highways.

2.4.2 Research Methodology

Development of curves that represent heavy vehicle performance on grades, and the use of these curves for establishing critical length of grades, requires information on the following factors:

Design or representative truck and recreational vehicle;

Weight to power ratio, engine and transmission details and general geometric details for the representative models.

The research methodology developed, takes into account the need for information. Figure 2.1 presents the overall research methodology that is followed in this study. At the start, the group of vehicles that should be considered (e.g. recreational vehicles, straight truck, semi-trailer and double-trailer) are defined. Design features and parameters are studied next. The main variables included in the study are: engine power and efficiency, gross mass, loading level, transmission characteristics, dimensions, tires and axle configurations etc. Further, the methodology and assumptions of all the existing works on performance curves were reviewed.

It was felt that simulation (Chapter 3 explains why simulation was preferred over other available methods of studying vehicle performance) modelling of trucks

Figure 2.1 *Research Methodology*

as well as recreational vehicles is required to give a complete picture of slow moving vehicles. In addition, simulation itself lent to a wide variety of sensitivity runs for different weight/power ratios, transmissions and entry speeds.

Two models were developed for estimating the speed-distance curves. The first model was a detailed simulation. The second was based on the Society of Automotive Engineers' (SAE) recommended procedure (15,16). The second method (Model II), though still a simulation procedure, used empirical formulations rather than use of basic principles as in Model I. In addition to various design features and parameters, operational parameters were also included in the Model I formulation. These are mentioned in Figure 2.1.

Next, these theoretical results were compared with the field observations and other up-to-date works as a check on accuracy and validity of these models. The results of these comparisons and outcomes have been reported in Chapter 7.

2.4.3 Rationale for Research

It is recognized that for the development and assessment of the performance curves, the following should be done:

- For discussion of any disagreement between theoretical and field characteristics of curves, theoretical weight/power ratio and the 'cube-out' phenomenon should be used as a basis;
- Variation of performance within and across the vehicle classes should be considered. To explore this variation, sets of curves representing various loading levels and entry speed for a given class of vehicle be produced.

In addition to the basic and detailed model (Model I), another simpler and aggregate model (Model II), based on the SAE procedure was also devised for comparison and comment on the others' applicability. With Model I, various types of truck configuration were simulated for various loading levels. The loading levels were: very heavy load (possibly an overload case - 210 kg/kw), heavy/full load

(nearly 100% load factor of 'load-out' case - 180 kg/kw), intermediate load (about 70% load factor or 'cube-out' case - 120 kg/kw) and lightly loaded (about 30% to 40% load factor, partially loaded - 60 kg/kw).

For Model II, as it is not capable of differentiating among truck types, only a generic truck was simulated for various loading levels. Outputs for both the Models I and II are in Appendix B. Two representative cases, 180 kg/kw and 120 kg/kw with the entry speed of 90 *km/h*, were selected for inclusion in this report.

Chapter 3

Performance Characteristics of On-Road Vehicles

Performance characteristics of an on-road vehicle are defined as its capability to accelerate and decelerate and to negotiate grades. The factors which largely influence the performance potential of the vehicle are tractive effort and the resisting forces.

3.1 Vehicle Kinetics

The external forces which act on a two axle vehicle, as in the case of straight trucks and recreational vehicles, are shown in Figure 3.1. These forces are aerodynamic resistance R_a , rolling resistances of front and rear tires R_{rf} and R_{rr} , drawbar load R_d , grade resistance R_g and tractive effort of the front and rear tires F_f and F_r . Depending on weather the vehicle is front wheel drive or rear wheel drive, values for F_r and F_f are respectively zero. The equation of motion is then:

$$M \frac{d^2 x}{dt^2} = a \frac{W}{g} = F_f + F_r - R_a - R_{rf} - R_{rr} - R_d - R_g \quad (3.1)$$

where M and W are vehicle mass and weight respectively and a or $\frac{d^2 x}{dt^2}$ is linear acceleration.

Representing R_r as total rolling resistance and F as total tractive effort, the above equation can be written as:

Figure 3.1 Forces acting on a Two Axle Vehicle

$$F = R_a + R_r + R_d + R_g + a \frac{\ddot{v}'}{g} \quad (3.2)$$

Two factors limit the tractive force developed by the vehicle. One factor is governed by coefficient of road-tire adhesion ¹ and the normal load on the driven axle and the other is determined by the engine and transmission characteristics. The smaller of the two will limit the performance of the vehicle (39).

To calculate the maximum tractive effort that the tire-ground contact can support, the normal loads W_f and W_r have to be determined. These are given as:

$$W_f = \frac{Wl_2 \cos \theta - R_a h_a - h \frac{W}{g} a - R_d h_d \mp Wh \sin \theta}{L} \quad (3.3)$$

and

$$W_r = \frac{Wl_1 \cos \theta + R_a h_a + h \frac{W}{g} a + R_d h_d \pm Wh \sin \theta}{L} \quad (3.4)$$

where variables are shown in Figure 3.1.

In the case of tractor semi-trailers, the maximum tractive effort which tire-ground contact can support can be found similarly. See Figure 3.2.

Generally, in most of the tractor semi-trailer assemblies the rear axle is the drive axle. Consequently to compute the maximum available tractive effort due to the road-tire adhesion, the normal load on the rear-axle (or group of axles) should be known. It is required to consider tractor and semi-trailer both as free bodies, as per details of Figure 3.2. Normal load at the semi-trailer is given as W_s and vertical and horizontal loads at the hitch point are W_{hi} and F_{hi} . Taking semi-trailer as a free body, equating forces and taking moments about the hitch point, we have:

¹ This is equal to static coefficient of friction (μ) (40).

Figure 3.2 Forces Acting on a Tractor-Semitrailer

$$W_s = \frac{W_2 d_2 \cos \theta + R_{a_2}(h_{a_2} - h_3) + (h_2 - h_3)a \frac{W_2}{g}}{L_2} \pm \frac{W_2(h_2 - h_3) \sin \theta + R_d(h_d - h_3) - R_{r_s} h_3}{L_2} \quad (3.5)$$

$$F_{hi} = R_{a_2} + a \frac{W_2}{g} \pm W_2 \sin \theta + R_d + R_{r_s} \quad (3.6)$$

and

$$W_{hi} = W_2 \cos \theta - W_s \quad (3.7)$$

Now taking the tractor as a free body and taking moments, we have:

$$W_r = \frac{W_1 l_1 \cos \theta + R_{a_1} h_{a_1} + h_1 a \frac{W_1}{g} \pm W_1 h_1 \sin \theta + F_{hi} h_3 + (L_1 - d_1) W_{hi}}{L_1} \quad (3.8)$$

3.2 Vehicle Drag

Drag is the force resisting the motion of the vehicle and should be known in detail for vehicle performance work. This force is a function of vehicle speed primarily, but is also affected by wind speed and ambient pressure and temperature.

Conventionally, vehicle drag include the forces resisting motion due to the deformation of the wheel and ground and the aerodynamic drag. The effect of ground deformation is negligible (40).

3.2.1 Deformation of Wheel

The pneumatic tire is particularly suitable for use with on-road vehicles because it contributes to comfort, and has excellent adhesion. The vehicle load and tractive effort, cause the tire to deform. On a typical road surface, the deformation of tires accounts for some 90-95% of the so-called 'rolling resistance' of a vehicle (39,40).

Tire construction, i.e. whether it is a cross-ply tire or a radial-ply tire, effects the rolling to a considerable extent. Rolling resistance offered by a cross-ply tire is higher than that offered by a radial-ply tire.

Other factors which affect rolling resistance of a pneumatic tire are tire temperature, inflation pressure, vehicle speed, tread thickness, number of plies, transmitted torque level and type of rubber. These are all secondary effects having some interaction between themselves, because of which they cannot be treated independently. Some of them also counter-act the effect of others. If the vehicle speed increases (upto a certain extend) and all the other factors are kept constant, the rolling resistance also increases, but generally most of the effect is counterbalanced by a corresponding increase in the tire temperature and pressure.

To account for the effect of speed on rolling resistance it is advisable to add another coefficient B_d (40) such that the

$$\text{Coefficient of rolling resistance}^2 = (A_d + B_d V)$$

where A_d is non-dimensional rolling resistance coefficient without the secondary effects and B_d is the speed dependent part. V represents vehicle speed. In the absence of reliable data and value for B_d it is better to assume zero (40).

3.2.2 Aerodynamic Drag

The aero-dynamic drag of the vehicle consists of three components. These are:

- 'Skin friction' which results from loss of momentum of the main stream due to the airflow in the boundary layer. It is not significant.

² This is determined experimentally and basically reflects the losses due to hysteresis, tire deformation, air circulation inside the tire and the fan effect of the rotating tire on the outside air (39). Only little contribution is due to the friction between tire and ground.

- 'Induced drag' resulting from the down wash of the trailing vortices at the back of the vehicle. This is also negligible.
- 'Normal pressure drag' which depends on the frontal area of the vehicle. This is the opposing force caused due to the separation of flow at the rear of the vehicle, resulting in low pressure.

The aerodynamic drag (normal pressure drag) is expressed in the following form:

$$R_a = \frac{\rho}{2} C_D A_f V^2 \quad (3.9)$$

where ρ is air density, C_D is the drag coefficient, A_f is the characteristic area (frontal area), V is the speed of the vehicle relative to the wind. As the drag force is dependent on the square of speed, the power (drag $\times$ speed) required to operate the vehicle will increase eight times for increasing the speed two times.

The coefficient of aerodynamic drag C_D is quite crucial and proper value should be used. In this study values for C_D were taken from the Society of Automotive Engineers (SAE) publication (25).

3.3 Engine and Transmission Characteristics

In the overall performance of a vehicle, engine and transmission characteristics play an important role. Two limiting factors as discussed earlier, on which the performance of a vehicle depends are maximum tractive effort that a tire-ground contact can support and the tractive effort that the engine with the given transmission can provide.

3.3.1 Engine Characteristics

Generally, internal combustion engines are used in commercial vehicles. Types of internal combustion engines which are commonly used are gasoline engines and diesel engines. Basic characteristics of these two types of engines are shown in Figure 3.3 (a) and Figure 3.3 (b).

(a) Gasoline Engine

Source: (39)

(b) Diesel Engine

Figure 3.3 Performance Characteristics of Engines

Optimum combustion and maximum torque are reached at intermediate engine speeds. With the increase in engine speed beyond maximum torque, engine torque declines and power output however increases upto maximum power and then starts declining. Generally in the optimum vehicle operation, engine speed beyond maximum engine power output is not recommended. The engine torque also reduces at high speeds especially due to growing losses in the air induction manifold.

The effective engine power available at the transmission input shaft is less than the gross engine power, which is the power measured without all the accessories and installation, not essential to operation. The losses are due to engine accessories such as fan for cooling system, the exhaust system, air cleaner and electric generators, etc.

Atmospheric conditions like ambient temperature t and pressure B_a also effect the engine performance. For a gasoline engine, the relationship between engine power under standard atmospheric conditions P_0 and that under given atmospheric conditions P is given by (39).

$$P = \frac{P_0(B_a - B_v)}{B_0} \sqrt{\frac{t_0}{t}} \quad (3.10)$$

where B_a and t are barometric pressure at the carburetor air inlet and ambient temperature ($^{\circ}K$) respectively. B_v is vapour pressure which may be neglected except for the extreme conditions. t_0 and B_0 are temperature ($^{\circ}K$) and barometric pressure at the standard condition of temperature and pressure.

For a diesel engine the relationship can be given as (39)

$$P = \frac{P_0(B_a - B_v)}{B_0} \frac{t_0}{t} \quad (3.11)$$

As information about temperature and pressure of the location where vehicle is operating is quite difficult to get, the combined effect for both of these can be taken by introducing altitude correction for engine performance, as it will be seen in chapters 5 and 6. This is because it is easy to get information on the altitude of

vehicle operation by knowing the topography.

3.3.2 Transmission Characteristics

The transmission usually consists of clutch, gearbox, propeller shaft and a drive axle. Drive axle has normally a constant gear reduction ratio known as drive axle ratio. The gearbox has a number of different gear reduction ratios normally ranging from 3 to 5 for recreational vehicles and 5 to 18 for trucks.

Maximum vehicle speed is determined by the gear ratio of the lowest gear (i.e. highest ratio), while gear ratio of the highest gear (i.e. lowest gear ratio) depends upon the maximum gradability of the vehicle required.

Gear ratios should be selected to provide smooth transition from one gear to the next without any sudden change in speed or tractive effort available and thus giving an ideal tractive effort and vehicle speed curve. Generally, for heavy duty vehicles, the gear ratios are in geometric progression.

Efficiency of manual transmission ranges from 90% for direct or highest gear ratio to 80% for high reduction or lowest gear ratio (39). These figures have over time improved and for our analysis the range considered was 93% to 85%.

The tractive effort of the vehicle can be given as:

$$F = \frac{M_e \xi_o \eta_T}{r} \quad (3.12)$$

Where M_e is engine output torque, ξ_o is overall gear reduction ratio, η_T is overall transmission efficiency, r is the rolling radius of the tire and F is the available tractive force. Another relationship between vehicle speed and engine speed is given as:

$$V = \frac{2\pi\eta_e r}{60\xi_o} (1 - i) \quad (3.13)$$

Where V is vehicle speed, η_e is engine speed in revolutions per minute and i is the percent slip of vehicle running gear.

3.4 Tire Growth

This phenomenon takes care of the fact that rolling radius of wheels may change with vehicle speed. Though the effect is not so crucial, but still it can be of some significance. The relationship is expressed by the so-called 'Dunlop's formula' (40)

$$R_{rv} = R_r(1 + KV^2) \quad (3.14)$$

where R_{rv} is rolling radius at vehicle speed V , and R_r is the static rolling radius. This increase in rolling radius of the vehicle is due to the centrifugal stresses developed in the rotating tire.

Value of K (for cross-ply tires) depends upon the units used, for V in km/h its value is 1.84×10^{-6} . K is termed as 'tire growth factor' and is zero for radial ply tires.

3.5 Approaches for Studying Vehicle Performance

The three major approaches to the development of techniques for studying vehicle performance on grades are:

- **Actual Field Testing**
- **Econometric Modelling**
- **Simulation Modelling**

Actual Field Testing is no doubt the most satisfactory method, to obtain vehicle performance, but it is rather laborious and expensive to conduct. Empirical relations can also be derived from the field observations for predicting vehicle performance. Result from this approach, are not easily transferable to other locations.

The **Econometric Modelling** approach involves collection of data on actual vehicle performance, vehicle characteristics, the driver, the roadway and the environment. These data are then used to calibrate the model which relates all relevant

factors to the vehicle's performance. An example application would be in developing a regression model using various factors like length of grade, percentage grade, approach speed, power, gross mass etc. The roadway and environment conditions are also to be recorded and controlled. Though this method allows for sensitivity runs, it is not valid beyond a certain range of parameter values and under environment and roadway conditions different from those observed. Models of this type can not be extended to other vehicle types i.e. using the same model for trucks and recreational vehicles is not possible.

The third major approach is **Simulation Modelling**. The simulation approach uses a basic model of vehicle motion and focuses on the various forces acting on the vehicle. It takes care of gear shift delays, rolling resistance, chassis resistance, grade resistance aerodynamic resistance and the available tractive force from the engine. Thus, simulation can deal with all the relevant vehicle factors and also the driver behaviour by considering 'gear shift delays'. Knowing all the forces acting on the vehicle and the mass of the vehicle, its speed-distance performance can be known at various grades.

Because of its basic nature, least expensive of the three and easy collection of data, simulation has an advantage over others. Therefore, this approach was selected for the study.

Chapter 4

Data Requirement and Surveys

Data is needed to determine the appropriate values for various input parameters used in the simulation models. At the input level, the current information on weight/power ratio and various loading levels for the heavy vehicles is required to establish the critical and representative vehicle. Next, the latest information is needed with respect to the technical and dimensional details of the representative vehicle, whereas the representative vehicle itself should have a typical power-train combination, as indicated by surveys (appendix D).

Also, field data (on truck performance on grades) is required for comparison with the model outputs. The study areas for the data collection should be of the similar type i.e. regions with different operating conditions should not be mixed.

4.1 Weight to Power Ratio Survey

The detailed actual loading level information was rather difficult to get, and for this reason several sources of information were looked into. There were three sources of data on weight/power ratio. The Ministry of Transportation, Ontario, has collected data from the truck manufacturers and operators in the Toronto region. The second source was a limited survey on truck power, mass and dimension (see Appendix E for the questionnaire copy). This second source was quite helpful in the process. Lastly, the data published in reference (41) was a good source of information on truck configurations and technical specifications.

The summary of information gave the following breakup as shown in Table 4.1.

Gross Weight (Kg)	Number of Axles	Installed Horsepower (hp)	Weight/Power Ratio	
			kg/kw	lb/hp
63,000	> 8 7 or 8 7 or 8 6 6 5 5 5	400 - 500	211.9 - 169.0	347 - 278
58,000		350 - 425	222.6 - 183.7	365 - 301
53,500		290 - 400	248.1 - 179.7	406 - 295
52,500		250 - 400	281.6 - 175.7	463 - 289
46,500		350 - 400	178.4 - 155.6	293 - 256
43,500		--	--	--
42,000		250 - 350	225.3 - 160.9	370 - 264
39,000		300 - 315	175.0 - 166.0	287 - 273
Light Weight 26,200	< 5	270 - 300	130.0 - 118.0	213 - 193

Source: (44)

Table 4.1 Truck Weight-to-Power Ratio

Also, a histogram of vehicle gross weight for the Ontario truck population is shown in Figure 4.1

On the basis of limited response from industry, an indication of 'cube-out' and 'weight-out' is shown in Table 4.2. For typical runs, the extent of the utilization of cubic capacity and the allowable gross weight are being used as indicators of 'cube-out' and 'weight-out' phenomena. (For questionnaire, please see appendix E)

As it is evident from the data analysed here, the gross weight/power ratio in the study area (Ontario) clusters around 180 kg/kw, having an overall range of 118 kg/kw (193 lb/hp) to 282 kg/kw (463 lb/hp). Though weight/power (W/P) ratio can be higher than 180 kg/kw, it is unlikely that such highly loaded vehicles will attain highway speed of 90 km/h or higher even at the level grade.

4.1.1 Trends in Weight/Power Ratio

Saal (31) studied the relationship between gross weight of a truck and its horsepower and reported a continuous improvement in performance of all truck categories. More recently, Wright and Tignor (32) studied weight to horsepower characteristics of trucks and classified them by number of axles used. It was found that there is a definite trend towards decreasing weight to power ratio for trucks operating on the highways.

Figure 4.2 gives the trends in weight to horsepower ratio. It can be observed that:

- over time the weight/power has been falling i.e. from 1949 to 1977.
- weight to power ratios may be somewhat stable now or may tend to increase in future, due to the liberalized weight limits, as shown in Figure 4.2

Source: (44)

Figure 4.1 A Histogram of Vehicle Gross Weight

Type Of Service	% Cubic Capacity Used (Range of Answers)
Truck Load Service	90 - 100
Less-Than-Truckload Service	80 - 100
Others (Specialized Loads)	85
Type Of Service	% Allowable Gross Weight Used (Range of Answers)
Truck Load Service	70 - 100
Less-Than-Truckload Service	70 - 100
Others (Specialized Loads)	90 - 95

Source: (44)

Table 4.3 'Weight-out' and 'Cube-out' Estimates

Source: FHWA (U.S.A.), Ref. 31, 32 & 44.

Figure 4.2 Trends in Weight/Power Ratio Since 1949

- the maximum theoretical weight/power ratio for Ontario province seems to be slightly higher than 180 kg/kw, but practically on road this ratio might still go down due to the 'cube-out' phenomenon.

Also reference (30) states that almost 100% of trucks have weight/power ratio of 180 kg/kw or less and that loading levels of 120 kg/kw and 60 kg/kw correspond to average and lightly loaded vehicles. This is confirmed in Chapter 7.

4.2 Technical and Dimensional Details

Technical and dimensional data for the following design/representative vehicle were sought. The vehicles under consideration were straight trucks, semi-trailers, double trailers and recreational vehicles.

4.2.1 Trucks

The weight limits and dimensions for semi-trailer and double trailer trucks were taken from a recently announced regulation.(37). It contains weight limits and geometrical details for semi-trailer and double-trailer. Straight trucks were considered as a special case of semi-trailer (3-axle case).

The basic performance variables were checked through various published sources. The main sources of information were:

- 1) Fleet Owners' Manual for details and data on engine characteristics, gear/transmission details, axle details, and overall dimensions of the various truck models.
- 2) Society for Automotive Engineers (SAE) publications for values of drag coefficients and various correction factors (e.g. for horsepower and aerodynamic drag). These publications were the basis for Model II.
- 3) Analysis of values used in previous studies.

Following this, the author carried out limited survey to confirm the data on trucks. The survey included truck dealers, engine and truck manufacturers and truck operators in the Ottawa-Hull region. Technical and operational data were collected from them. The whole effort of collecting the data was useful in establishing a representative and realistic vehicle.

In specifying truck characteristics, various perspectives were addressed using the surveys. They include (42):

- Types of commodities and loads (i.e. dedicated loads, shared loads, or special loads, etc.) carried;
- Topography and type of roadway.
- Top speed of the vehicle desired by the operator or carrier, acceleration or torque requirements and the grade ability preferred by the trucking company.
- Region of operation i.e. whether it is a service area, distribution, or retail network.
- Overall balance of speed, fuel economy and operating costs desired by the fleet owner, broker or operator.
- Truck selection also accounts for the fact that for inter-provincial operations (at present) regulations regarding axle and gross weights vary from province to province. Standardization is anticipated soon.

For the accuracy and relevance of simulation, following steps were taken:

- 1) Engine characteristics were acquired directly from engine manufacturers such as Cummins, Mack, Caterpillar etc. and from Ref. (41).
- 2) Truck data was collected for actual and practically feasible power-train combinations (i.e. proper combination of engine, transmission and axle ratio).

- 3) In view of information from all the sources, actual permissible and the most typical combinations were used for simulation.
- 4) Tire manufacturers were also surveyed for tire details.

It was concluded that numerous feasible combinations of truck components are possible, which depend upon the purchaser and the availability of components. The probability of having any two trucks identical in configuration, is quite low. As a remedy to this, dealers were asked to identify the most relevant and typical truck combination in order to establish the representative model.

Taking into consideration the practical trend, technical feasibility and gross weight limits, the following two models were chosen for the simulation process, with the feasible power-train combinations (42).

- LTL - 9000 Ford Truck Model (for 180 kg/kw and 210 kg/kw category)
- LNT - 8000 Ford Truck Model (for 120 kg/kw and 60 kg/kw category)

4.2.2 Recreational Vehicles

It was recognized that the typical recreational vehicles which pose problems on highways are normal 4-6 cylinder passenger cars which are used for the recreational purposes. Normally in these cases the load being towed exceeds the towing capacity of cars (it varies from 500 kg to 1500 kg) and hence acceleration or grade capabilities are reduced.

Details for cars were collected from various automobile dealers and manufacturers. The engine and transmission characteristics which are not normally available, were provided by manufacturers. Dealers were surveyed to find out a typical car being used for recreational purposes and to have trailer (recreational) weights and dimensions (43).

Finally, the Hyundai Sonata (2351 c.c. displacement engine) model was selected to simulate the recreational vehicle performance for weight/power ratio of

40 kg/kw. The towing weight was assumed within the permissible limits. The reason, this vehicle was selected as a representative recreational vehicle is that the information acquired with respect to technical and dimensional details, was complete as compared to other candidate models.

4.3 Field Study on Truck and Recreational Vehicle Performance

Besides collecting information on the technical and configurational details of the design (representative) vehicles, field observations, at four selected highway up grade locations were obtained to assess the up grade performance of vehicles.

Out of the four sites selected, three of them were on highway 17 and one on highway 417. In order to supplement these data, field data from both MTO and FHWA (U.S.A.) were also used.

4.3.1 Location

The four sites selected for speed studies are shown in Figure 4.3. The details of the sites i.e. location, percent grade and length are as given in Table 4.3. A schematic diagram showing the location of speed observation stations, at the bottom and at the crest of the grade is shown in Figure 4.4.

4.3.2 Equipment Used

Radar meters were used for the observation of truck and recreational vehicle speeds. The device is quite effective and accurate. It is a standard equipment used by traffic engineers and law enforcement personnel. Radar meters used in this research were obtained from the local office of the Ministry of Transportation, Ontario (MTO).

Figure 4.3 Highway Map Locating Observation Sites

Site Details	Site 1	Site 2	Site 3	Site 4
Location	HW #17 near exit for Pembroke	HW #17 near O'Brian Renfrew exit	HW #17 near Granger Park Rd. exit	HW #417 near Moodie Drive exit
Grade (%)	5.3	3.5	3.0	3.0
Length (m)	200	1000	1300	900

Source: (44)

Table 4.3 Sites for Speed Studies

Figure 4.4 *Schematic Layout of an Observation Location*

Radar meters operate on the Doppler's principle, which states that the speed of a moving target is proportional to the change in frequency between the radio beam transmitted to the target and the reflected beam. The radar meter measures this difference and converts it to a direct reading in km/h or mph.

The meter should be setup so as to keep the angle between the direction of vehicle travel and a straight line from the transmitter-receiver to the vehicle, at a minimum. The meter should normally be positioned at the edge of the roadway, at an angle of about 15 degrees with the vehicle motion line. The radar meters are sensitive enough to cover the entire range of vehicle speed on highways.

4.3.3 Data

Field data on truck and recreational vehicle speed are required for the comparison of the model simulated results with the observed field values. Observations and sample size are noted in Table 4.4. The data measured on these sites were:

- 1) Speed measurements for trucks and recreational vehicles, at the foot and at the crest of grade. Radar meters were used for this task.
- 2) Distance was measured between the locations of speed observations (i.e. the bottom and the crest of the grade), in metres. It was possible by the use of car odometer.
- 3) Information about the grade percentage was acquired from MTO.

It should be noted that as a part of field observations, the vehicle weight and power information could not be obtained. Resources required for such observations could be quite prohibitive.

4.3.4 Sources of Error

There are few factors which may affect the observations taken during the field study. These are:

- The accuracy of speed determination for the equipment used is ± 3.2 kilometres per hour up to speed of 160 kilometres per hour.

- It might be difficult to distinguish a single vehicle being observed, in heavy or multi-lane traffic.
- Some error due to the angle of observation, may be introduced in the speed observations. The magnitude of error is directly related to the cosine of the angle between observation line and vehicle travel-line. Angles up to 15 degrees do not affect the reading significantly.

4.3.5 Data Analysis

For all the four sites mean, median and standard deviation of the speed values measured at the approach of grade as well at the crest of the grade, were calculated. This was done both for trucks and recreational vehicles. Vehicle population distribution was also observed to find the 50 and 12.5 percentile speed values. As explained later, these values are considered to be representative of the average loading and heavy loading for the trucks.

Table 4.4 gives the mean, median and standard deviation values for the truck and recreational vehicle speeds along with the sample size. The 50 and 12.5 percentile speed values are also noted in Table 7.2.

A fair amount of confidence can be placed on the observed data, as at any given observation location, two or more persons were noting the observations. Radar meters were all fully operational and properly calibrated.

Vehicle Type	Site 1	Site 2	Site 3	Site 4
Truck				
Mean Speed				
Approach	(18) 71.0 *	(29) 96.7	(51) 92.5	(137) 93.5
Upgrade	(27) 65.6	(34) 74.0	(48) 74.2	(110) 67.8
Median Speed				
Approach	38.0 *	98.0	93.0	94.0
Upgrade	68.0	77.3	74.1	69.0
Std. Deviation				
Approach	16.6	7.5	11.0	10.6
Upgrade	12.0	11.3	7.2	9.1
Recreational Vehicle				
Mean Speed				
Approach	(3) 80.0 *	(8) 98.8	(27) 94.1	(23) 89.4
Upgrade	(6) 67.0	(13) 72.9	(25) 76.0	(19) 67.8
Median Speed				
Approach	79.0 *	96.5	92.0	88.0
Upgrade	74.0	78.5	77.3	68.0
Std. Deviation				
Approach	3.6	5.5	9.1	7.8
Upgrade	8.1	14.8	7.2	8.0
<p>() Figures in bracket are sample sizes. Due to weekdays recreational vehicles were low in case of sites 1&2.</p> <p>* The approach speeds for site 1 were generally low due to the presence of railway grade crossing near the grade approach. The presence of crossing caused the speed reduction.</p>				

Source: (44)

Table 4.4 Field Data: Truck and Recreational Vehicle Speed, (km/h)

Chapter 5

Model I: A Detailed Simulation Model for Truck and Recreational Vehicle Performance on Grade

5.1 Model Structure

The ability of a vehicle to negotiate grades is largely dependent on its performance characteristics. The tractive effort developed at the driven tires is the result of engine torque being transmitted through the transmission assembly. This tractive force is also limited by the product of road-tire-adhesion coefficient and the normal load on the driven tires.

The force which is responsible for the vehicle's motion is the net tractive force available after considering vehicle drag. The main forces opposing the vehicle motion are:

- 1) Aerodynamic drag
- 2) Rolling resistance of tires
- 3) Grade resistance, which might be favorable or unfavorable to the vehicle motion, depending upon whether the vehicle is travelling up grade or down grade.
- 4) Resistance due to the drawbar load (as in the case of a double-trailer and a recreational vehicle towing a trailer).

Tractive effort, rolling resistance and aerodynamic drag are all speed dependent, while grade resistance is constant over a given grade and changes only with a change

in grade. See Figure 5.1. The notations shown in the figure are defined as follows:

ATF	available tractive force from the engine
E_0	equilibrium point, representing maximum attainable steady speed, at which the vehicle can negotiate a given grade
$F_{net,a}$	net tractive force available for vehicle acceleration
$F_{net,b}$	net force causing the vehicle to decelerate, when entering up grade at speed V_2 higher than the maximum attainable speed of V_0 , as shown in Figure 5.1
R_a	aerodynamic drag
ΣR_g	summation of all resisting forces including aerodynamic drag, rolling resistance, grade resistance etc.
ΣR_0	resultant resisting force on a level grade
RR	rolling resistance
V_f	maximum speed on the level grade which can be attained by the vehicle, given no speed limit
V_{max}	maximum allowable highway speed on the level grade
V_0	equilibrium speed at any given grade

5.2 Computer Simulation

The objective of this program is to obtain the acceleration and deceleration curves for the vehicle (speed vs. distance curves) at different grades. The program consists of several inter-connected modules. Programming is done in a user-friendly manner with the option of using either the default values built within the program or using the user supplied input values.

The first module calculates the truck speed and available tractive force, given the basic characteristics of the engine (torque, speed) and the gear ratios as inputs. In the second module, these values are then fitted onto a polynomial allowing the

Figure 5.1 The Basic Model of Vehicle Performance

truck speed and corresponding tractive effort to be determined at an interval of 0.1 km/h , giving very narrow intervals. A tractive effort envelope, based on engine characteristics, is thus obtained.

The third module calculates various resisting forces and the overall resistance for a given grade over the entire speed range.

The tractive force available at the driven wheels is limited by the nature of tire-road adhesion and the normal reaction on the driven tires. At any vehicle speed the maximum realizable tractive force is the lesser of the tractive force determined by the engine and transmission characteristics and the tractive force limited by the nature of the tire-road adhesion. This is the fourth module.

To take into account the effects of inertia of the rotating parts on the vehicle acceleration, a fifth module was formulated to include the calculation of the mass factor for the vehicle. This gives us equivalent mass of the vehicle which is greater than the actual mass.

Given all the forces acting on the vehicle and the equivalent vehicle mass, the last two modules calculate the vehicle acceleration and deceleration.

Figure 5.2 shows a basic flowchart of the computer simulation process, and Figure 5.3 gives a detailed simulation process for Model I.

5.2.1 Module 1: Calculation of Truck Speed V and Engine Tractive Effort $TE(2)$

The basic inputs for this module are the engine characteristics, in terms of engine speed (rpm) and engine torque (N-m). As many as 30 different data pairs can be read from the engine torque-engine speed curve (made available by the manufacturer or from the literature) and for each set of values, corresponding truck speed (km/h) and tractive force (N) are calculated. This is done for all the available gear ratios.

Figure 5.2 *Basic Flowchart for the Simulation of Vehicle Speed-Distance Curves*

The key equations involved are presented below:

$$V = \frac{1 - \sqrt{1 - 4A^2K}}{2AK} \quad (5.1)$$

This value of V (truck speed) also takes care of the effect of tire growth, by introducing the tire-growth factor 'K'.

$$TE(2) = TE(2)' A_t \quad (5.2)$$

$$TE(2)' = \frac{TC_2 \eta_T \alpha}{R_{rv}} \quad (Ref.39)(5.3)$$

$$R_{rv} = R_r(1 + KV^2) \quad (Ref.40)(5.4)$$

$$A_t = (1 - 1.312 \times 10^{-4} E) \quad (Ref.16)(5.5)$$

where:

η_T	=	0.85 for the first one third of the gear ratios, starting from the first gear
	=	0.88 for the next one third of the gear ratios
	=	0.93 for the last one third of the gear ratios

These values of η_T are obtained with some modification from Ref. 39, page 140.

and

A	$\frac{3C_1}{25C_2}$
A_t	altitude factor for engine performance correction
C_1	$N_e R_r \pi$
C_2	$g_a g_g$
E	altitude above the sea level (m)

g_a	drive axle ratio
g_g	gear box ratio
K	tire growth factor
	0 (for radial ply tires)
	1.84×10^{-6} (for cross ply tires, for V in km/h)
N_e	engine speed (rpm)
R_r	static rolling radius of drive axle wheel (m)
R_{rv}	dynamic rolling radius of drive axle wheel (m)
T	engine torque ($N - m$)
$TE(2)$	tractive force available as per engine characteristics, with altitude correction (N)
$TE(2)'$	tractive force available as per engine characteristics, without altitude correction (N)
V	vehicle speed (km/h)
α	engine utilization factor (≤ 1)
η_T	transmission efficiency

The K -factor takes into account the effect on tire rolling radius due to truck speed. The altitude factor allows us to correct the performance of the vehicle engine with respect to the operating conditions of ambient temperature and atmospheric pressure. The correction factor for altitude is basically a function of altitude with which both the temperature and atmospheric pressure change.

α is the engine utilization factor which accounts for the driver's behaviour and the roadway operating conditions like: traffic and speed limits.

Care has been taken to account for slip of the vehicle running gear. The average value for this is taken as 3% (39).

From the above calculations, V and $TE(2)$ data pairs for each gear are obtained. These pairs are equal to the number of discrete input points for engine speed N_e .

and engine torque T . These paired values serve as input for the next module.

5.2.2 Module 2: Polynomial Curve Fitting for Tractive Effort Envelope

The output of Module 1 serves as an input for Module 2. This module fits a polynomial to the discrete V and $TE(2)$ data pairs for each gear.

The polynomial fitted is of the 10th order, which is sufficiently high for precise results (normally the curve fitted is of 6th degree). The subroutines used for this purpose are from a standard mathematical library, 'SLATEC'.

This allows us to have the V and $TE(2)$ values starting from $V = 0 \text{ km/h}$ at increments of 0.1 km/h , till the maximum speed that is allowed on the highway is reached. This is done for all the gears.

The data pairs appropriate to the operating range of each gear are taken for determining the speed-distance curves. Every gear, starting from the first gear, is utilized to its full extent and then the gear change takes place.

The final output of this module gives an envelope of tractive effort encompassing all the gears. This is taken as $TE(2)$ -envelope. Depending upon the intersection of individual gear's tractive effort curve, the envelope might look as in Figure 5.4 (a) or 5.4 (b).

5.2.3 Module 3: Calculation of Resisting Forces

For all the values of speed, this module calculates all the resisting forces acting on the vehicle while in motion on level or grade. These forces are aerodynamic drag AR , rolling resistance RR , and grade resistance GR .

Also included in this module is the account for gear change delay. Calculation of forces acting on a vehicle during gear delay time gives us the speed drop, during the delay time. Default value of gear change delay is taken as 1.5 seconds, which represents the normal driver operation.

(a) *Intersecting Individual Gear Tractive Effort Curves*

(b) *Non-intersecting Individual Gear Tractive Effort Curves*

Figure 5.4 *Envelope for Engine Tractive Effort $TE(2)$*

The aerodynamic drag has been divided into component drags for tractor, semi-trailer and double-trailer, by taking into consideration appropriate drag coefficients and drag area (24,25) for the different units.

Masses of different vehicle units enter as separate inputs. Depending upon the axle configurations and number of tires in the tractor, in driven axle, in semi-trailer and in double trailer, are entered as separate inputs.

In the case of rolling resistance RR , the rolling resistance coefficient used, also takes care of the dynamic part of the rolling resistance which changes due to the speed change. It is known that:

- RR varies with vehicle speed and level of loading
- AR varies with vehicle speed but not with grade
- GR varies with grade but not with speed

Thus the total opposing force OR , which is equal to the summation of all resistances, changes with the speed as well as with the percent grade. The relevant relationships used are as follows:

$$RR = (A_c + B_d V) M_v g \quad (5.6)$$

$$AR_i = 0.07716 Z A_i C_{di} \quad (5.7)$$

$$AR = \sum_{i=1}^n AR_i \quad (5.8)$$

$$GR = M_v g p 10^{-2} \quad (5.9)$$

$$OR = RR + AR + GR \quad (5.10)$$

All these resistances are in Newton.

where:

A_d	static rolling resistance coefficient
A_i	respective frontal areas for tractor, semi-trailer and double-trailers (m^2)
AR	total aerodynamic drag (N)
AR_i	respective aerodynamic drags for tractor, semi-trailer and double-trailer (N)
B_d	dynamic rolling resistance coefficient
C_{di}	respective aerodynamic drag coefficients for tractor, semi-trailer and double trailer
g	gravitational constant (m/s^2)
GR	total grade resistance (N)
M_v	gross mass of the vehicle (kg)
n	represents the different number of vehicle or truck units like tractor, semi-trailer or double-trailer
OR	sum of all the opposing forces (N)
p	percent grade (denoted as $+p$ for up grade and $-p$ for down grade)
RR	total rolling resistance (N)
Z	$0.5\rho(V + V_w)^2$
V	vehicle speed (km/h)
V_w	wind speed (km/h)
ρ	air density (kg/m^3)

These values of resistances are calculated for all speeds (0 to V_{max}) and for all grades -9% to $+9\%$.

5.2.4 Module 4: Engine Tractive Effort $TE(2)$ Variation During Gear Shift

This subroutine calculates the value of tractive effort transmitted by the engine onto the driven wheels, just after the gear shift has taken place. In such cases the value of tractive effort is interpolated or extrapolated. This is necessary because when the vehicle shifts a gear the speed reduces during coasting and hence corresponding value of $TE(2)$ for the next gear has to be calculated for that particular velocity at which the actual gear change takes place.

This module rewrites the tractive effort $TE(2)$ values corresponding to speed values from 0 to V_{max} at the interval of 0.1 km/h including the values corresponding to particular gear change velocity. Now for the purpose of comparing tractive efforts as will be seen in Module 6, values from this module and from the forthcoming Module 5 will be taken.

5.2.5 Module 5: Calculation of Tractive Effort $TE(1)$ Available Due to Road-Tire Adhesion

This module basically calculates the available tractive force at the driven wheels, due to the road-tire adhesion. This tractive effort is designated as $TE(1)$ and is the product of normal reaction on the drive axle and coefficient of road-tire adhesion μ which depends upon the type of road surface.

Two different sub-modules (sub-programs) have been written in order to calculate drive axle reactions. One deals with the case of straight trucks and recreational vehicles and the other with semi-trailers and double-trailers. Further, both of them have the option of considering either dynamic or static load at the drive axle.

Dynamic load differs from the static loading in the sense that it takes into account the load transfer due to vehicle acceleration. In the case of dynamic loading, acceleration is found by the iterative process for each speed at each grade. Option of using static loading or dynamic loading depends upon the level of preciseness sought.

Key equations used in determining the loading on drive axle (or center of axles) are given below:

Dynamic Loading

(a) Dynamic Loading - Straight Truck and Recreational Vehicle Case

The relevant relations used are given below. Please refer to Figure 5.5 for schematic layout.¹

$$W_{drive_1} = \frac{M_v g L_3 + AR_1 h_{a_1} + M_v h_1 A_c + R_{d_1} h_d + M_v h_1 p g 10^{-2}}{L_1} \quad (5.11)$$

$$TE(1) = \mu W_{drive_1} \quad (5.12)$$

where:

A_c	truck or recreational vehicle acceleration (m/s^2)
AR_1	aerodynamic drag on the vehicle (N)
L_1	vehicle wheel base (m)
L_3	distance between front axle and centre of gravity of the vehicle (m)
M_v	gross mass of the vehicle (kg)
p	percent grade
R_{d_1}	drawbar pull in case of recreational vehicle (N)
$TE(1)$	tractive force available as per the nature of road-tire adhesion (N)
W_{drive_1}	normal reaction at the drive axle (N)
μ	coefficient of road-tire adhesion

¹ For a small angle (θ), $\cos \theta$ tends to be unity. As such it is assumed to be unity in the forthcoming equations.

Figure 5.5 Schematic Diagram for Straight Truck/Recreational Vehicle

Other variables. e.g. h_1 , h_d , and h_{a_1} are as shown in the Figure 5.5.

(b) Dynamic Loading - Semi-trailer and Double-trailer Case

The relevant relations used are given below. Please refer to Figure 5.6 for schematic layout.

$$W_{drive_2} = \frac{M_1 g L_3 + M_1 A_c h_1 + M_1 g p h_1 10^{-2} + F_{hi} h_3 + A R_1 h_{a_1} + (L_1 - d_1) W_{hi}}{L_1} \quad (5.13)$$

$$TE(1) = \mu W_{drive_2} \quad (5.14)$$

where:

$A R_1$	aerodynamic drag on the tractor (N)
d_1	distance between hitch and the center of drive axle (m)
F_{hi}	horizontal reaction at hitch due to semi-trailer and/or double-trailer (N)
L_1	tractor wheel-base (m)
L_3	distance between front axle and C.G. of the tractor (m)
M_1	mass of the tractor (kg)
W_{drive_2}	normal reaction at the drive axle (N)
W_{hi}	vertical reaction at hitch due to semi-trailer and/or double-trailer (N)

Also,

$$W_{hi} = M_2 g - W_s \quad (5.15)$$

$$W_s = \frac{M_2 \{g d_2 + A_c (h_2 - h_3) + g p 10^{-2} (h_2 - h_3)\} + A R_2 (h_{a_2} - h_3) + R_d (h_d - h_3)}{(L_2 + X h_3)} \quad (5.16)$$

$$F_{hi} = M_2(A_c + pg10^{-2}) + AR_2 + R_d + XW_s \quad (5.17)$$

for semi-trailer case

$$R_d = 0 \quad (5.18a)$$

for double-trailer case

$$R_d = AR_3 + M_3(gp10^{-2} + A_c + gX) \quad (5.18b)$$

where:

AR_2	aerodynamic drag on the semi-trailer (N)
AR_3	aerodynamic drag on the double-trailer (N)
d_2	distance between semi-trailer C.G. and the hitch (m)
L_2	distance between the hitch and the rear axle (or at centre of group of rear axles) of semi-trailer (m)
M_2	mass of semi-trailer (kg)
M_3	mass of double-trailer (kg)
W_s	normal reaction at the rear axle (or the centre of group of rear axles) of semi-trailer (N)
X	$(A_d + B_dV)$

Other variables like h_1 , h_2 , h_3 , h_d , h_{a_1} and h_{a_2} are as shown in the Figure 5.6.

Static Loading

In the case of static loading, the forces are considered to be acting on a stationary vehicles. Also no load transfers, due to the vehicle motion are considered.

Figure 5.6 Schematic Diagram for Semi-trailer/Double-trailer

The choice of static or dynamic loading in the calculation of $TE(1)$ depends upon the level of precision required.

5.2.6 Module 6: Comparison of Tractive Forces $TE(1)$ and $TE(2)$ and Calculation of Equivalent Mass ME

This subroutine compares the values of $TE(2)$ from module 4 and $TE(1)$ from module 5, for all the speed intervals and for all the grades. The lesser of the two tractive efforts is selected as the final tractive force TE , available for propulsion.

To account for rotating inertia of wheels, engine and driveline components, the concept of equivalent mass is introduced. A mass factor γ_m is used, which uses values of engine and propeller shaft inertia. Equivalent mass ME is then the product of gross mass of vehicle and mass factor γ_m (γ_m is always > 1). Differentiation of γ_m is also made depending on whether the final tractive force TE is governed by $TE(1)$ or by $TE(2)$. Relationships for γ_m in both the cases are (39):

If TE is governed by $TE(1)$, then;

$$\gamma_m = 1 + \left[\frac{(TN - TND)I_w}{M_v R_{rv}^2} \right] \quad (5.19)$$

If TE is governed by $TE(2)$, then;

$$\gamma_m = 1 + \left[\frac{I_w(TN)}{M_v R_{rv}^2} + \frac{\sum G_i^2 I_i}{M_v R_{rv}^2} \right] \quad (5.20)$$

and then:

$$ME = \gamma_m M_v \quad (5.21)$$

where:

G_i	is the gear ratio with respect to driven wheel
I_i	mass moment of inertia of the rotating components

	connected with the driveline having gear ratio G , with respect to the drive wheel ($kg - m^2$)
I_w	mass moment of inertia of each tire with rim ($kg - m^2$)
ME	equivalent mass of the vehicle (kg)
M_v	gross mass of the truck/vehicle (kg)
R_{rv}	dynamic rolling radius of drive axle wheel (m)
γ_m	mass factor
TE	tractive force available (N)
TN	total number of wheels in vehicle assembly
TND	total number of wheels in tractor/truck drive axle

The difference between two γ_m 's is that, in the first case, when $TE(1)$ is less than what is determined from the engine and driveline characteristics i.e. $TE(2)$, then we deal with maximum transferable tractive force that the tire-road contact can support. Here, we are not concerned about the driveline torque or inertia. The tractive force does not have to overcome the inertia of the engine which is assumed to be taken into account before $TE(1)$ becomes available at the ground. As such, the tractive effort has to overcome only translatory and small part of rotating inertia of the non-driven wheels. So the equation (5.19) considers only $(TN - TND)$ wheels and also the inertia of rotating part of the engine is omitted (46). This equation should be used when TE is governed by $TE(1)$.

The scenario changes when TE is governed by $TE(2)$. Here the tractive force is reflected back to engine and the engine torque must now overcome both the wheel inertia of drive axle and other axles, as well as engine and driveline inertia. In this case, equation (5.20) should be used.

Further, the option of whether or not to include the mass-factor, gives added flexibility.

5.2.7 Module 7: Truck Acceleration

Given all the required inputs for estimating vehicle acceleration, such as tractive force TE available, total force opposing the vehicle motion and the equivalent mass,

the acceleration and distance travelled can be calculated.

For estimating the acceleration (starting from $V = 0 \text{ km/h}$), median values of all the forces and equivalent mass is taken for a particular speed interval ΔV i.e. $(V_{j+1} - V_j)$. See Figure 5.7.

The relationships involved are:

$$A_L = \frac{(TE_j + TE_{j+1}) - (OR_j + OR_{j+1})}{(ME_j + ME_{j+1})} \quad (5.22)$$

$$S_L = 0.07716 \frac{(V_{j+1}^2 - V_j^2)}{2A_L} \quad (5.23)$$

where:

A_L	acceleration up/down grade (m/s^2)
j	denotes the j^{th} speed interval
ME_j	equivalent mass of vehicle at j^{th} speed interval (kg)
ME_{j+1}	equivalent mass of vehicle at $(j+1)^{th}$ speed interval (kg)
OR_j	total opposing resistance at j^{th} speed interval (N)
OR_{j+1}	total opposing resistance at $(j+1)^{th}$ speed interval (N)
S_L	distance covered for the given speed interval (ΔV), during acceleration (m)
TE_j	tractive force available at j^{th} speed interval (N)
TE_{j+1}	tractive force available at $(j+1)^{th}$ speed interval (N)
V_j	vehicle speed at j^{th} speed interval (km/h)
V_{j+1}	vehicle speed at $(j+1)^{th}$ speed interval (km/h)
ΔV	$V_{j+1} - V_j$ (km/h)

When A_L is less than or equal to $0.0001m/s^2$, the vehicle is assumed to be operating at constant speed and no more calculations are done. Vehicle/truck speed is then plotted against the cumulative distance travelled up/down, for all the grades.

5.2.8 Module 8: Truck Deceleration

Estimation of truck deceleration is done in a manner similar to the acceleration case. Calculations are done starting from V equal to V_{max} or grade entering speed, up to the equilibrium speed or sustained speed. Deceleration is calculated until the vehicle attains a constant negotiable speed for the given grade. This constant speed is characterized by deceleration value of $0.0001m/s^2$ or less. Also distance covered by the vehicle during each interval is calculated. The relationships used are:

$$D_L = \frac{(OR_j + OR_{j-1}) - (TE_j + TE_{j-1})}{(ME_j + ME_{j-1})} \quad (5.24)$$

$$T_L = \frac{0.07716(V_j^2 - V_{j-1}^2)}{2D_L} \quad (5.25)$$

where:

D_L	deceleration up grade (m/s^2)
j	denotes the j^{th} speed interval
ME_j	equivalent mass of vehicle at j^{th} speed interval (kg)
ME_{j-1}	equivalent mass of vehicle at $(j - 1)^{th}$ speed interval (kg)
OR_j	total opposing resistance at j^{th} speed interval (N)
OR_{j-1}	total opposing resistance at $(j - 1)^{th}$ speed interval (N)
T_L	distance covered for the given speed interval (ΔV), during deceleration (m)
TE_j	tractive force available at j^{th} speed interval (N)
TE_{j-1}	tractive force available at $(j - 1)^{th}$ speed interval (N)
V_j	vehicle speed at j^{th} speed interval (km/h)
V_{j-1}	vehicle speed at $(j - 1)^{th}$ speed interval (km/h)
ΔV	$V_j - V_{j-1}$ (km/h)

Starting from V_{max} (i.e. allowable speed limit), vehicle/truck speed is plotted against cumulative distance. See Figure 5.7.

2

METRO

Figure 5.7 *Vehicle Acceleration and Deceleration Case*

Other variables are as explained in Section 5.2.7.

5.3 Gear Shift Delay

This simulation model can take into account the effect of gear shift delay. Provision has been made in modules 3 and 4 to include the gear delays. The option of whether or not to include the gear delay, with and without the default value of gear change delay, is also included. The value normally used as the delay time is 1.5 seconds, as concluded from various previous works. (18,21,22)

During the gear change, tractive force available is set to zero and only the resisting forces act as a result of which there is a certain speed drop before the next gear is engaged. The use of gear shift feature results in discontinuities in the speed-distance curves. Smoothing is however required for using these curves in decision and design purposes.

A sample output featuring gear change delay for 180 kg/kw double-trailer, is attached at the end of appendix B. This includes the selected grade comparisons with and without gear change delay for a typical case of 180 kg/kw double-trailer entering the grade at 90 km/h. The differences between the grade crawl speeds with and without the gear change delay, are all within 1 km/h. These differences may still be less in case of semi-trailers and straight trucks. In case of acceleration down grade the difference is more pronounced because it does not represent the final crawl speed.

5.4 Application to Recreational Vehicle

This same model can be used effectively to evaluate the performance of recreational vehicles. To account for slippage in running gear a slip-factor is introduced in the first module while calculating the vehicle speeds.

5.5 Salient Features of Detailed Simulation Model (Model I)

1. The case, where the tractive force available at wheels may be limited by the nature of road-tire adhesion, is also considered. This may be significant for the light weight trucks and recreational vehicles.
2. Tire growth factor is introduced to account for the change in rolling radius of wheel with change in vehicle speed. It is expressed in the relation known as '*Dunlop's Formula*' and is as a function of V^2 . It is a reasonable relationship since stresses due to centrifugal effect in a rotating body vary with V^2 (40).
3. The simulation program takes care of the rotating inertia of the wheels and engine. All these considerations are reflected in the factor known as 'mass factor' γ_m . The calculation of γ_m depends upon whether the available tractive force at the driven wheels is governed by engine torque driveline characteristics or by the road-tire adhesion. Depending upon the accuracy desired, γ_m may or may not be used in the final calculations.
4. Introduction of engine power utilization factor, α , enables us to take into account the individual truck driver behaviour and operating conditions. It is a direct indication of the throttle opening of the engine, while the vehicle is in motion. It can differ from driver to driver, under otherwise identical circumstances.
5. For a better understanding of aerodynamic drag on the vehicle units (tractor, semi and double trailer), the areas and drag coefficients are used separately for each unit. The effect of separation between the tractor and the semi-trailer and between the semi-trailer and the double, on their respective drag coefficient is also taken into account.
6. Instead of static rolling resistance coefficient, dynamic rolling resistance coefficient has been used. It changes with the vehicle speed.
7. The overall simulation program treats straight truck, semi-trailer, double-trailer

or recreational vehicle distinctly, and accounts for different axle and tire configurations.

8. Option for the use of either static load or dynamic load has been provided to suit the desired level of precision.
9. The computer program is versatile and can be used for predicting performance characteristics of different types of on-road vehicle including cars, vans, etc.
10. The simulation program has been designed as a user-friendly system, accepting either user-input values or default values. This feature is particularly useful in the absence of reliable and detailed data required for this simulation.

Chapter 6

Model II: A Simulation Model for Truck and Recreational Vehicle Performance on Grade – Based on SAE Procedure

6.1 Model Structure

This simulation model, unlike Model I, is based on the procedure recommended by the Society for Automotive Engineers (SAE) for predicting truck performance (15,16). The simulation process consists of five basic modules. These various modules deal with:

- the calculation of the tractive effort and vehicle speed as determined by the engine and drive-line characteristics.
- fitting these sets of values to a polynomial for obtaining a continuous tractive effort vs. speed envelope.
- computation of overall motion resistance, including rolling resistance, aerodynamic resistance and grade resistance.
- calculation of vehicle acceleration and deceleration on up grade and down grade.

Few modifications were made in order to apply the model for estimating recreational vehicle performance. The basic structure of Model II is shown in Figure 6.1.

Figure 6.1 *Computer Simulation Model Based on SAE Procedure*

6.2 Computer Simulation

The process followed here, in principle, is alike to what was followed in Model I. Gear shift delay feature is not given by the SAE procedure and hence this version has no capabilities to estimate the effect of gear change. The various modules are described in later sections.

The relationships in the SAE procedure are given in English units. However, proper conversion factors have been used in the simulation model framework so that the inputs and the outputs can be expressed in SI units. Also the SAE equations which are in 'power' terms have been modified as 'force' equations.

For proper understanding of the origin of the modified equations as used in the computer program, it is necessary to describe the equations as they appear in the SAE publication (16). These equations are in terms of *power* and are expressed in *English units*.

Equations as they appear in the SAE document (16) are as follows:

Apparent Road Speed:

$$mph = \frac{rpm}{GR \times TF} \quad (6.1)$$

Net Engine Power Corrected for Altitude:

$$NHP_e = (1 - 0.00004 \times E) \times NHP \quad (6.2)$$

Rolling Resistance Horsepower:

$$RHP = \frac{(7.6 + 0.09mph) \times mph \times GW}{375,000} \quad (6.3)$$

Air Resistance Horsepower at Sea Level:

$$AHP_s = \frac{0.002 \times (mph)^3 \times A}{375} \quad (6.4)$$

$$A(\text{approx}) = \left(\text{Height} - \frac{3}{4} \right) \times \text{Width} \quad (6.5)$$

Altitude Correction for Air Resistance Horsepower:

$$AHP_e = AHP_s (1 - 0.000006887 \times E)^{4.255} \quad (6.6)$$

Chassis Friction Horsepower:

$$FHP = (1 + (0.0000002 \times \text{rpm} \times GWR)) \quad (6.7)$$

Grade Resistance Horsepower:

$$GHP = \frac{GW \times GP \times \text{mph}}{37,500} \quad (6.8)$$

where:

<i>A</i>	frontal area of vehicle, <i>ft</i> ²
<i>AHP_e</i>	air resistance horsepower at the given altitude
<i>AHP_s</i>	air resistance horsepower at sea level
<i>E</i>	altitude, feet above sea level
<i>FHP</i>	chassis friction horsepower
<i>GHP</i>	grade resistance or acceleration horsepower
<i>GP</i>	grade, % (feet of rise per 100 ft. on the horizontal)
<i>GR</i>	total gear reduction (product of axle and transmission ratio)
<i>GW</i>	total gross weight, <i>lb</i>
<i>GWR</i>	manufacturer's maximum gross vehicle weight rating of powered unit, <i>lb</i>
<i>mph</i>	road speed, <i>mph</i>
<i>NHP</i>	certified net engine horsepower at sea level
<i>NHP_e</i>	net engine horsepower corrected for altitude

<i>RHP</i>	rolling resistance horsepower
<i>rpm</i>	engine speed, <i>rpm</i>
<i>TF</i>	tire factor, tire rpm at 1mph

6.2.1 Module 1: Vehicle Speed and Net Tractive Effort

This sub-program computes the speed of the vehicle and net tractive force available after accounting for the chassis frictional losses. These losses are accounted by using a term called 'chassis friction'. The slippage of the vehicle running gear is also accounted and average value is taken to be 3%. A factor *SLIPF* is introduced to take care of this slippage. Engine performance also varies with change in atmospheric pressure and ambient temperature and as such altitude correction factor is used.

The primary inputs for this section are the engine characteristics in terms of engine-speed and engine-torque and transmission characteristics in terms of gear box ratios and drive axle ratio.

Basic equations as used in the computer program, are the modified version of these SAE (16) equations as described earlier. As used in the computer program these relationships are all in terms of *force* having the inputs in *S.I. units*. As a modification, slippage of the vehicle running gear is also introduced in vehicle speed calculations and instead of using engine horsepower, engine tractive effort (equation 6.13) is used.¹

$$V = \frac{N_e(SLIPF)}{C_2(TF)} Z_1 \quad (6.9)$$

$$SLIPF = \left(1 - \frac{SLIP}{100} \right) \quad (6.10)$$

¹ The reader may note that all the variables used in equations 6.9 to 6.19 are expressed in S.I. units and the various conversion factors (Z_1 to Z_4 and 0.27777) used in these equations provide a link between the equations of the computer program and the equations in the SAE document (16). For direct correspondence with the computer program, the multiplying factor of 4.448 (in few of these equations), can be replaced by the term $\frac{1}{375 \times Z_1 \times Z_2 \times 0.27777}$. Also, in equation (6.19) 9.81 can be replaced by $Z_4 \times 4.448$.

$$C_2 = g_g g_a \quad (6.11)$$

$$NTE = GTE - FR \quad (6.12)$$

$$GTE = \frac{TC_2(AF)}{r} \quad (6.13)$$

$$FR = \frac{(1 + 2.0 \times 10^{-7} N_e (GVWR \times Z_4))}{Z_2 V \times 0.27777} \quad (6.14)$$

$$AF = (1 - 4.0 \times 10^{-5} E \times Z_3) \quad (6.15)$$

where:

<i>AF</i>	altitude factor for engine performance correction
<i>C₂</i>	overall gear ratio
<i>E</i>	altitude of operation, above the sea level (<i>m</i>)
<i>g_a</i>	axle gear ratio
<i>g_g</i>	transmission gear ratio
<i>GTE</i>	tractive effort (<i>N</i>)
<i>GVWR</i>	manufacturer maximum gross vehicle mass rating of powered unit (<i>kg</i>)
<i>FR</i>	frictional resistance of chassis (<i>N</i>)
<i>N_e</i>	engine speed (<i>rpm</i>)
<i>NTE</i>	net tractive effort (<i>N</i>)
<i>SLIPF</i>	slippage factor
<i>SLIP</i>	percentage slip of vehicle running gear
<i>r</i>	loaded static radius of tire (<i>m</i>)
<i>TF</i>	tire factor (i.e., tire <i>rpm</i> at the vehicle speed of 1 mph)
<i>T</i>	engine torque (<i>N - m</i>)
<i>V</i>	vehicle speed (<i>km/h</i>)
<i>Z₁</i>	= 1.6093, multiplying conversion factor for <i>mph</i> to <i>km/h</i>
<i>Z₂</i>	= 1.3410×10^{-3} , multiplying conversion factor for <i>N - m/s (watts)</i> to <i>hp</i>
<i>Z₃</i>	= 3.2808, multiplying conversion factor for <i>m</i> to <i>ft</i>

Z_4 = 2.2046, multiplying conversion factor for kg to lb
 0.27777 multiplying conversion factor for km/h to m/s

This set of calculations is done for all available gear ratios of the transmission.

6.2.2 Module 2: Polynomial Curve Fitting

Akin to Section 5.2.2, this module fits the data pairs of tractive effort and vehicle speed to a polynomial of 10th order. The values of NTE is thus interpolated for every 0.1 km/h interval of vehicle speed. This gives us a tractive effort envelope similar to either Figure 5.4 (a) or Figure 5.4 (b).

6.2.3 Module 3: External Opposing Forces to Vehicle Motion

This module calculates the rolling resistance, aerodynamic drag and the grade resistance and finally the resultant opposing force for each speed interval.

The process is repeated for the entire speed range for all gear ratios. Also, for each grade, the process is repeated.

The calculation of the various resistances is based on the empirical equations and relationships recommended by the SAE with some modifications. Various input and output values are in SI units. These equations, are as follows:

1. Rolling Resistance

$$RR = \left[\frac{(7.6 + 0.09 \frac{V}{Z_1}) G V W \times Z_4}{1000} \right] \times 4.448 \quad (6.16)$$

2. Aerodynamic Drag

$$AR = \left[0.002 \{ (HT \times Z_3 - 0.75) W D \times Z_3 \} \left(\frac{V}{Z_1} \right)^2 \right] (AFAR) \times 4.448 \quad (6.17)$$

$$AFAR = (1 - 6.887 \times 10^{-6} E \times Z_3)^{4.255} \quad (6.18)$$

3. Grade Resistance

$$GR = \left(\frac{GP}{100} \right) \times GVW \times 9.81 \quad (6.19)$$

where:

<i>AFAR</i>	altitude correction factor for air drag
<i>AR</i>	aerodynamic drag (<i>N</i>)
<i>GP</i>	percentage of grade
<i>GR</i>	grade resistance (<i>N</i>)
<i>E</i>	altitude of vehicle operation, above the sea level (<i>m</i>)
<i>HT</i>	height of vehicle (<i>m</i>)
<i>GVW</i>	gross vehicle mass (<i>kg</i>)
<i>RR</i>	rolling resistance (<i>N</i>)
<i>WD</i>	width of the vehicle (<i>m</i>)
<i>V</i>	vehicle speed (<i>km/h</i>)
<i>Z₁ to Z₄</i>	as defined earlier

This set of calculations is performed for all gears and for all grades ranging from -9% to +9%.

6.2.4 Module 4: Truck Acceleration

With the known inputs, such as *NTE*, resultant motion resistance and *GVW*, the acceleration for each speed interval is calculated for up grade and down grade motion. The vehicle (input) speed ranges from zero to the maximum allowed value. This is similar to section 5.2.7

6.2.5 Module 5: Truck Deceleration

This last module is akin to Section 5.2.8 of chapter 5. The relationships used are similar to that of chapter 5. The vehicle enters the grade with a certain entering speed (in our case maximum allowable speed on highways) and decelerates as it goes up, attaining constant negotiable speed.

6.3 Application to Recreational Vehicle

This simulation program can also be used for the recreational vehicle performance. To account for slippage in vehicle running gear, a slip-factor is used for speed calculations. It is also advisable to ascertain the validity of the SAE empirical relations for use in the case of cars and other light vehicles, as these relations may have been basically developed for heavy commercial vehicles.

6.4 Input Data for Two Models - Availability and Reliability

The accuracy of predicting a vehicle's acceleration and deceleration capability largely depends upon the validity of the input parameters and coefficients.

For Model II (SAE version), the relevant factors and coefficients were taken from (15,16,25). These factors may need to be validated at the present time, due to changes in truck-use patterns, engine transmission and aerodynamic characteristics. Model I requires far more number of input parameters and coefficients as compared to SAE approach. As Model I is highly sensitive and disaggregate in nature, the requirement for the accuracy of input parameters also increases. It is believed that if more recent and precise data is available, Model I will give quite accurate and comprehensive prediction of the vehicle's performance.

6.5 Comparison of the Two Models

It would be interesting to highlight the procedural differences between the two simulation models developed in this study. Quite evidently Model II (SAE version) is aggregate in nature, still its use may be preferred over the use of Model I in absence of detailed and realistic data, given the fact that Model II has far less number of input parameters.

Table 6.1 compares the main features of these two models.

Factors	Model I Detailed Version	Model II SAE Version
Engine power utilization factor	YES	NO
Altitude factor for engine power and aerodynamic drag	YES	YES
Tire growth factor	YES	NO
Inclusion of gear change delays	YES	NO
Seperate aerodynamic drag components for each vehicle unit	YES	NO
Driveline resistance consideration	Through use of efficiency term	Through use of chassis resistance
Inclusion of tractive effort limitations due to road-tire adhesion	YES	NO
Inclusion of engine and rotating parts inertia	YES	NO
Applicability to vehicles other than trucks	For cars, vans and etc.	To be researched
Consideration of static and dynamic loading	YES	NO
Differentiation between different truck configuration	YES	NO

Table 6.1 *Comparison of the Two Modelling Approaches*

Chapter 7

Model Outputs and Comparisons

7.1 Overview

In this study, two simulation models were developed to predict the performance characteristics of heavy and recreational vehicles which normally pose problems on a two-lane highway grade due to their unacceptable speed loss. These two models are described in detail in chapters 5 and 6. Other sources of the similar information are Ministry of Transportation, Ontario (MTO) (28), Transportation Research Board (TRB) (30), American Association of State and Highway Transportation Officials (AASHTO) (19) and Roads Transportation Association of Canada (RTAC) (29). Also, field studies have been done by MTO and the Federal Highway Works Administration (FHWA, U.S.A.) (45).

In the present chapter, the results obtained from our two models (Model I and II) are interpreted. Comparisons between various available sources is also done. The outputs for Model I and II are included in Appendix B.

7.2 Model Output Interpretation

Appendix B contains selected outputs for Model I and II. The entry speed for all is 90 km/h and loading levels are 120 kg/kw and 180 kg/kw for trucks and 40

kg/kw for recreational vehicles. For analysis, entry speeds other than 90 km/h (i.e. 80 km/h and 100 km/h) and loading levels of 60 kg/kw and 210 kg/kw were also considered.

For Model I, truck type is well defined, and for Model II a generic truck is considered. The curves include the acceleration capabilities of vehicles for grades of -9% to +9% and deceleration capabilities for grades of 0% to +9%. These curves represent that in absence of any external obstruction or hindrance the vehicle (with defined weight/power ratio and entering speed) on the given grade will follow a speed-distance profile as shown in the output.

Even on a level road it was observed that heavy trucks are unable to attain speeds of 100 km/h for a load level of 180 kg/kw or higher, and for loading level of 210 kg/kw, even a speed of 90 km/h was hard to attain. It can be explained by the fact that given the weight/power ratio and other transmission characteristics, these vehicles cannot achieve these speeds as the power available is low to haul the load at that speed. To attain higher speeds, a change in engine power or loading level has to be made, so as to lower the weight/power ratio.

The use of these speed-distance performance curves for a heavy vehicle gives an estimate of its speed and also the speed of the following vehicles, in lack of suitable passing opportunity. Its main usage is in designing and locating climbing lanes on two-lane highways. The routes which contain significant slow-moving traffic may have trucks or recreational vehicles, or both. Critical length of a grade on these routes, (as discussed in chapter 1) has to be determined by using these curves.

7.3 Rationale for Comparison

Various models differ in their form and as well as in their input values. The model structure and level of details are specific to the model. Truck characteristics differ substantially in terms of engine transmission, aerodynamics, axle configuration and other related factors. As such, these various outputs cannot be compared in a very strict fashion. However, all of these models attempt to define truck or long combination vehicle performance on roadway. It will be of interest to observe their validity in present context along with their similarities and differences.

Besides this, the common criteria which can be used to compare these different model outputs is vehicle weight/power ratio.

Comparison with field observed data will further substantiate the model outputs, by noting any agreements and disagreements. Field observations vary within a reasonable range and as such vehicle speeds cannot be directly matched with the given weight to power ratio. Proper statistical analysis of field data is required to find the matching vehicle population. Generally, 12.5 percentile and 50 percentile of the vehicle population will give the most critical and commonly observed weight to power ratios, respectively (45).

The population of trucks using a roadway, encompasses a broad range of performance capabilities, and as such it is hard to find a 'typical' performance representative of all. This is also illustrated by Figure 7.1, which shows the cumulative distribution of tractor-trailer deceleration measured near the beginning of a grade on five different locations (45). By observation it is evident that trucks near the top of distribution are not significant impediment to traffic. It is the trucks from the mid-point and down represented by 50 percentile and less, which cause reasonable

Source: (45)

Figure 7.1 *Probability Distribution of Spatial Acceleration for Tractor-Trailers on Five Different Sites*

impediment to traffic. The trucks at the bottom of the distribution, which experience the greatest deceleration are the vehicles causing traffic impediment. These can be characterized by 12.5 percentile (45).

Thus, a possible way to characterize the truck population distribution, is to characterize it by at least by 12.5 and 50 percentile values, in addition to any other percentile value desired. For highway design stress should be placed on 12.5 percentile level because vehicles below that depart markedly in their performance and hence it will be unreasonable to characterize them as representative.

7.4 Comparison of Model Outputs With Other Sources

Basically two sets of comparisons will be made, one amongst the two models developed, and other between the developed models and available performance curves. The outputs for both the developed models are given in Appendix B. Comparison of Model I and Model II outputs suggests that the detailed model (Model I), shows a higher sensitivity with respect to loading levels (as shown later) as compared to Model II, owing to the aggregate nature of the latter.

In Table 7.1, selected outputs of Models I and II are compared for different loading levels and for sample grades of 3% and 5%. Entry speed of 90 km/h is used for 180kg/kw, and 120kg/kw levels and 80 km/h, for 210 kg/kw. Crawl speeds estimated by the speed-distance curves of other sources are also noted in Table 7.1.

It should be well recognized that while comparing the results of Model I and II, there cannot be exact similarity due to the difference in vehicle configuration, engine and transmission characteristics. Inputs used for both the models are also noted in Appendix B.

Vehicle Category	Grade, %	
	3 %	5%
Model I (Detailed Simulation)		
180 kg/kw Straight Truck	44	28
210 kg.kw Semi-Trailer	34	23
180 kg/kw Semi-Trailer	42	28
120 kg/kw Semi-Trailer	60	42
180 kg.kw Double Trailer	42	27
40 kg/kw Recreational Vehicle	90	74
Model I I (SAE Version)		
210 kg/kw Truck	38	27
180 kg/kw Truck	42	30
120 kg/kw Truck	54	42
40 kg/kw Recreational Vehicle	89	77
MTO Capacity Seminar and RTAC Manual		
200 kg/kw Truck	42	30
AASHTO		
300 lb/hp (180 kg/kw)	43	29
TRB		
200 lb/hp (120 kg/kw)	59	42
300 lb/hp (180 kg/kw)	43	29

Source: Appendix B for Model I & II Outputs and Ref. 19, 28, 29 & 30.

Table 7.1 Comparison of Selected Vehicle Crawl Speeds, (km/h)
Estimated by Various Models

Model I outputs are more sensitive to truck configuration and drag area characteristics, as they change quite a bit in the various cases of straight truck, semi-trailer and double-trailer. Considering the loading level of 180 kg/kw for Model I, differences in crawl speeds can be seen in the straight truck case as compared to semi or double trailer. Now considering a possible correspondence of Model II 180 kg/kw truck, to possible match in Model I, it is observed that the semi-trailer fits in well.

Furthermore, within Model I semi-trailers, it is seen that sensitivity with respect to loading level of 210kg/kw, 180kg/kw, and 120 kg/kw is more enhanced as compared to the sensitivity of Model II outputs with same different types of loading levels. Also in Model I, double trailers perform relatively bad, especially at the higher grades.

Recreational vehicles compare well. In the case of recreational vehicle, the loading level (40 kg/kw) considered is of the threshold level and corresponds to the weight/power ratio as achieved by considering the maximum allowable towing load by a passenger car.

The second set of comparisons compares the output of two models developed in this study with those of AASHTO, TRB, RTAC and MTO. It is observed that Model I corresponds to some extent with these published curves for the case of semi-trailer. Values for straight truck and double trailer are somewhat higher and lower respectively, which might be obvious due to Model I's characteristics. Model II outputs correspond reasonably well with those of TRB and AASHTO, because they have also used the SAE method with some modifications.

It is noticed that though MTO and RTAC give a typical vehicle as 200 kg/kw (328 lb/hp) category, their values are in vicinity to 180 kg/kw (300 lb/hp) case of AASHTO and TRB. By observations and comparisons it seems that by use of

Model I, Model II, AASHTO and TRB curves for the loading level of 200 kg/kw, the crawl speeds will be lower than those given by MTO and RTAC. Probably MTO and RTAC guidelines are over-estimating the truck performance at the loading level of 200 kg/kw (328 lb/hp).

7.5 Comparison of Model Outputs With Field Data

After having done the comparison with other published sources, it is quite desirable and imperative to observe the validity of these model outputs with respect to field data observed on sites, as well as with the field data available as a result of previous works and studies.

Besides considering the data obtained by Federal Highway Works Administration (FHWA) and study by Ministry of Transportation, Ontario (MTO), limited field observations were done on four highway sites near Ottawa. Location, grade percent and length of these four sites are given in Table 4.3.

The grades used in the field observation are in the range of 3.0% to 5.3% with lengths ranging from 200m to 1300m. Significant amongst the factors is that, the observations were taken in a near free-flowing conditions with respect to heavy vehicles, as the performance curves basically reflect only these speeds.

Observations at a location with high queues and peak traffic will defy the objective. As such, sites considered here are believed, not to be affecting trucks in any other way except by the virtue of their grades, i.e. secondary causes other than the grade are not present. At site 1 the entry speeds were affected due to the presence of railway crossing near the foot of the grade and at site 2 the entry speeds of the vehicles were somewhat higher due to the presence of a down grade before the foot of the grade.

Table 4.4, summarizing the observation for trucks and recreational vehicles, gives an impression that the drop in truck speed is somewhat in-line of what is expected as compared to speed drop of recreational vehicles, which seem to be higher than what can be predicted from the model. The reason for this observation can be that drivers of private vehicles are not utilizing full engine power or to the extent as is assumed in the model simulation.

Now comparisons are to be made with this observed data and data from other sources (45) as discussed earlier. The comparisons are shown in Table 7.2 and Table 7.3. Table 7.2 contains comparisons of Model I results with observed field data. As the classification of trucks and their speed distribution is not known by the truck type (i.e. straight truck, semi-trailer or double trailer), a semi-trailer category was chosen with a design weight/power ratio of 180 kg/kw with entering speed of 90 km/h.

As discussed earlier in Section 7.3, 50 and 12.5 percentile speeds are used from the collected data for trucks and in case of recreational vehicle 50 percentile was used. Had observation been taken in more details and by truck types, application of Model I would have direct comparison. This was not possible due to time and budget constraints. Proper adjustments and approximations are made where the entry speeds at different grades differ from the standard entry speeds of Model I outputs (i.e. 90 km/h).

By examining Table 7.2, it can be inferred that the 50 percentile truck speed roughly corresponds to 120 kg/kw category and in the case of the 12.5 percentile truck speed it can be approximated with 180 kg/kw category. The results in case of site 1 and site 4 are in better agreement than others.

In the case of recreational vehicle, the speeds estimated from the model are higher than observed as 50 percentile speed. One of reasons for this disagreement may be insufficient use of engine power by recreational vehicle drivers.

Site Details	Site 1	Site 2	Site 3	Site 4
Grade (%) Length (m)	5.3 200	3.5 1000	3.0 1300	3.0 900
Field Data: Trucks				
50 percentile speed (km/h)	68.0	77.0	74.0	69.0
12.5 percentile speed (km/h)	48.0	65.0	64.0	56.0
Model i[*] Results				
120 kg/kw Semi-trailer	64.0	67.0	64.0	70.0
180 kg/kw Semi-trailer	50.0	53.0	49.0	58.0
Field Data: Rec. Vehicle				
50 percentile speed (km/h)	70.0	79.0	77.0	68.0
Model i[*] Results				
40 kg/kw Rec. Vehicle	77.0	87.0	89.0	89.0

* Refer table 4.4 for the approach speeds.

Source: Appendix B and Ref. 44

Table 7.2 Comparison of Model Results with Observed Field Data

In Table 7.3, comparison of both models is done with F.H.W.A. field data. In case of Model I, semi-trailer and double-trailers of 120 and 180 kg/kw loading levels are compared with F.H.W.A. data and for Model II, a generic truck type with the same 120 and 180 kg/kw loading levels is compared with F.H.W.A. data.

As per U.S. field data (FHWA) 50 and 12.5 percentile speed of the double-trailer is less than corresponding percentile speeds of straight trucks. On comparison, Model II output for 120 kg/kw falls between 50 percentile vehicles of U.S. data (i.e. between double-trailer and straight truck and semi-trailer), and that for 180 kg/kw generic truck loading it compares with 12.5 percentile of U.S. data. This seems to be acceptable as Model II cannot really distinguish between different truck types.

For Model I speeds are averaged for semi-trailers and straight trucks, so as to compare directly with the U.S. field data. It is seen that there is quite good correspondence between 180 kg/kw double trailer and 120 kg/kw semi-trailers of Model I to 12.5 percentile double-trailer and 50 percentile semi-trailer from the FHWA (U.S.) data. While as in the case of the 180 kg/kw semi-trailer, Model I under-estimates slightly as compared to 12.5 percentile of 'straight trucks and semi-trailers' of the FHWA data. Also for 120 kg/kw of the double-trailer category, Model I over-estimates the speeds as compared to 50 percentile value of FHWA double-trailer.

The explanation for this discrepancy can be that the 180 kg/kw and 120 kg/kw category of semi-trailers and double-trailers do not necessarily correspond to 12.5 percentile semi-trailers and 50 percentile of double-trailers respectively. Giving an indication thereby that in practice, for loads of 180 kg/kw double-trailers are more often used and for loads of 120 kg/kw semi-trailers or straight trucks are preferred, which to some extent sounds reasonable. If this is true, correspondence of Model I

	Crawl Speed, Km/h	
	3% Grade	5% Grade
U. S. Field Data		
50 percentile vehicle speed		
Double Trailer	50.0	36.0
Straight Truck and Semi-Trailer	61.0	45.0
12.5 percentile vehicle speed		
Double Trailer	42.0	29.0
Straight Truck and Semi-Trailer	50.0	34.0
Model I Output		
120 kg/kw Double Trailer	61.0	42.0
120 kg/kw Semi-Trailer & St. Truck	60.0	44.0
180 kg/kw Double Trailer	42.0	27.0
180 kg/kw Semi-Trailer & St. Truck	44.0	29.0
Model II Output		
120 kg/kw Truck	54.0	42.0
180 kg/kw Truck	42.0	30.0

Source: Appendix B and Ref. 44, 45

Table 7.3 *Comparison of Model Results with U.S. Field Data*

outputs to field data may fit in well.

For the validity of Model II, similar comparisons can be made (see Ref. 44). Lastly, three graphical comparisons are made for Model I output as follows:-

Figure 7.2 compares the Model I output for light (60 kg/kw) and heavy (180 kg/kw) semi-trailers case with MTO data. It is known that semi-trailers represent an average and commonly used truck assembly on Canadian highways (33). The field data from MTO representing average and loaded trucks fits in quite well within the envelope created by Model I output of heavy and lightly loaded trucks.

Figure 7.3 gives a feel of speed-distance profile of MTO's tractor trailer test. This MTO data seems to fit in closely to the 180 kg/kw semi-trailer category, but it is slightly less than 180 kg/kw level, as its crawl speed is higher than that for 180 kg/kw.

Ultimately, Model I has been compared graphically with the field data of site 2. For illustration, entry and final speeds at the beginning and end of the grade, are plotted assuming linear speed decay. To compare with the Model I entry speed of 90 km/h, the plot is translated to match 90 km/h assumed entry speed and it is found that this field data for site 2 fits in the theoretical envelope given by Model I fairly well. The average loading level observed, is between 60 kg/kw and 180 kg/kw, but closer to 180 kg/kw. See Figure 7.4.

7.6 Study Assumptions

1. The effect of vehicle maintenance on the overall variation in the vehicle performance during regular use and normal wear and tear is quite insignificant. The majority of vehicle owners and operators service and maintain their vehicles

Figure 7.2 *Comparison of Model I Output and MTO Field Data, 5% Upgrade*

Figure 7.3 Comparison of Model I Output and MTO Tractor-Trailer Test Data, 5% Upgrade

Figure 7.4 Comparison of Model I Output and Field Data: Site (2),
9.5% Upgrade

regularly so that the performance does not decrease with regular use. Also, the practical performance on road may differ somewhat from the theoretical performance, due to improper handling and operation. Driving and gear shifting pattern of a driver can also effect the vehicle's performance.

It is quite hard to quantify and account for the exact effect of driver behaviour and tendencies. For simplicity, it is assumed that drivers are well trained and informed about the normal vehicle operation.

2. The configuration, dimensions and loading levels have been kept in accordance with Appendix C (37).
3. Engine Utilization Factor α has been assumed equal to unity considering optimum engine use and maximum throttle opening.
4. Generally heavy trucks are fitted with manual gear transmissions and as such manual gear transmission was used.
5. No skin friction drag and air flow resistance within the radiator is considered in value of C_D , as it tends to be insignificant.
6. Presence of aerodynamic lift and running gear slip in trucks has been assumed to be negligible, as these are more relevant in light vehicle simulations.
7. It is assumed that on grades, drivers at all the given times use full throttle and even after gear change they go on to the next gear with the same throttle opening, giving an instantaneous jump in speed.
8. The simulation programs developed are designed to handle maximum number of gears as 20, maximum vehicle speed as 120 km/h and maximum number of

input pairs for engine-torque and engine-speed as 30. The recommended minimum number of these engine-torque and engine-speed points for reasonable accuracy are 12, as the curve fitted is of the 10th order.

Chapter 8

Applications of Performance Curves

8.1 General

Knowledge of heavy vehicles (i.e. trucks and other long combination vehicles) performance characteristics as discussed in earlier chapters, is quite important in knowing the operational behaviour of these typical vehicles on roads.

Performance curves serve as a good tool in estimating the speeds of vehicles and aid in decisions making for climbing lane location, critical length of grades, truck equivalency factors and finding equivalent grade for a composite grade section. The severity of the problem posed due to the slow moving vehicles, is illustrated by the fact that beyond 15 km/h drop in speed, the accident involvement rate of vehicles increases rapidly (29,44).

This fact is also illustrated by Figure 1.4. Thus from a safety point of view a limit of 15 km/h drop in speed is used for the calculation of critical lengths and in locating climbing lanes.

The main applications of performance curves are as follows:

- determination of critical length of grade
- finding location and length of truck climbing lanes
- calculating equivalent grade for a composite grade section
- arriving at the truck equivalency factor for the mixed traffic

For all the illustrations in the above applications, Model I performance curves for 180 kg/kw semi-trailer are used.

8.2 Determination of Critical Grade Length

As defined earlier in chapter 1, critical lengths are useful in determining whether a climbing lane is required or not for a given grade with the given permissible speed reduction. These critical length curves are given in the form of speed reduction curves. These curves give us the acceptable length of a particular grade, up to which no climbing lane is required, as the speed-drop up to this point is within the permissible speed reduction limits. Figure 8.1 shows the speed reduction curves for 180 kg/kw semi-trailer entering the grade at 90 km/h. Model I curves are used for this. The speed reduction curves are illustrated for 10, 15, and 20 km/h of speed reductions.

Thus taking the case of 15 km/h drop for a typical design truck (semi-trailer, 180 kg/kw (300 lb/hp)) entering an upgrade of +4% with the speed of 90 km/h, the critical length is 273m (Figure 8.1). That is, a climbing lane should be provided only beyond 273m, if this grade exceeds this length.

For comparisons, values of critical lengths obtained from other sources are: Highway Capacity Manual (HCM) (30), 261 m for a standard truck of 300 lb/hp; AASHTO, 1984 (19), 267 m for a standard truck of 300 lb/hp; MTO (27) and RTAC (29) for a standard truck of 200 g/w (329 lb/hp), 292 m; Model II for a standard truck of 180kg/kw (300 lb/hp), 278m. It is seen that both MTO and RTAC are over-estimating the truck performance as both the critical length as well as the loading level are higher than that of Model I and other sources. AASHTO and HCM both under-estimate the truck performance as compared to Model I. Model II also over-estimates as compared to Model I.

Figure 8.1 Speed Reduction Curves for Design Truck of 180 kg/kw (90 km/h)

8.3 Location and Length of Truck Climbing Lanes

Climbing lanes have been defined earlier in chapter 1. An application of these speed-distance curves is in determining where the climbing lane should start (usually beyond the critical length) and how long should it be, so as to keep the slow moving vehicles off the main traffic stream until their speed is within allowable limits.

As a result of a recent study, it was determined that allowable speed reduction should be limited to 15 km/h for the safety and economic reasons and that the design vehicle be 180 kg/kw (44).

It is concluded that the climbing lane should start where the vehicle experiences speed drop of 15 km/h or more, and should continue to the point where the vehicle has regained the speed to be within 15 km/h of the highway operating speed. Also minimum length of 500m is recommended to manoeuvre overtaking. If the sight distances are restricted, even after the vehicle attains the permissible speed, the length of the climbing lane should be extended to provide requisite sight distance (29).

As an illustration, Figure 8.2 shows a typical composite grade section, for which location and length of the climbing lane is to be determined. Figure 8.3 shows the deceleration and acceleration curves for 180 kg/kw, semi-trailer entering the grade at 90 km/h.

Location and length of the climbing lane is contingent upon the speed drop of the vehicle. To arrive at the vehicle speed at different points on grade we proceed as follows:

Starting at 90 km/h (*point A*) on the deceleration curve in Figure 8.3 follow +3% grade until 600m. The speed then changes to 67 km/h (*point B*) and continuing with this speed transfer to +4% grade curve and cover a further distance of 500m. The terminal speed at the end of this grade is 43 km/h (*point C*). Now with this speed go on to the acceleration curve of +2% grade and follow

200m on it to get the speed of 46 km/h (*point D*). Further travelling 1170m on the 0% grade, the vehicle attains 75 km/h which corresponds to 15 km/h speed drop (*point E*).

We also observe that the speed of the vehicle falls to 75 km/h (15 km/h reduction) between *A* and *B* at 386m from *A* and further regains speed of 75 km/h at *E*, 1170m from *D* at 0% level grade.

The location of climbing lane is thus marked in the Figure 8.2 and its length is equal to 2084m i.e. 2.08km. The length of the climbing lane has been approximated by tangents and not by the length of vertical curves. Transition length can also be added at the beginning and end of the climbing lane.

8.4 Calculation of Equivalent Grade for a Composite Grade Section

For the determination of passenger car equivalents (*PCE*) for heavy vehicles on grades, one has to have the knowledge of percentage of grade. According to the Highway Capacity Manual (30) if the total length of the composite grade is greater than 4000ft (1220m) or if any single grade exceeds 4% then the 'overall average grade' cannot be substituted for the given series of grades.

In these conditions, it is recommended (30) that truck performance curves should be used to get the equivalent uniform grade percent, which will then be used in finding passenger car equivalents. It is more often used for capacity analysis.

For an illustration, see Figure 8.2. Though no individual grade is greater than 4% but the total length of the composite grade is 1300m ($> 4000ft$). The precise method in this case is to find the equivalent grade of 1300m which would result in the same final speed of the truck, as in 600m of 3% grade followed by 500m of 4% grade, followed by 200m of 2% grade. The procedure for this, as illustrated in Figure 8.3 is:

Figure 8.2 A Typical Highway Section

Figure 8.3 Acceleration and Deceleration Curves for 180 kg/kw Truck (90 km/h)

1. Enter 3% deceleration curve and follow it for a distance of 600m, next enter deceleration curve of 4% grade at speed with which 3% grade ended. Next, after going 500m on 4%, move to the acceleration curve of 2% grade and cover 200m on it. The final speed is thus 46 km/h i.e. *point D*.
2. Now with this speed of the truck, find the percent grade curve which intersects this speed at a distance of 1300m. This gives *point F* and the equivalent grade as 2.5 percent up grade.
3. Next, the passenger car equivalents can be determined for this uniform grade of 2.5 percent.

Though this procedure does ignore vertical curves joining the grades, but still gives sufficient accuracy as compared to taking an overall average grade.

8.5 Determination of Truck Equivalency Factor

These performance curves can be used in conjunction with other information in arriving at the truck factor, given the percent passing opportunity and the highway design speed.

For the determination of truck equivalency factors, zero traffic speed of every type of impeder vehicle (i.e. truck, recreational vehicle) must be known. These zero traffic speed estimates are arrived at by the use of vehicle performance curves.

The truck factor is represented by:

$$F_T = \frac{1}{(2r_0 + 1)^{\frac{1}{2}}} \quad (8.1)$$

$$r_0 = \frac{P_T}{100}(\nu - 1) \quad (8.2)$$

where:

F_T truck factor

P_T	percentage of trucks
ν	truck equivalence kernel

ν is a function of zero traffic (free) speed of the impeder vehicle. This relationship uses the simulation results of speed and flow rates for the passenger cars in the mixed flow (18). This truck equivalence kernel ν can be determined for individual vehicle type on rolling terrain as well as on grades. It has a non-linear relationship with the equivalent number of passenger cars as contrary to conventional equivalences which correspond directly to the number of passenger cars. This variable ν which plays a pivotal role in the determination of Truck Equivalency Factor, can be expressed (18) as an exponential function of zero traffic truck speed on different grades. These speeds are arrived at from the truck performance curves. Detailed application can be found in reference 18.

Chapter 9

Conclusions and Recommendations

9.1 Conclusions

From this study, the following main conclusions can be made.

- 1. Two models were developed to estimate the performance of heavy commercial vehicles or typical recreational vehicles. Model I, which is developed in this study, is quite detailed and has the potential to deal with the different types of trucks, based on their configuration and aerodynamic characteristics. It acts more as a research tool. Model II on the other hand, is based on the Society of Automotive Engineers (SAE) recommended procedure using empirical relations. Model II can only simulate a generic truck or a recreational vehicle.**
- 2. Development of the two models was necessary so as to examine the validity of currently available sources in the light of changes in truck technology and usage, various input parameters and changes in weight/power ratio trend over time.**
- 3. The outputs of both the models compare grossly within a reasonable range, with the other available sources and field data. Model II shows less sensitivity to loading levels and entry speeds. On the contrary, Model I output shows higher sensitivity to the truck type, loading level, axle and tire configurations etc. The results seem to be dispersed more. This type of difference is obvious, given the difference of Model I's approach to Model II's approach.**

4. Even on the level road, the trucks are not able to attain maximum speed of 100km/h for a loading level of 180 kg/kw and 90 km/h for a loading level of 210 kg/kw (outputs not included). The outputs included in Appendix B are only for 120 and 180 kg/kw with the entry speed of 90 km/h. The significance of this observation is that the heavy trucks of 180 kg/kw, on two-lane highways will normally not travel at the posted maximum allowable speeds of 100 km/h and would thus enter grades at a speed, lower than that of cars and other light traffic.
5. The vehicles used for simulations are believed to be representative of their class. The weight to power ratio used for truck simulations, covers a wide range of loading levels. The 60 kg/kw loading level represents light loading level whereas 120 kg/kw level is for an average or typical truck corresponding to 50 percentile truck speed. A loading level of 180 kg/kw is considered to be heavily loaded and corresponds to 12.5 percentile truck speed. Weight to power ratio for very heavy hauling of grains, forest products, gravel and the like products can lie in the category of 210 kg/kw.
6. These values and loading levels are the best estimates that could have been made in the absence of detailed and sufficient data on truck weight to power ratio. In future, to operate with the increased allowable weights (as per Ref. (37)), truck power will also have to be increased for maintaining the required minimum highway speed. Therefore, representative weight/power ratios may not change appreciably.
7. In the case of recreational vehicles, the performance from the model output is a bit over-estimated for grades up to 4%. The reason for this may be that drivers are not utilizing the engine power to the extent it is assumed in the simulation process, due to the reasons discussed earlier. As compared to the truck drivers who are known to use engine power to a very high degree, private vehicle owners, like that of recreational vehicles, trade off speed with full engine use. Another reason for the lack of correspondence between field and model

simulated results may be the effect of horizontal and vertical alignment of road on the driver.

Drivers of recreational vehicles tend to use near-full power on about 6% grade or higher. It may also be recognised that instead of maximum recommended loading of 40 kg/kw, in practice recreational vehicles may normally be overloaded to the extend of 60-80 kg/kw and thereby giving lower speeds as compared to 40 kg/kw model simulation. This will further improve the agreement between simulated and field results.

8. For illustration, a sample output for gear change delay has been attached for a 180 kg/kw double-trailer case. Discontinuities would again require smoothing of curves for further use.

Given the difficulty of simulating the gear shift behaviour of drivers, variation of engine transmission characteristics and the small difference (typically around 1 km/h or so) in the crawl speeds, it may not be always necessary to use the gear change feature. The effect of gear change is more noticeable at lower speeds, i.e. at the higher gears, and tends to become negligible at higher or crawl speeds, i.e. at lower gears.

This difference may not be even recognizable in the case of automatic transmission. Previous works have either overlooked the gear shift feature or reported the average values (20).

9. Besides examining the validity and applicability of previous works on vehicle performance characteristics, this study also provides a very basic, accurate (subject to data availability), handy and readily available vehicle performance model. This model should serve as a valid and basic reference for any future use.

9.2 Recommendations

1. The representative heavy truck of weight/power ratio of 200 kg/kw (328 lb/hp) as used by MTO and RTAC manual should be reduced to 180 kg/kw category, as this then represents the 12.5 percentile of truck speed. Designing climbing lanes for loading level of 200 kg/kw may result in redundancy and over-design of the highway section, as it will lie below 12.5 percentile truck speed.
2. Only where the situation demands due to the nature and region of operation, weight/power ratio of representative vehicles may be taken higher than 180 kg/kw e.g. 210 kg/kw, denoting a heavy trucking and logging area. Also depending upon regional differences and truck majority, loading of 120 kg/kw can be selected. In otherwise normal conditions, design vehicle should be taken as 180 kg/kw.
3. If on certain routes, percentage of different weight/power ratio is known, a weighted average can be taken for arriving at the climbing lane critical length.
4. Further research should be carried out to develop various factors (e.g. engine utilization factor, altitude factor, tire growth factor etc.) and coefficients (e.g. drag coefficients, rolling resistance coefficient etc.) which are up-to-date and reliable. Collection of field data has to be very extensive and exhaustive to select the correct representative vehicle. One way of making inventory of the vehicle population (vehicle type and engine power), is to get all the relevant information at the time of sale and registration. This will help us to know the truck population in detail and by region.
5. More work has to be done in order to simulate driver behaviour and reactions, and to get the real picture. Some sort of quantification scale should also be developed.
6. Given the detailed version and input requirements for Model I, Model II can be preferred over Model I in the instances where reliable and detailed data is not

readily available.

7. If the simulation has to be done for trucks in particular without the knowledge of truck type, then for Model I, semi-trailer category can be used.
8. Depending upon the volume of trucks or recreational vehicles or both, on a given roadway, proper vehicular mix should be used for design purposes. It should be noted however, that for recreational vehicles models over-estimate the performance at less than 5 percent grade, as explained earlier. Slight overloading of recreational vehicles up to the extent of 60-80 kg/kw could also be considered for bigger travel homes and heavy trailers.
9. The speed-distance calculations, as a result of these models can be further utilized to give critical grade lengths for different percent grades with different allowable speeds reductions and with various grade entry speeds. This again can be repeated for one or more loading levels. A suitable computer program should be developed for this purpose to aid in the climbing lane decision making.

References

- [1] **Ministry of Transportation, Ontario, *Provincial Highways - Trends Overview*, Highway Program Analysis Office, MTO, December 1988.**
- [2] **Roads and Transportation Association of Canada, *Canada's Highways: A Profile*, RTAC, Ottawa, 1988.**
- [3] **ADI Limited, *Passing Manoeuvres and Passing Lanes: Design, Operational and Safety Evaluations*, Report Prepared for Transport Canada, Project No. 1264-36, March 1989.**
- [4] **ADI Limited, *Evaluation of Passing Lane Safety*, Draft Report Prepared for Transport Canada, Project No. 1264-36, September 1988.**
- [5] **Saal C. C., *Hill Climbing Ability of Motor Trucks*, Public Roads, May 1942.**
- [6] **Taragin A., *Effect of Length of Grade on Speed of Motor Vehicles*, Highway Research Board Proceedings, Vol. 25, 1945**
- [7] **American Association of State Highway Officials, *A Policy on Geometric Design of Rural Highways*, 1954.**
- [8] **Willey W. E., *Uphill Truck Speeds*, Roads and Streets, Jan. 1950.**
- [9] **Huff T.S. and Scrivner H.H., *Simplified Climbing-Lane Design Theory and Road-Test Results*, HRB Bulletin 104, 1955.**
- [10] **Firey J.C. and Peterson E.W., *An Analysis of Speed Changes for Large Transport Trucks*, HRB Bulletin 334, 1962.**
- [11] **American Association of State Highway Officials, *A Policy on Geometric Design of Rural Highways*, Association's General Office, 1965.**
- [12] **Glennon John C., *An Evaluation of Design Criteria for Operating Trucks Safely on Grades*. Highway Research Record No. 312, National Research Council, 1970.**

- [13] **Smith G. L.**, *Commercial Vehicle Performance and Fuel Economy*, SAE paper SP 355, Jan. 1979.
- [14] **St. John A. D. et. al.**, *Vehicle Handling, Acceleration and Speed Maintenance*, Final Report No. FH 11-6908, National Highway Safety Bureau, 1969.
- [15] **Society of Automotive Engineers**, *Truck Ability Prediction Procedure*, SAE Recommended Practice, SAE J688, August 1987.
- [16] **Society of Automotive Engineers**, *Truck Ability Prediction Procedure, HS-82*, Detailed report in conjunction with SAE J688, Society of Automotive Engineers, Inc. Warrendale, PA.
- [17] **Nemeczky J. A. et. al.**, *Grade Effects on Traffic Flow and Capacity*, System Development Corporation, NCHRP Project 3-19, 1972.
- [18] **St. John A. D. and Kobett D. R.**, *Grade Effects on Traffic Flow Stability and Capacity*. TRB, NCHRP Report 185, 1978.
- [19] **American Association of State Highway and Transportation Officials**, *A Policy on Geometric Design of Highways and Streets*, Washington D.C., 1984.
- [20] **Hayhoe G.F. and Grundmann J. G.**, *Review of Vehicle Weight/Horsepower Ratio as Related to Passing Lane Design Criteria*. NCHRP Report PT1 7806. Oct. 1978. Pennsylvania State University.
- [21] **Abbas M. S. and May A. D.**, *Acceleration Performance Capability of Five-Axle Trucks*, Research Report UCB-ITS-RR-82-2, University of California at Berkley, 1982.
- [22] **Safwat K. and Walton C. M.**, *Expected Performance of Longer Combination Vehicles on Highway Grades*. Transportation Research Record 1052, TRB, 1986.
- [23] **Transportation Research Board**, *Symposium on Geometric Design for Large Trucks*, Record No. 1052, National Research Council, 1986.
- [24] **Sovran Gino et. al.**, *Aerodynamic Drag Mechanism of Bluff Bodies and Road Vehicles*, Plenum Press, New York, 1976.

- [25] **Marks Colin H. and Buckley Frank T., *The Effect of Tractor-Trailer Flow Interaction on the Drag and Distribution of Drag of Tractor-Trailer Trucks.*** SAE technical paper series 801403, 1980.
- [26] **Scibbar A. J., *Road Vehicle Aerodynamics,*** Pentech Press, London, 1975.
- [27] **Ministry of Transportation, Ontario, *Geometric Design Standards for Ontario Highways,*** Downsview, Ontario, 1976 and 1985.
- [28] **Ministry of Transportation, Ontario, *Highway Capacity Seminar Notes,*** Downsview, Ontario.
- [29] **Roads and Transportation Association of Canada (RTAC), *Manual for Geometric Design Standards for Canadian Roads,*** 1986, Metric Edition.
- [30] **Transportation Research Board, *Highway Capacity Manual, Special Report 209,*** National Research Council, Washington D.C., 1985.
- [31] **Saal C. C., *Relationship Between Gross Weight of Motor Trucks and Their Horsepower,*** Public Roads, Vol. 29, No. 10, 1957.
- [32] **Wright J. M. and Tignor J. C., *Relationship Between Gross Weight and Horsepower of Commercial Vehiclces Operating on Public Roads,*** SAE Transaction, Vol. 73, 1965.
- [33] **Ervin R. D., *A Survey of the Characteristics of Equipment in the Canadian Trucking Fleet,*** Interim Technical Report, Number 1, RTAC, 1984.
- [34] **Ervin R. D., *The Influence of Weights and Dimensions on the Stability and Control of Heavy Trucks in Canada, Volume 1,*** Canroad Transportation Research Corporation, 1986.
- [35] **Solomon D., *Accidents on Main Rural Highways Related to Speed, Driver and Vehicles,*** Bureau of Public Roads, U.S. Department of Commerce, July 1964.
- [36] ***Guide for Monitoring and Enhancing Safety on the National Truck Network,*** Federal Highway Administration, Office of Highway Safety, Oct. 1986.

- [37] **Roads and Transportation Association of Canada**, *The Memorandum of Understanding on Interprovincial Vehicle Weights and Dimensions, Summary Information*, February 1988.
- [38] **Clark M. F. et. al.**, *Heavy Vehicle Weights and Dimensions in Canada*. Paper presented at 65th Annual Meeting, TRB, Washington D.C., 1986.
- [39] **Wong J. Y.**, *Theory of Ground Vehicles*. John Wiley & Sons Inc., 1978.
- [40] **Lucas G. G.**, *Road Vehicle Performance*. Gordon and Breach Science Publisher, 1986.
- [41] **Fleet Owner**, *Annual Specs and Buyers' Directory*, October 1987.
- [42] *Personal Interviews and Discussions With the Truck Dealers in Ottawa-Hull Region*, Ottawa, November 1988.
- [43] *Survey and Data Collection From the Recreational Vehicle Dealers*, Ottawa, December 1988.
- [44] **Khan A.M., Wong J.Y., Rastogi M. et. al.**, *Heavy Vehicle Performance on Grade and Climbing Lane Criteria*. Report prepared for R & D Branch, Ministry of Transportation Ontario, Downsview, Ontario, March 1989.
- [45] **Gillespie T.D.**, *Methods for Predicting Truck Speed Loss on Grades - Final Technical Report*, FHWA, U.S. DOT, Report No. FHWA/RD-86/059, Oct. 1986.
- [46] **Cole D.E.**, *Elementary Vehicle Dynamics*, Department of Mechanical Engineering, University of Michigan, January 1971.
- [47] **Sharma K.D.**, *Programming in Fortran*, Affiliated East-West Press Pvt. Ltd. New Delhi. 1976.
- [48] *National Truck Weight Regulation - Historical Background and Emerging Issues*, TR News, No. 134, Jan-Feb 1988.

Appendix A

Input Variables and Program Source Listing

Both the simulation models are written in **FORTRAN 77** for the Apollo Domain 3000 computer system. The programming is done in the user friendly and interactive manner with the options of using either user-input values or the built-in default values.

In case, where precise and exact values of coefficients and dimensions are not available, the user has an option of using the default values built within the program. Such an option is available for all the relevant inputs.

Listings of 'POLFIT' and 'PVALUE' subroutines, along with other related subroutines, have not been included. These were used for curve fitting procedures in both the models. These subroutines are taken from the standard math library known as 'SLATEC'.

The final curves were possible using a graphics package called 'GRAPH' available on the Apollo computer system. Any other suitable graphics package, can also be employed for the purpose. The final distance and speed values from which the curves are plotted are contained in the subroutines 'ACCEL' and 'DECCEL'.

This appendix includes:

- 1) Input Variables and Program Source Listing – Model I
- 2) Input Variables and Program Source Listing – Model II

List of Input Variables for Model I

AD	<i>static rolling resistance coefficient</i>
AIRSPEED	<i>speed of the air</i>
ALPHA	<i>engine utilization factor</i>
AXLRATIO	<i>drive axle gear ratio</i>
A1	<i>frontal drag area of the tractor</i>
A2	<i>frontal drag area of the semi-trailer</i>
A3	<i>frontal drag area of the double-trailer</i>
BD	<i>dynamic rolling resistance coefficient</i>
CD1	<i>drag coefficient for the tractor</i>
CD2	<i>drag coefficient for the semi-trailer</i>
CD3	<i>drag coefficient for the double-trailer</i>
D1	<i>distance between hitch and drive axle</i>
D2	<i>distance between the semi-trailer C.G. and hitch</i>
DTRAILMAS	<i>mass of the double-trailer</i>
E	<i>altitude of the vehicle operation</i>
EDAT	<i>engine data for torque and speed</i>
GDAT	<i>gear box data for different gear ratios</i>
GF	<i>tire growth factor</i>
GRDLY	<i>gear change delay time</i>
H1	<i>height of the truck/tractor C.G.</i>
H2	<i>height of semi-trailer C.G. from the road level</i>
H3	<i>height of the hitch point from the road level</i>
HA1	<i>height of the application of air drag force on the tractor</i>
HA2	<i>height of the application of air drag force on the semi-trailer</i>
HD	<i>height of the application of the draw-bar load</i>
IE	<i>engine and rotating part inertia</i>
IP	<i>propeller shaft inertia</i>

L1	<i>truck/tractor wheelbase</i>
L2	<i>distance between the hitch and rear axle of semi-trailer</i>
L3	<i>distance between front axle and C.G. of the truck/tractor</i>
MAXSPEED	<i>maximum speed allowed on the highway</i>
MU	<i>coefficient of road-tire adhesion</i>
N1	<i>number of tires in the tractor unit</i>
N2	<i>number of tires in the semi-trailer unit</i>
N3	<i>number of tires in the double-trailer unit</i>
NGEAR	<i>total number of gears</i>
RD1	<i>draw-bar pull in case of RV's and double-trailer</i>
ROLRAD	<i>rolling radius of the drive axle wheel</i>
ROW	<i>air density</i>
STRAILMAS	<i>mass of the semi-trailer</i>
TIREMAS	<i>mass of the tire with rim</i>
TRACTMAS	<i>mass of the tractor</i>
VEHILE_TYPE	<i>type of the vehicle i.e. truck or RV</i>

Program Source Listing

Model I

```

C      This subroutine calculates tractive effort available
C      and the vehicle speed.
      PROGRAM SIMUFTN

      IMPLICIT LOGICAL (A-Z)

      REAL SPEED, ENGSPEED(30), TORQUE(30), EFFICY, ROLRAD, ROLRADV,
+      ALPHA, GF, C1, C2, AXLRATIO, GEARATIO(20), DATA1,
+      TRACEFF2, MAXSPEED, SLIPF, A,
+      SPEED1, E, VEHICLE_TYPE, SLIP

      INTEGER I, J, NGEAR, K, COUNT, M

      COMMON /A1/ AXLRATIO, MAXSPEED, ROLRAD, GF, NGEAR
      COMMON /A2/ DATA1(30, 125)
      COMMON /A3/ COUNT

      PRINT *, ' DETAILED SIMULATION MODEL FOR HEAVY VEHICLE '
      PRINT *, '          PERFORMANCE ON GRADES '
      PRINT *, ' '
      PRINT *, '          Developed by '
      PRINT *, ' '
      PRINT *, '          MAYANK RASTOGI '
      PRINT *, ' Carleton University, Ottawa, Canada '
      PRINT *, '          August 1989 '
      PRINT *, ' '
      PRINT *, '*****'
      PRINT *, ' '
      PRINT *, '          Please Enter the Inputs'
      PRINT *, ' '
      PRINT *, '-----'
      PRINT *, ' '
      PRINT *, ' '

      PAUSE

      OPEN (UNIT=20, FILE='EDAT18')
      OPEN (UNIT=21, FILE='G DAT9')
C      OPEN (UNIT=25, FILE='CURVESA')
C      OPEN (UNIT=29, FILE='CURV PLOT')
      REWIND (20)
      REWIND (21)
C      REWIND (25)
C      REWIND (29)

```

```

COUNT = 0
DO 10 I =1,100
    READ (20,*,END = 15) TORQUE(I),ENGSPD(I)
    COUNT = COUNT+1
10 CONTINUE
15 PRINT *, 'SPECIFY CATEGORY OF VEHICLE TO BE SIMULATED,'
    PRINT *, ' ENTER 1 FOR TRUCKS OF ALL TYPES AND 2 FOR'
    PRINT *, '      RECREATIONAL VEHICLES'
    READ *,VEHICLE_TYPE
    PRINT *, 'ENTER DRIVE AXLE RATIO (axlratio)'
    READ *,AXLRATIO
    PRINT *, 'ENTER NUMBER OF GEARS (ngear)'
    READ *, NGEAR
    PRINT *, 'ENTER ROLLING RADIUS OF DRIVE AXLE TYRE (rolrad)'
    PRINT *, 'FOR USING DEFAULT VALUE OF ROLLING RADIUS IN'
    PRINT *, 'CASE OF TRUCKS ENTER "ZERO (0)". AND IN CASE'
    PRINT *, '      OF RVs ENTER "ONE (1)"'
    READ *,ROLRAD
        IF (ROLRAD .EQ. 0) THEN
            ROLRAD = 0.5235
        ELSEIF (ROLRAD .EQ. 1) THEN
            ROLRAD = 0.274
        ENDIF
    PRINT *, 'ENTER TYRE GROWTH FACTOR,(GF) FOR USING'
    PRINT *, ' DEFAULT VALUE FOR CROSS PLY TIRE ENTER'
    PRINT *, '"ZERO (0)".FOR RADIAL TIRES THIS IS ZERO'
    READ *,GF
        IF (GF .EQ. 0) THEN
            GF = 1.84E-06
        ENDIF
    PRINT *, 'ENTER ENGINE UTILIZATION FACTOR,(alpha)'
    PRINT *, 'FOR USING DEFAULT VALUE OF UNITY'
    PRINT *, '      ENTER "ZERO (0)"'
    READ *,ALPHA
        IF (ALPHA .EQ. 0) THEN
            ALPHA = 1.00
        ENDIF
    PRINT *, 'ENTER THE ALTITUDE (E) ABOVE SEA-LEVEL AT WHICH'
    PRINT *, ' THE VEHICLE IS OPERATING (in meter)'
    PRINT *, ' FOR USING DEFAULT VALUE OF 150m (500ft)'
    PRINT *, 'ENTER "ZERO (0)" OR ELSE ENTER YOUR VALUE'
    READ *, E
        IF (E .EQ. 0) THEN

```

```

      E = 150.00
    ENDIF

    PRINT *, 'ENTER MAXIMUM ALLOWABLE SPEED (MAX. IS '
    PRINT *, ' 120 km/h), FOR USING DEFAULT VALUE OF '
    PRINT *, ' 90.0 km/h ENTER "ZERO (0)" '
    READ *, MAXSPEED

    IF (MAXSPEED .EQ. 0) THEN
      MAXSPEED = 90.00
    ENDIF

    DO 20 I = 1, NGEAR
      READ (21, *) GEARATIO(I)
20 CONTINUE

    PRINT *, ' ENTER PERCENTAGE SLIP OF THE VEHICLE'
    PRINT *, ' RUNNING GEAR, GENERALLY IT IS BETWEEN 2-5'
    PRINT *, ' PERCENT. ENTER NUMERICAL VALUE OF PERCENTAGE'
    PRINT *, ' FOR TRUCK ENTER ZERO (0) IF THE VALUE '
    PRINT *, ' IS NOT KNOWN'

    READ *, SLIP

    SLIPF = (1 - (SLIP/100.00))

    K = 0
    DO 100 I = 1, (5*NGEAR).5
      K = K+1

      DO 90 J = 1, COUNT
        C1 = ENGSPEED(J)*ROLRAD*3.14286
        C2 = AXLRATIO*GEARATIO(K)
        A = (3*C1)/(25*C2)
        SPEED = (1-SQRT(1-4*A**2*GF))/(2*A*GF)
        SPEED = SPEED*SLIPF
        SPEED1 = SPEED* 0.27777

        ROLRADV = ROLRAD*(1.0 + (GF*(SPEED**2)))

      IF (K .LE. NGEAR/3) THEN
        EFFICY = 0.85
      ELSEIF((K .GT. NGEAR/3).AND.(K .LE. 2*NGEAR/3)) THEN
        EFFICY = 0.88

```

```

ELSEIF((K .GT. 2*NGEAR/3).AND.(K .LE. NGEAR)) THEN
    EFFICY = 0.93
ENDIF
TRACEFF2 = (TORQUE(J)*C2*EFFICY*ALPHA)/ROLRADV
TRACEFF2 = TRACEFF2 * (1 - 1.312*1.0E-04*E)
DATA1(J,I) = SPEED
DATA1(J,(I+1)) = EFFICY
DATA1(J,(I+2)) = TRACEFF2
DATA1(J,(I+3)) = REAL(K)
DATA1(J,(I+4)) = GEARATIO(K)
90 CONTINUE
100 CONTINUE

CC    FOR WRITING IN THE RESULT FILE 'CURVESA'
C    DO 200 I = 1,(5*NGEAR),5
C        IF ((I .GT. 1) .AND.(I .LE. 5*NGEAR)) THEN
C            WRITE (25,186)
C 186    FORMAT ( /, 'NEXT GEAR' , / )
C        ENDIF
C    DO 180 J = 1,COUNT
C        WRITE (25,185) (DATA1(J,M),M=I,I+4)
C 185    FORMAT (F8.3,2X,F5.3,4X,F11.2,3X,F5.2,2X,F6.2)
C 180 CONTINUE
C 200 CONTINUE

CC    FOR PLOTTING THE GRAPHS FROM FILE 'CURVEPLOT'
C    DO 250 J = 1,COUNT
C        WRITE (29,255) (DATA1(J,I),I=1,(5*NGEAR),5),
C            + (DATA1(J,I),I=5,(5*NGEAR),5)
C 255    FORMAT ( 12(F6.2),12(F8.2))
C 250 CONTINUE

        CLOSE (20)
        CLOSE (21)
C    CLOSE (25)
C    CLOSE (29)

CALL CURVFIT

STOP
END

C    This subroutine fits in the output of module 1 on to
C    a polynomial of 10th degree and calculates engine

```

```

C      tractive effort and vehicle speed for every 0.1 km/h
C      of vehicle speed.
      SUBROUTINE CURVFIT

      IMPLICIT LOGICAL (A-Z)

      REAL X(30),Y(30),W(30),R(30),EPS,A(125),WVALU(30,25),
+        YFIT,YP(30), AVALU(125,25),MAXSPEED,I1,
+        DATA1,DATA3,AXLRATIO,DIF,NX,
+        TOTRES,ROLRAD,GF,J1,I2,DATA2(1200,30)

      INTEGER IERR,N,MAXDEG,NDEG,I,L,NDER,J,K,NGEAR,N1,M,
+        COUNT,SPEDINDX,IX

      COMMON /A1/ AXLRATIO,MAXSPEED,ROLRAD,GF,NGEAR
      COMMON /A2/ DATA1(30,125)
      COMMON /A3/ COUNT
      COMMON /A4/ DATA3(1200,10)
      COMMON /A5/ SPEDINDX

C      OPEN (UNIT=30,FILE='CURVES1')
C      OPEN (UNIT=35,FILE='ENVE')
C      REWIND (35)
C      REWIND (30)

      K = 0
      DO 10 I = 1,(5*NGEAR),5
          K = K+1
          DO 5 J = 1,COUNT
              WVALU(J,K) = 1.0/(DATA1(J,(I+2))**2)
5          CONTINUE
          A(I) = 0.
10 CONTINUE
      K = 0
      DO 100 I = 1,(5*NGEAR),5
          K = K+1
          DO 15 J = 1,COUNT
              X(J) = DATA1(J,I)
              Y(J) = DATA1(J,(I+2))
              W(J) = WVALU(J,K)
15          CONTINUE
          MAXDEG = 10
          N = COUNT
          EPS = 0.

```

```

CC      CALL POLFIT(N,X,Y,W,MAXDEG,NDEG,EPS,R,IERR,A)
CC
      DO 17 J = 1,125
          AVALU(J,K) = A(J)
17      CONTINUE
          L = NDEG
          NDER = 0.
      DO 40 J = 0,(10*MAXSPEED),1
          J1 = J/10.0000
          X(1) = J1
CC
          CALL PVALUE (L,NDER,X,YFIT,YP,A)
CC
          DATA2(J,K) = YFIT
      40 CONTINUE
      100 CONTINUE
C      DO 60 I = 0,(10*MAXSPEED),1
C          I1 = I/10.0000
C          X(1) = I1
C          WRITE(30,36) X(1),(DATA2(I,J),J=1,NGEAR)
C      36      FORMAT(F5.1,1X,25(E11.4))
C      60 CONTINUE
          I = -1
          I2 = -0.10000
          J = 0
          M = 0
          SPEDINDX = 0
          DO 200 K = 1,(5*NGEAR),5
              J = J+1
210          I2 = I2+0.10000
              I = I+1
              M = M+1
              IF ( I2 .GT. MAXSPEED ) GOTO 300
              SPEDINDX = SPEDINDX + 1
              IF ( I2 .LE. DATA1(1,1)) THEN
                  DATA3(SPEDINDX,4) = DATA1(1,5)
                  DATA3(SPEDINDX,3) = DATA1(1,4)
                  DATA3(SPEDINDX,2) = DATA1(1,3)
                  DATA3(SPEDINDX,1) = I2
                  GOTO 210
              ELSEIF (I2 .LE. DATA1(COUNT,K)) THEN
                  DATA3(SPEDINDX,4) = DATA1(J,K+4)
                  DATA3(SPEDINDX,3) = DATA1(J,K+3)

```



```

        DATA3(SPEDINDX,2) = DATA2(I,J)
        DATA3(SPEDINDX,1) = I2
        GOTO 210
    ELSEIF ( ( I2 .GT. DATA1(COUNT,K)) .AND.
+         (I2 .LE. REAL(MAXSPEED))) THEN
        DATA3(SPEDINDX,4) = DATA1(COUNT,K+4)
        DATA3(SPEDINDX,3) = DATA1(COUNT,K+3)
        DATA3(SPEDINDX,2) = DATA1(COUNT,K+2)
        DATA3(SPEDINDX,1) = DATA1(COUNT,K)
        SPEDINDX = SPEDINDX+1
        DATA3(SPEDINDX,4) = DATA1(J,K+9)
        DATA3(SPEDINDX,3) = DATA1(J,K+8)
        DATA3(SPEDINDX,2) = DATA2(I,J+1)
        DATA3(SPEDINDX,1) = I2
        GOTO 200
    ENDIF
200 CONTINUE
300 DO 220 I = 1, SPEDINDX
    DIF = (DATA3((I+1),2) - DATA3(I,2))
    IF (DIF .LT. 0.0) THEN
        NX = DATA3(I,2)
        IX = I
        GOTO 225
    ENDIF
220 CONTINUE
225 DO 230 K = IX,1,-1
    DATA3(K,2) = NX
230 CONTINUE
C      DO 250 I = 1,SPEDINDX
C          WRITE (35,265) (DATA3(I,M),M=1,4)
C 265      FORMAT (4(F12.2))
C 250 CONTINUE
C      CLOSE (35)
C      CLOSE (30)

    CALL RESISTANCE

    RETURN
    END

C      This subroutine calculates the individual forces
C      opposing the vehicle motion and their total sum.
C      Inclusion of gear change delay is also done to
C      estimate the decelerated speeds during coasting.

```

SUBROUTINE RESISTANCE

IMPLICIT LOGICAL (A-Z)

```

REAL MAXSPEED,ROLRES,AR1,AR2,AR3,AERORES,TOTRES,
+   TRACTMAS,STRAILMAS,DTRAILMAS,VMAS,AD,BD,ROW,Z,
+   A1,A2,A3,AIRSPED,GRADRES,DATA3,
+   AXLRATIO,GF,ROLRAD,CS,CV,CP,GRDLY,DAT,
+   VMAS1,TIREMAS,DATA4,CD1,CD2,CD3,
+   DATA5, DATA1

```

```

INTEGER I,J,K,GRADE,M,SPEDINDX,NGEAR,L,K1,COUNT,
+   N3,TN,AZ,CZ,P,N1,N2

```

```

COMMON /A1/ AXLRATIO,MAXSPEED,ROLRAD,GF,NGEAR
COMMON /A2/ DATA1(30,125)
COMMON /A3/ COUNT
COMMON /A4/ DATA3(1200,10)
COMMON /A5/ SPEDINDX
COMMON /A6/ DATA4(1200,200)
COMMON /A7/ DATA5(1200,50)
COMMON /A8/ STRAILMAS,DTRAILMAS,VMAS,AD,BD
COMMON /A9/ N1,N2,N3
COMMON /A10/ TIREMAS,TRACTMAS
COMMON /A12/ TN,TND

```

```

C   OPEN (UNIT=40,FILE='RESCURVE')
C   REWIND (40)

```

```

PRINT *, 'ENTER MASS OF THE TRACTOR OR STRAIGHT '
PRINT *, 'TRUCK OR RV (AS PER CASE) IN kg (tractmas)'
READ *,TRACTMAS
PRINT *, 'ENTER SEMI TRAILER AND DOUBLE TRAILER'
PRINT *, 'MASSES IN kg. ENTER BOTH OF THESE AS '
PRINT *, 'ZERO FOR ST.TRUCK/RV CASE.(STRAILMAS,'
print *, '          DTRAILMAS) '
READ *,STRAILMAS,DTRAILMAS
PRINT *, 'ENTER TOTAL NUMBER OF TIRES (N1)'
PRINT *, '          IN TRACTOR UNIT'
READ *,N1
PRINT *, 'ENTER TOTAL NUMBER OF TIRES (N2) IN '
PRINT *, '          SEMI-TRAILER UNIT'
READ *,N2
PRINT *, 'ENTER TOTAL NUMBER OF TIRES (N3) IN '

```

```

PRINT *, '    DOUBLE-TRAILER UNIT'
READ *, N3
PRINT *, 'ENTER MASS OF THE TIRE, kg.(TIREMAS). FOR'
PRINT *, 'USING DEFAULT VALUE IN CASE OF ALL TRUCKS'
PRINT *, 'ENTER "ZERO (0)" OR ELSE IN CASE OF RVs '
PRINT *, '    ENTER "ONE(1)"'
READ *, TIREMAS
    IF (TIREMAS .EQ. 0) THEN
        TIREMAS = 110.0
    ELSEIF (TIREMAS .EQ. 1) THEN
        TIREMAS = 35.0
    ENDIF
PRINT *, 'ENTER STATIC ROLLING RESISTANCE COEFFICIENT'
PRINT *, '(AD) FOR USING DEFAULT VALUE ENTER "ZERO (0)"'
READ *, AD
    IF (AD .EQ. 0) THEN
        AD = 0.0095
    ENDIF
PRINT *, 'ENTER DYNAMIC ROLLING RESISTANCE COEFF.(BD)'
PRINT *, 'FOR USING DEFAULT VALUE ENTER "ZERO (0)"'
READ *, BD
    IF (BD .EQ. 0) THEN
        BD = 6.25E-05
    ENDIF
PRINT *, 'ENTER AIR DENSITY IN kg/m**3 (ROW)'
PRINT *, 'FOR USING DEFAULT VALUE ENTER "ZERO (0)"'
READ *, ROW
    IF (ROW .EQ. 0) THEN
        ROW = 1.23
    ENDIF
PRINT *, 'ENTER AERODYNAMIC DRAG COEFFICIENTS FOR '
PRINT *, 'TRACTOR (CD1), SEMI TRAILER (CD2) AND DOUBLE'
PRINT *, 'TRAILER (CD3). FOR USING DEFAULT VALUES OF'
PRINT *, 'DRAG COEFFICIENTS, IN CASE OF STRAIGHT TRUCK '
PRINT *, 'AND RV ENTER 0, IN CASE OF SEMI TRAILER'
PRINT *, 'ENTER 1, IN CASE OF DOUBLE-TRAILER'
PRINT *, 'ENTER 2, AND IN CASE OF RV ENTER 3,'
PRINT *, 'BUT, IF YOU WANT TO USE YOUR OWN VALUES'
PRINT *, '    PLEASE ENTER 4'
READ *, CZ
    IF (CZ .EQ. 0) THEN
        CD1 = 0.43
        CD2 = 0.0
        CD3 = 0.0

```

```

ELSEIF (CZ .EQ. 1) THEN
    CD1 = 0.51
    CD2 = 0.11
    CD3 = 0.0
ELSEIF (CZ .EQ. 2) THEN
    CD1 = 0.51
    CD2 = 0.11
    CD3 = 0.11
ELSEIF (CZ .EQ. 3) THEN
    CD1 = 0.60
    CD2 = 0.0
    CD3 = 0.0
ELSEIF (CZ .EQ. 4) THEN
PRINT *, ' PLEASE ENTER THE DRAG COEFFICIENTS'
PRINT *, ' IN ORDER OF TRACTOR, SEMI-TRAILER '
PRINT *, ' AND DOUBLE-TRAILER. PLEASE NOTE THAT'
PRINT *, ' IN CASE OF ST. TRUCK AND RV LAST TWO'
PRINT *, ' ENTRIES WILL BE 0.0 AND IN CASE OF'
PRINT *, ' SEMI TRAILER LAST ENTRY IS 0.0'
READ *, CD1,CD2,CD3
ENDIF
PRINT *, 'ENTER PROJECTED FRONTAL AREA FOR TRACTOR,'
PRINT *, '(A1) SEMI TRAILER (A2) AND DOUBLE TRAILER.'
PRINT *, '(A3). FOR USING DEFAULT VALUE FOR FRONTAL'
PRINT *, 'AREAS, IN CASE OF STRAIGHT TRUCK ENTER 0,'
PRINT *, 'FOR SEMI-TRAILER ENTER 1, IN CASE OF DOUBLE'
PRINT *, 'TRAILER ENTER 2, AND IN CASE OF RV ENTER 3,'
PRINT *, 'BUT, IF YOU WANT TO USE YOUR OWN VALUES'
PRINT *, ' PLEASE ENTER 4'
READ *,AZ
IF (AZ .EQ. 0) THEN
    A1 = 7.78
C    A1 = 2.43(m) * 3.20(m)
    A2 = 0.0
    A3 = 0.0
ELSEIF (AZ .EQ. 1) THEN
    A1 = 9.25
    A2 = 9.25
    A3 = 0.0
ELSEIF (AZ .EQ. 2) THEN
    A1 = 9.25
    A2 = 9.25
    A3 = 4.62
C For double trailer value of area is assumed to half

```

```

C      of semi-trailer area.
          ELSEIF (AZ .EQ. 3) THEN
              A1 = 5.75
              A2 = 0.0
              A3 = 0.0
          ELSEIF (AZ .EQ. 4) THEN
              PRINT *, 'PLEASE ENTER THE FRONTAL AREAS IN ORDER'
              PRINT *, ' OF TRACTOR, SEMI-TRAILER AND DOUBLE'
              PRINT *, ' TRAILER. PLEASE NOTE THAT IN CASE OF'
              PRINT *, 'ST. TRUCK AND RV LAST TWO ENTRIES WILL'
              PRINT *, ' BE 0.0 AND IN CASE OF SEMI TRAILER '
              PRINT *, '          LAST ENTRY IS 0'
              READ *, A1,A2,A3
          ENDIF
              PRINT *, '          ENTER THE SPEED OF AIR'
              PRINT *, 'FOR USING DEFAULT VALUE (WHICH IS ZERO)'
              PRINT *, '          ENTER "ZERO (0)"'
              READ *, AIRSPEED
                  IF (AIRSPEED .EQ. 0) THEN
                      AIRSPEED = 0.0
                  ENDIF
              PRINT *, 'DO YOU WANT TO ACCOUNT FOR GEAR CHANGE DELAY ?'
              PRINT *, 'IF NO, PLEASE ENTER "ZERO (0)". IF YES, PLEASE'
              PRINT *, 'ENTER THE VALUE OF GEAR CHANGE DELAY IN SECONDS'
              PRINT *, ' OR ENTER 100, FOR USING THE DEFAULT VALUE.'
              READ *, GRDLY
                  IF (GRDLY .EQ. 100) THEN
                      GRDLY = 1.5
                  ENDIF

              TN = N1+N2+N3
              VMAS = TRACTMAS+STRAILMAS+DTRAILMAS
              VMAS1 = VMAS + (TN*TIREMAS)
C=====
C      Calculation of rolling resistance, aerodynamic
C      resistance (on different truck components),
C      grade resistance and total resistance.
C=====
              I = -7
              M = 1
              DO 100 GRADE = -10,10,1
                  K1 = 1
                  I = I+8
                  DO 50 K = 1,SPEDINDX

```

```

DATA4(K,I) = DATA3(K,1)
ROLRES = (AD+BD*DATA3(K,1))*VMAS*9.81
DATA4(K,I+1) = ROLRES
Z = .5*ROW*(DATA3(K,1)+AIRSPEED)**2
AR1 = Z*A1*CD1*.07716
DATA4(K,I+2) = AR1
AR2 = Z*A2*CD2*.07716
DATA4(K,I+3) = AR2
AR3 = Z*A3*CD3*.07716
DATA4(K,I+4) = AR3
AERORES = AR1+AR2+AR3
DATA4(K,I+5) = AERORES
GRADRES = VMAS*REAL(GRADE)*9.81*1.E-02
TOTRES = ROLRES+AERORES+GRADRES
DATA4(K,I+6) = TOTRES
DATA4(K,I+7) = DATA3(K,3)
  IF (K .GT. K1+2) THEN
    GOTO 10
  ELSE
    GOTO 50
  ENDIF

```

C=====

C Calculation of change in vehicle speed due to
C gear change delay

C=====

```

10      IF ( DATA4(K,I+7) .GT. DATA4(K-1,I+7)) THEN
          DATA4(K,I) = (DATA4(K-1,I) -
+              (GRDLY*3.6*DATA4(K-1,I+6)/VMAS1))
          DAT = (DATA4(K,I)+DATA4(K-1,I))/2.0
          ROLRES = (AD+BD*DAT)*9.81*VMAS
          Z = 0.5*ROW*(DAT+AIRSPEED)**2
          DATA4(K,I+1) = ROLRES
          AR1 = Z*A1*CD1*.07716
          DATA4(K,I+2) = AR1
          AR2 = Z*A2*CD2*.07716
          DATA4(K,I+3) = AR2
          AR3 = Z*A3*CD3*.07716
          DATA4(K,I+4) = AR3
          AERORES = AR1+AR2+AR3
          DATA4(K,I+5) = AERORES
          GRADRES = VMAS*REAL(GRADE)*9.81*1.E-02
          TOTRES = ROLRES+AERORES+GRADRES
          DATA4(K,I+6) = TOTRES
          K1 = K

```

```

                                ENDIF
      50      CONTINUE
100 CONTINUE
C          P = -10
C          DO 500 I=1,168,8
C          P = P+1
C          IF ((I .GT. 1) .AND.(I .LE. 168)) THEN
C          WRITE (40,186)
C 186      FORMAT (/, /,'*****NEXT GRADE*****',/,/ )
C          WRITE (40,187) P
C 187      FORMAT (/, /,'*****',I4,'*****', /,/)
C          ENDIF
C          DO 550 J =1,SPEDINDX
C          WRITE(40,40) (DATA4(J,M),M=I,I+7)
C 40      FORMAT(8F11.2)
C          IF (DATA4(J+1,I+7) .GT. DATA4(J,I+7)) THEN
C          WRITE (40,196)
C 196      FORMAT (/, 'NEXT GEAR',/ )
C          ENDIF
C 550      CONTINUE
C 500 CONTINUE

C      CLOSE (40)
      CALL GEARDLY

      RETURN
      END

C      This subroutine calculates the tractive force
C      available at the velocity just before the
C      next gear engagement. It rewrites the whole
C      set of values at the interval of 0.1 km/h
C      after inserting gear change delay effect.
      SUBROUTINE GEARDLY

      IMPLICIT LOGICAL (A-Z)

      REAL DATA3, DATA4, MAXSPEED,
+   STRAILMAS,DTRAILMAS,VMAS,AD,BD,TIREMAS,GF,
+   AXLRATIO,NDATA3,X,Y,X2,Y1,TRACTMAS,
+   ROLRAD

      INTEGER  SPEDINDX,NGEAR,COUNT,N1,N2,N3,TN,K,
+   M,J,J2,L,P,Z

```

```

COMMON /A1/ AXLRATIO,MAXSPEED,ROLRAD,GF,NGEAR
COMMON /A3/ COUNT
COMMON /A4/ DATA3(1200,10)
COMMON /A5/ SPEDINDX
COMMON /A6/ DATA4(1200,200)
COMMON /A8/ STRAILMAS,DTRAILMAS,VMAS,AD,BD
COMMON /A9/ N1,N2,N3
COMMON /A10/ TIREMAS,TRACTMAS
COMMON /A11/ NDATA3(1200,100)
COMMON /A12/ TN,TND

```

```

C      OPEN (UNIT=36, FILE = 'ENVE.NEW')
C      REWIND 36
      K = 0
      DO 230 M = 1,168.8
        K = K+1
        DO 200 J = 1,SPEDINDX,1
          NDATA3(J,K) = DATA4(J,M)
          IF (J .EQ. SPEDINDX) THEN
            NDATA3(J,K+1) = DATA3(J,2)
            NDATA3(J,K+2) = DATA4(J,M+7)
            NDATA3(J,K+3) = DATA3(J,4)
          ENDIF
          IF (DATA4(J,M+7) .EQ. DATA4(J+1,M+7)) THEN
            NDATA3(J,K+1) = DATA3(J,2)
            NDATA3(J,K+2) = DATA4(J,M+7)
            NDATA3(J,K+3) = DATA3(J,4)
            GOTO 200
          ELSEIF (DATA4(J,M+7) .LT. DATA4(J+1,M+7)) THEN
            NDATA3(J,K+1) = DATA3(J,2)
            NDATA3(J,K+2) = DATA4(J,M+7)
            NDATA3(J,K+3) = DATA3(J,4)
            J = J+1
          NDATA3(J,K) = DATA4(J,M)
          NDATA3(J,K+2) = DATA4(J,M+7)
          NDATA3(J,K+3) = DATA3(J,4)
          IF (DATA4(J,M) .LE. DATA3(J,1)) THEN
            X = DATA3(J,2) - DATA3(J+1,2)
            Y = DATA3(J+1,1) - DATA4(J,M)
            Y1 = DATA3(J+1,1) - DATA3(J,1)
            NDATA3(J,K+1) = ((X*Y)/Y1) + DATA3(J+1,2)
          ELSEIF (DATA4(J,M) .GT. DATA3(J,1)) THEN
            Z = J+1

```



```

      DO 150 J2 = Z,SPEDINDX,1
        X2 = DATA4(J,M) - DATA3(J2,1)
        IF ((X2 .GT. 0.0) .AND. (DATA4(J2,M+7) .EQ.
+          DATA4(J2+1,M+7))) THEN
          GOTO 150
        ELSEIF ((X2 .EQ. 0.0) .AND. (DATA4(J2,M+7) .EQ.
+          DATA4(J2+1,M+7))) THEN
          NDATA3(J,K+1) = DATA3(J2,2)
        ELSEIF ((X2 .LT. 0.0) .AND. (DATA4(J2,M+7) .LE.
+          DATA4(J2+1,M+7))) THEN
          X = DATA3(J2,2) - DATA3(J2-1,2)
          Y = DATA4(J,M) - DATA3(J2-1,1)
          Y1 = DATA3(J2,1) - DATA3(J2-1,1)
          NDATA3(J,K+1) = ((X*Y)/Y1) + DATA3(J2-1,2)
        ELSEIF ((X2 .GT. 0.0) .AND. (DATA4(J2,M+7) .LT.
+          DATA4(J2+1,M+7))) THEN
          X = DATA3(J2-1,2) - DATA3(J2,2)
          Y = DATA4(J,M) - DATA3(J2-1,1)
          Y1 = DATA3(J2,1) - DATA3(J2-1,1)
          NDATA3(J,K+1) = DATA3(J2-1,2) - ((X*Y)/Y1)
        ENDIF
        GOTO 200
150    CONTINUE
        ENDIF
        ENDIF
200    CONTINUE
        K = K+3
230    CONTINUE
CC    FOR WRITING IN THE FILE 'ENVE.NEW'
C      DO 260 L = 1,84,4
C        IF ((L .GT. 1) .AND. (L .LE. 84), THEN
C          WRITE (36,186)
C 186    FORMAT (/ , / , '*****NEXT GRADE*****' , / , / )
C        EN)IF
C      DO 250 J = 1,SPEDINDX,1
C        WRITE (36,266) (NDATA3(J,P), P = L,L+3,1)
C 266    FORMAT (4(F12.2))
C 250 CONTINUE
C 260 CONTINUE
C      CLOSE (36)

      CALL TRACTIVE1

      RETURN

```

END

C This subroutine calculates the available tractive
C force due to road-tire adhesion and considers
C dynamic as well as static loadings. Differentiation
C is also done for different truck types.

SUBROUTINE TRACTIVE1

IMPLICIT LOGICAL (A-Z)

REAL VMAS, NDATA3, DATA4,
+ DATA5, STRAILMAS, DTRAILMAS, AD,
+ BD, AX, WDRIVE1, ROLRAD, GF, MAXSPEED

REAL X, AC, L2, HA2, H2, WDRVFNC1, TEST1, RD1, TIREMAS,
+ D2, H3, HD, L3, HA1, H1, D1, L1, MU, WHI, FHI, TRACTMAS,
+ WS, W2, F, WDRIVE2, RD, AXFAC, AXFAC1, L1Z, L2Z, L3Z,
+ AXLRATIO, DAT_AC(1200,50), WDRVFNC2, HA1Z, HA2Z,
+ H1Z, H2Z, H3Z, HDZ, D1Z, L2Z, M2

INTEGER I, J, K, M, SPEDINDX, NGEAR, N1, N2, N3, TN, TND,
+ DRLOAD, N

COMMON /A1/ AXLRATIO, MAXSPEED, ROLRAD, GF, NGEAR
COMMON /A5/ SPEDINDX
COMMON /A6/ DATA4(1200,200)
COMMON /A7/ DATA5(1200,50)
COMMON /A8/ STRAILMAS, DTRAILMAS, VMAS, AD, BD
COMMON /A9/ N1, N2, N3
COMMON /A10/ TIREMAS, TRACTMAS
COMMON /A11/ NDATA3(1200,100)
COMMON /A12/ TN, TND

LOGICAL WDRIVEA, WDRIVEB, CHOICE

C OPEN (UNIT=47, FILE='TE11')
C OPEN (UNIT=48, FILE='TE12')
C OPEN (UNIT=49, FILE='ACVALU')
C REWIND (47)
C REWIND (48)
C REWIND (49)

CC CONTENTS OF RESULT FILES

C TE11 - FOR GRADES -10% TO -1% (10 GRADES)

C TE12 - FOR GRADES 0% TO +10% (11 GRADES)
 C ACVALU - ASSUMED/ITERATED VALUES OF VEHICLE
 C - ACCELERATION (FOR 21 GRADES), CALCULATED
 C - ONLY IN CASE OF DYNAMIC LOADING.

PRINT *, 'ENTER T FOR STRAIGHT TRUCK/RECREATIONAL'
 PRINT *, ' VEHICLE CASE AND F FOR SEMI'
 PRINT *, ' TRAILER/DOUBLE TRAILER CASE '
 READ *, CHOICE

IF (CHOICE) THEN
 WDRIVEA = .TRUE.
 WDRIVEB = .FALSE.

ELSE
 WDRIVEA = .FALSE.
 WDRIVEB = .TRUE.

ENDIF

PRINT *, 'PLEASE ENTER, L1 (in metre) VALUE OF'
 PRINT *, 'TRACTOR WHEELBASE, IN CASE OF SEMI AND'
 PRINT *, 'DOUBLE, OR VEHICLE WHEELBASE IN CASE'
 PRINT *, ' OF STRAIGHT TRUCK AND RVs.'
 PRINT *, ' FOR USING DEFAULT VALUES IN CASE OF '
 PRINT *, ' STRAIGHT TRUCK ENTER 0, FOR SEMI AND '
 PRINT *, ' DOUBLE ENTER 1, AND FOR RVs ENTER 2.'
 PRINT *, '-OR- FOR USING YOUR OWN VALUE ENTER 3'
 READ *, L1Z

IF (L1Z .EQ. 0) THEN
 L1 = 5.63
 ELSEIF (L1Z .EQ. 1) THEN
 L1 = 6.20
 ELSEIF (L1Z .EQ. 2) THEN
 L1 = 2.65
 ELSEIF (L1Z .EQ. 3) THEN

PRINT *, 'ENTER YOUR VALUE FOR TRACTOR/VEHICLE'
 PRINT *, ' WHEELBASE (in metre)'
 READ *, L1

ENDIF

PRINT *, 'PLEASE ENTER, L2 THE DISTANCE BETWEEN SEMI-'
 PRINT *, ' TRAILER REAR AXLE, AND THE HITCH ON THE'
 PRINT *, ' TRACTOR (only in case of semi/double)'
 PRINT *, '===== '
 PRINT *, ' ALWAYS ENTER 0.0, IN CASE OF STRAIGHT TRUCKS'
 PRINT *, ' AND RVs '
 PRINT *, '===== '
 PRINT *, 'FOR DEFAULT VALUES IN CASE OF SEMI AND DOUBLE'

```

PRINT *, ' SIMULATION PLEASE ENTER 1. OR ELSE ENTER 2'
PRINT *, '          FOR USING YOUR OWN VALUE'
READ *, L2Z
      IF (L2Z .EQ. 1) THEN
        L2 = 9.4
      ELSEIF (L2Z .EQ. 2) THEN
PRINT *, 'PLEASE ENTER YOUR VALUE'
READ *, L2
      ENDIF
PRINT *, 'PLEASE ENTER, L3 (in metre), THE DISTANCE '
PRINT *, 'BETWEEN FRONT AXLE AND C.G. OF THE TRACTOR'
PRINT *, 'OR ST. TRUCK OR RV. FOR DEFAULT VALUES IN '
PRINT *, 'CASE OF STRAIGHT TRUCK ENTER 1, FOR SEMI'
PRINT *, 'AND DOUBLE ENTER 2, AND FOR RVs ENTER 3'
PRINT *, 'BUT, FOR USING YOUR OWN VALUE ENTER 4'
READ *, L3Z
      IF (L3Z .EQ. 1) THEN
        L3 = 2.0
      ELSEIF (L3Z .EQ. 2) THEN
        L3 = 2.75
      ELSEIF (L3Z .EQ. 3) THEN
        L3 = 1.03
      ELSEIF (L3Z .EQ. 4) THEN
PRINT *, 'PLEASE ENTER YOUR VALUE'
READ *, L3
      ENDIF
PRINT *, 'ENTER VALUE OF, MU COEFFICIENT OF ROAD '
PRINT *, 'TIRE ADHESION. FOR DEFAULT OPTION ENTER 0'
READ *, MU
      IF (MU .EQ. 0) THEN
        MU = 0.85
      ENDIF
PRINT *, 'ENTER DRAWBAR PULL, M2 IN CASE OF RVs OR'
PRINT *, 'ST.TRUCK (if hauling). ELSE ENTER 0.0 FOR ALL'
PRINT *, 'OTHERS. FOR THE DEFAULT VALUE IN CASE OF'
PRINT *, 'RV/TRUCK, ENTER 1 , OR ELSE ENTER 2 FOR '
PRINT *, 'USING YOUR OWN VALUE'
READ *, M2
      IF (M2 .EQ. 1) THEN
        M2 = 1500.0
      ELSEIF (M2 .EQ. 2) THEN
PRINT *, ' PLEASE ENTER  YOUR VALUE'
READ *, M2
      ENDIF

```

```

PRINT *, 'ENTER HEIGHT, HA1 (in m) OF APPLICATION OF '
PRINT *, 'AERODYNAMIC FORCE ON THE TRACTOR OR ST. TRUCK'
PRINT *, 'OR RV. FOR DEFAULT VALUES IN CASE OF TRUCKS'
PRINT *, 'ENTER 1, FOR SEMI AND DOUBLE TRAILERS ENTER 2'
PRINT *, 'AND FOR RVs ENTER 3, BUT FOR USING YOUR'
PRINT *, 'OWN VALUE PLEASE ENTER 4'
READ *, HA1Z

```

```

      IF (HA1Z .EQ. 1) THEN
        HA1 = 1.45
      ELSEIF (HA1Z .EQ. 2) THEN
        HA1 = 1.99
      ELSEIF (HA1Z .EQ. 3) THEN
        HA1 = 0.71
      ELSEIF (HA1Z .EQ. 4) THEN

```

```

PRINT *, ' PLEASE ENTER YOUR VALUE'
READ *, HA1

```

```

      ENDIF

```

```

PRINT *, 'ENTER HEIGHT, HA2 (in m) OF APPLICATION OF'
PRINT *, ' AERODYNAMIC FORCE ON THE SEMI TRAILER'
PRINT *, ' (only in case of semis and doubles).'
PRINT *, 'ALWAYS ENTER 0.0 FOR ST. TRUCKS AND RVs.'
PRINT *, 'FOR DEFAULT VALUES IN CASE OF SEMI AND'
PRINT *, ' DOUBLES ENTER 1 BUT FOR USING YOUR'
PRINT *, ' OWN VALUE PLEASE ENTER 2'
READ *, HA2Z

```

```

      IF (HA2Z .EQ. 1) THEN
        HA2 = 3.10
      ELSEIF (HA2Z .EQ. 2) THEN

```

```

PRINT *, ' PLEASE ENTER YOUR VALUE'
READ *, HA2

```

```

      ENDIF

```

```

PRINT *, 'ENTER HEIGHT, H1 (in m) OF THE CENTER OF GRAVITY'
PRINT *, 'OF THE TRACTOR (for semi & doubles) OR TRUCK OR'
PRINT *, 'RV. FOR USING DEFAULT VALUES IN CASE OF ST.'
PRINT *, 'TRUCK ENTER 1, FOR SEMI AND DOUBLES ENTER 2'
PRINT *, 'AND FOR RV ENTER 3. BUT FOR USING YOUR'
PRINT *, 'OWN VALUE PLEASE ENTER 4'
READ *, H1Z

```

```

      IF (H1Z .EQ. 1) THEN
        H1 = 1.35
      ELSEIF (H1Z .EQ. 2) THEN
        H1 = 1.02
      ELSEIF (H1Z .EQ. 3) THEN
        H1 = 0.47

```

```

                ELSEIF (H1Z .EQ. 4) THEN
PRINT *, ' PLEASE ENTER YOUR VALUE'
READ *, H1

                ENDIF

PRINT *, 'ENTER HEIGHT, H2 (in m) OF CENTER OF GRAVITY '
PRINT *, 'OF THE SEMI TRAILER (for semi & doubles only) '
PRINT *, 'ENTER 0.0 FOR THE CASES OF ST. TRUCK AND RVs '
PRINT *, 'FOR USING DEFAULT VALUES IN CASE OF SEMI AND'
PRINT *, 'DOUBLES ENTER 1, OR ELSE ENTER 2 FOR USING'
PRINT *, '          YOUR OWN VALUE'
READ *, H2Z

                IF (H2Z .EQ. 1) THEN
                        H2 = 2.27
                ELSEIF (H2Z .EQ. 2) THEN

PRINT *, ' PLEASE ENTER YOUR VALUE'
READ *, H2

                ENDIF

PRINT *, 'ENTER HEIGHT, H3 (in m) OF THE HITCH POINT '
PRINT *, 'ABOVE GROUND (for semi & doubles only) '
PRINT *, 'ENTER 0.0 FOR THE CASES OF ST. TRUCK AND RVs'
PRINT *, 'FOR USING DEFAULT VALUES IN CASE OF SEMI AND'
PRINT *, 'DOUBLES ENTER 1, OR ELSE ENTER 2 FOR USING'
PRINT *, '          YOUR OWN VALUE'
READ *, H3Z

                IF (H3Z .EQ. 1) THEN
                        H3 = 1.30
                ELSEIF (H3Z .EQ. 2) THEN

PRINT *, ' PLEASE ENTER YOUR VALUE'
READ *, H3

                ENDIF

PRINT *, 'ENTER HEIGHT, HD (in m) OF APPLICATION OF '
PRINT *, 'DRAW-BAR LOAD ABOVE GROUND (for RVs only) '
PRINT *, 'ENTER 0.0 FOR ALL CASES OF TRUCKS'
PRINT *, 'FOR USING DEFAULT VALUE ONLY FOR RV'
PRINT *, 'PLEASE ENTER 1, OR ELSE ENTER 2 FOR USING'
PRINT *, '          YOUR OWN VALUE'
READ *, HDZ

                IF (HDZ .EQ. 1) THEN
                        HD = 0.50
                ELSEIF (HDZ .EQ. 2) THEN

PRINT *, ' PLEASE ENTER YOUR VALUE'
READ *, HD

                ENDIF

PRINT *, 'ENTER DISTANCE, D1 (in m) BETWEEN THE'

```

```

PRINT *, 'HITCH POINT AND C.G. OF THE TRACTOR '
PRINT *, 'REAR AXLE (for semi & doubles only).'
PRINT *, 'ENTER 0.0 FOR THE CASES OF ST. TRUCK'
PRINT *, 'AND RVs. FOR USING DEFAULT VALUES '
PRINT *, 'IN CASE OF SEMI AND DOUBLES ENTER 1,'
PRINT *, 'OR ELSE ENTER 2 FOR USING YOUR OWN VALUE'
READ *, D1Z

```

```

      IF (D1Z .EQ. 1) THEN

```

```

          D1 = 0.65

```

```

      ELSEIF (D1Z .EQ. 2) THEN

```

```

PRINT *, ' PLEASE ENTER YOUR VALUE'

```

```

READ *, D1

```

```

      ENDIF

```

```

PRINT *, 'ENTER DISTANCE, D2 (in m) BETWEEN THE'
PRINT *, 'HITCH POINT AND C.G. OF THE SEMI TRAILER '
PRINT *, '      (for semi & doubles only).'
PRINT *, 'ENTER 0.0 FOR THE CASES OF ST. TRUCK'
PRINT *, 'AND RVs. FOR USING DEFAULT VALUES '
PRINT *, 'IN CASE OF SEMI AND DOUBLES ENTER 1,'
PRINT *, 'OR ELSE ENTER 2 FOR USING YOUR OWN VALUE'
READ *, D2Z

```

```

      IF (D2Z .EQ. 1) THEN

```

```

          D2 = 5.35

```

```

      ELSEIF (D2Z .EQ. 2) THEN

```

```

PRINT *, ' PLEASE ENTER YOUR VALUE'

```

```

READ *, D2

```

```

      ENDIF

```

```

TND = N1-2

```

```

CC  OPTION OF . STATIC      OR DYNAMIC LOADING

```

```

PRINT *, 'ENTER, 1 - FOR      STATIC      LOAD ON DRIVE AXLE,'

```

```

PRINT *, ' 2 - FOR DYNAMIC LOAD ON DRIVE AXLE '

```

```

READ *, DRLOAD

```

```

      IF (DRLOAD .EQ. 1 ) THEN

```

```

          GOTO 20

```

```

      ELSEIF (DRLOAD .EQ. 2 ) THEN

```

```

          GOTO 10

```

```

      ENDIF

```

```

CC  CALCULATION OF DYNAMIC LOADING

```

```

10  K = -11

```

```

     M = 1

```

```

     N = 0

```

```

IF (WDRIVEA) THEN
  DO 300 I = 1,168,8
    K = K+1
    M = M+1
    N = N+1
    DO 200 J = 1,SPEDINDX,1
      DATA5(J,1) = DATA4(J,I)
      AC = .5
      X = AD+BD*DATA5(J,1)
210    AX = AXFAC(I,J,AC,VMAS,L3,HA1,
      +      H1,K,X,L1,MU,M2,HD)
      TEST1 = (AC-AX)/AC
      IF(TEST1 .GT. -.01) THEN
        AC = AX
        RD1 = M2*(9.81*REAL(K)*1.E-02 + 9.81*X + AC)
        WDRIVE1 = (VMAS*(9.81*L3+9.81*1.E-02*H1*
      +      REAL(K)+H1*AC)+HA1*DATA4(J,I+5)+RD1*HD)/L1
        DATA5(J,M) = MU* WDRIVE1
        DAT_AC(J,N) = AC
      ELSE
        AC = AC+.05
        GOTO 210
      ENDIF
200    CONTINUE
300 CONTINUE
ELSEIF(WDRIVEB) THEN
  DO 500 I = 1,168,8
    K = K+1
    M = M+1
    N = N+1
    DO 400 J = 1,SPEDINDX,1
      DATA5(J,1) = DATA4(J,I)
      AC = .5
      X = AD+BD*DATA5(J,1)
410    AX = AXFAC1 (J,X,K,N3,
      +      AC,L2,HA2,N2,H2,D2,H3,
      +      HD,L3,HA1,H1,D1,L1,MU,I)
      TEST1 = (AC-AX)/AC
      IF(TEST1 .GT. -.01) THEN
        AC = AX
        WDRIVE2 = WDRVFNC1 (J,X,K,N3,
      +      AC,L2,HA2,N2,H2,D2,H3,HD,
      +      L3,HA1,H1,D1,L1,I)
        DATA5(J,M) = MU* WDRIVE2

```



```

        DAT_AC(J,N) = AC
    ELSE
        AC = AC+.05
        GOTO 410
    ENDIF
400    CONTINUE
500 CONTINUE
    ENDIF
C      DO 550 I = 1,SPEDINDX,1
C          WRITE (49,575) (DAT_AC(I,N),N=1,21,1)
C 575    FORMAT (21(1X,F6.2))
C 550 CONTINUE
C      GOTO 800
CC  CALCULATION OF STATIC LOADING
20    K = -11
    M = 1
    N = 0
    IF (WDRIVEA) THEN
        DO 750 I = 1,168,8
            K = K+1
            M = M+1
            N = N+1
            DO 740 J = 1,SPEDINDX,1
                DATA4(J,I+5) = 0.0
                DATA5(J,1) = DATA4(J,I)
                X = AD+BD*DATA5(J,1)
                RD1 = M2*(9.81*REAL(K)*1.E-02 + 9.81*X)
                WDRIVE1 = (VMAS*(9.81*L3+9.81*1.E-02*H1*
+                REAL(K))+HA1*DATA4(J,I+5)+RD1*HD)/L1
                DATA5(J,M) = MU* WDRIVE1
740    CONTINUE
750 CONTINUE

    ELSEIF(WDRIVEB) THEN
        DO 770 I = 1,168,8
            K = K+1
            M = M+1
            N = N+1
            DO 760 J = 1,SPEDINDX,1
                DATA5(J,1) = DATA4(J,I)
                X = AD+BD*DATA5(J,1)
                WDRIVE2 = WDRVFNC2 (J,X,K,N3,
+                L2,HA2,N2,H2,D2,H3,HD,
+                L3,HA1,H1,D1,L1,I)

```

```

                                DATA5(J,M) = MU* WDRIVE2
760          CONTINUE
770 CONTINUE
    ENDIF

C          GOTO 800
CC  FOR PRINTING IN RESULT FILE
CC      'TE11' & 'TE12'
C  800  DO 600 I = 1,SPEDINDX,1
C          WRITE (47,650) (DATA5(I,M),M=2,11)
C          WRITE (48,650) (DATA5(I,M),M=12,22)
C  650      FORMAT (11(1X,F10.2))
C  600 CONTINUE
C      CLOSE (47)
C      CLOSE (48)
C      CLOSE (49)

      CALL EQMAS

      RETURN
      END

C  This part contains calculations for real
C  functions used in the previous subrouine
      REAL FUNCTION AXFAC(I,J,AC,VMAS,L3,HA1,
+      H1,K,X,L1,MU,M2,HD)

      IMPLICIT LOGICAL (A-Z)

      REAL VMAS,L3,DATA4,HA1,L1,M2,
+      AC,F,MU,WDRIVE1,H1,RD1,HD,X

      INTEGER K,I,J
      COMMON /A6/ DATA4(1200,200)
      RD1 = M2*(9.81*REAL(K)*1.E-02 + 9.81*X + AC)
      WDRIVE1 = (VMAS*(9.81*L3+9.81*1.E-02*H1
+      *REAL(K)+H1*AC)+HA1*DATA4(J,I+5)+RD1*HD)/L1
      F = MU* WDRIVE1
      AXFAC = (F - (DATA4(J,I+5)+DATA4(J,I+1)+RD1+
+      VMAS*REAL(K)*9.81*1.E-02))/VMAS
      RETURN
      END
CC
      REAL FUNCTION WDRVFNC1 (J,X,K,N3,

```

```

+ AC,L2,HA2,N2,H2,D2,H3,HD,
+ L3,HA1,H1,D1,L1,I)

```

IMPLICIT LOGICAL (A-Z)

```

REAL X,DATA4,DTRAILMAS,N3,TIREMAS,
+ STRAILMAS,D2,H3,HD,L3,HA1,H1,TRACTMAS,
+ WS,W2,F,WDRIVE2,RD,AC,L2,HA2,N2,H2,
+ D1,L1,MU,WHI,FHI

```

INTEGER I,J,K

COMMON /A6/ DATA4(1200,200)

COMMON /A8/ STRAILMAS,DTRAILMAS,VMAS,AD,BD

COMMON /A10/ TIREMAS,TRACTMAS

```

RD = DATA4(J,I+4)+(DTRAILMAS+(N3*TIREMAS))*
+ (9.81*REAL(K) *1.OE-02+AC+9.81*X)
WS = ((STRAILMAS+(N2*TIREMAS))*(9.81*D2+AC+
+ H2+9.81*(H2-H3)*REAL(K)*1.OE-02) +RD*(HD-H3)
+ DATA4(J,I+3)*(HA2-H3))/(L2+X*H3)
FHI = ((STRAILMAS+(N2*TIREMAS))*(AC+REAL(K)*
+ 9.81*1.OE-02))+DATA4(J,I+3)+X*WS+RD
WHI = ((STRAILMAS+(N2*TIREMAS))*9.81)-WS
WDRVFNC1 = ((TRACTMAS*(9.81*L3+AC*H1+9.81*H1*
+ REAL(K)*1.OE-02))+DATA4(J,I+2)*HA1+FHI*H3+
+ (L1-D1)*WHI)/L1
RETURN
END

```

CC

```

REAL FUNCTION AXFAC1 (J,X,K,N3,
+ AC,L2,HA2,N2,H2,D2,H3,
+ HD,L3,HA1,H1,D1,L1,MU,I)

```

IMPLICIT LOGICAL (A-Z)

```

REAL X,DATA4,DTRAILMAS,N3,TIREMAS,
+ AC,L2,HA2,N2,H2,STRAILMAS,D2,H3,HD,L3,HA1,
+ H1,TRACTMAS,D1,L1,MU,WHI,FHI,WS,W2,F,
+ WDRIVE2,RD

```

INTEGER I,J,K

COMMON /A6/ DATA4(1200,200)

COMMON /A8/ STRAILMAS,DTRAILMAS,VMAS,AD,BD

COMMON /A10/ TIREMAS,TRACTMAS

```

RD = DATA4(J,I+4)+(DTRAILMAS+(N3*TIREMAS))
+ *(9.81*REAL(K)*1.OE-02+AC+9.81*X)
WS = ((STRAILMAS+(N2*TIREMAS))*(9.81*D2+AC+
+ (H2-H3)+9.81*(H2-H3)*REAL(K)*1.OE-02)
+ +RD*(HD-H3)+DATA4(J,I+3)*(HA2-H3))/(L2*X*H3)
FHI = (STRAILMAS+(N2*TIREMAS))*(AC+REAL(K)*
+ 9.81*1.OE-02)+DATA4(J,I+3)+X*WS+RD
WHI = ((STRAILMAS+(N2*TIREMAS))*9.81)-WS
WDRIVE2 = ((TRACTMAS*(9.81*L3+AC*H1+9.81*H1*REAL(K)
+ *1.OE-02))+DATA4(J,I+2)*HA1+FHI*
+ H3+(L1-D1)*WHI)/L1
F = MU*WDRIVE2
AXFAC1 = (F-(DATA4(J,I+2)+(TRACTMAS*9.81*REAL(K)*
+ 1.OE-02)+(X*((TRACTMAS*9.81)+WHI))+
+ FHI))/TRACTMAS
RETURN
END

```

CC

```

REAL FUNCTION WDRVFNC2 (J,X,K,N3,
+ L2,HA2,N2,H2,D2,H3,HD,
+ L3,HA1,H1,D1,L1,I)

IMPLICIT LOGICAL (A-Z)
REAL X,DATA4,DTRAILMAS,N3,TIREMAS,
+ L2,HA2,N2,H2,WS,W2,F,WDRIVE2,RD,
+ STRAILMAS,D2,H3,HD,L3,HA1,H1,TRACTMAS,
+ D1,L1,MU,WHI,FHI
INTEGER I,J,K
COMMON /A6/ DATA4(1200,200)
COMMON /A8/ STRAILMAS,DTRAILMAS,VMAS,AD,BD
COMMON /A10/ TIREMAS,TRACTMAS
DATA4(J,I+2) = 0.0
DATA4(J,I+3) = 0.0
DATA4(J,I+4) = 0.0
DATA4(J,I+5) = 0.0
RD = DATA4(J,I+4)+(DTRAILMAS+(N3*TIREMAS))*
+ (9.81*REAL(K)*1.OE-02+9.81*X)
WS = ((STRAILMAS+(N2*TIREMAS))*(9.81*D2+
+ 9.81*(H2-H3)*REAL(K)*1.OE-02) +RD*(HD-H3)
+ +DATA4(J,I+3)*(HA2-H3))/(L2*X*H3)
FHI = (STRAILMAS+(N2*TIREMAS))*(REAL(K)*
+ 9.81*1.OE-02)+DATA4(J,I+3)+X*WS+RD
WHI = ((STRAILMAS+(N2*TIREMAS))*9.81)-WS

```

```

WDRVFNC2 = ((TRACTMAS*(9.81*L3+9.81*H1*REAL(K)
+          *1.OE-02))+DATA4(J,I+2)*HA1+FHI*H3+
+          (L1-D1)*WHI)/L1
RETURN
END

```

```

C      This subroutine compares the two tractive forces
C      available as per engine characteristics and as
C      per nature of road-tire adhesion, and selects
C      the smaller of the two. Its also includes effect
C      of engine, wheel and other rotating parts inertia
C      by introduction of mass factor. Finally it gives
C      final tractive effort envelope for use in acceleration
C      and deceleration calculations.
SUBROUTINE EQMAS

```

```

IMPLICIT LOGICAL (A-Z)

```

```

REAL DATA5,DATA6,TIREMAS,
+     AXLRATIO,VMAS,DATA4,GAMAM,
+     ETATE,IE,IP,RRV,TRACTMAS,OPTION,MAXSPEED,
+     NDATA3,ROLRAD,GF,SPEED2

```

```

INTEGER I,J,K,M,SPEDINDX,NGEAR,TN,TND,N,P
COMMON /A1/ AXLRATIO,MAXSPEED,ROLRAD,GF,NGEAR
COMMON /A5/ SPEDINDX
COMMON /A6/ DATA4(1200,200)
COMMON /A7/ DATA5(1200,50)
COMMON /A8/ STRAILMAS,DTRAILMAS,VMAS,AD,BD
COMMON /A10/ TIREMAS,TRACTMAS
COMMON /A11/ NDATA3(1200,100)
COMMON /A12/ TN,TND
COMMON /A13/ DATA6(1200,100)

```

```

C      OPEN (UNIT=51,FILE='MEQ')
C      REWIND (51)
PRINT *, 'ENTER ENGINE INERTIA (IE) IN KG/M**2, FOR '
PRINT *, 'USING DEFAULT VALUE PLEASE ENTER "ZERO (0)" '
READ *, IE
      IF (IE .EQ. 0) THEN
          IE = TRACTMAS*0.20*1.OE-03
      ENDIF
PRINT *, 'ENTER PROPELLER SHAFT INERTIA (IP) IN KG/M**2'
PRINT *, 'FOR USING DEFAULT VALUE (WHICH IS 0.0)'

```

```
PRINT *, 'PLEASE ENTER "ZERO (0)"'
```

```
READ *,IP
```

```
IF (IP .EQ. 0) THEN
```

```
IP = 0.0
```

```
ENDIF
```

```
C Here IE (engine inertia) and IP (propeller shaft
C inertia) in the program are the component
C break-ups for the term I in the model text. G in
C the text is product of axle ratio and
C transmission ratio for the IE and is only axle
C ratio when used for IP.
```

```
PRINT *, 'WANT TO ACCOUNT FOR MASS-FACTOR ?'
```

```
PRINT *, ' PRINT 1 FOR YES & 2 FOR NO'
```

```
READ *, OPTION
```

```
P = -3
```

```
M = 1
```

```
DO 600 K = -10,10
```

```
M = M+1
```

```
P = P+4
```

```
DO 400 I = 1,SPEDINDX
```

```
IF (DATA5(I,M) .LT. NDATA3(I,P+1)) THEN
```

```
DATA6(I,1) = NDATA3(I,P+2)
```

```
DATA6(I,2) = NDATA3(I,P+3)
```

```
DATA6(I,M+1) = DATA5(I,M)
```

```
IF (OPTION .EQ. 1) THEN
```

```
GAMAM = 1+(TIREMAS*(TN-TND)/(VMAS*2.0))
```

```
DATA6(I,M+22) = GAMAM*VMAS
```

```
ELSEIF ( OPTION .EQ. 2 ) THEN
```

```
DATA6(I,M+22) = VMAS
```

```
ENDIF
```

```
ELSEIF (DATA5(I,M) .GE. NDATA3(I,P+1)) THEN
```

```
DATA6(I,1) = NDATA3(I,P+2)
```

```
DATA6(I,2) = NDATA3(I,P+3)
```

```
DATA6(I,M+1) = NDATA3(I,P+1)
```

```
IF ( OPTION .EQ. 1 ) THEN
```

```
SPEED2 = NDATA3(I,P)*0.27777
```

```
IF (DATA6(I,1) .LE. NGEAR/3) THEN
```

```
ETATE = 0.85
```

```
ELSEIF ((DATA6(I,1) .GT. NGEAR/3) .AND.
```

```
+ (DATA6(I,1) .LE. 2*NGEAR/3)) THEN
```

```
ETATE = 0.88
```

```
ELSEIF ((DATA6(I,1) .GT. 2*NGEAR/3) .AND.
```

```
+ (DATA6(I,1) .LE. NGEAR)) THEN
```

```
ETATE = 0.93
```

```

      ENDIF
      RRV = ROLRAD*(1.0+(GF*(NDATA3(I,P)**2)))
      GAMAM = 1+(TIREMAS*TN/(VMAS*2.0))+
+          (((AXLRATIO/RRV)**2)*(IP+(IE*
+          (DATA6(I,2)**2))))/VMAS)
      DATA6(I,M+22) = GAMAM*VMAS
      ELSEIF (OPTION .EQ. 2 ) THEN
          DATA6(I,M+22) = VMAS
      ENDIF
    ENDIF
  ENDIF
400    CONTINUE
600 CONTINUE

C      DO 200 J = 1,44,9
C      DO 100 I = 1,SPEDINDX
C      WRITE (51,110) (DATA6(I,M),M = J,J+8)
C 110  FORMAT (F10.2,1X,F10.2,1X,F10.2,1X,6(F10.2,1X))
C 100 CONTINUE
C 200 CONTINUE
C      CLOSE (51)

      CALL ACCEL

      RETURN
      END

C      This subroutine calculates the vehicle acceleration
C      up and down the grade, given the final tractive
C      force available and the total opposing forces.
      SUBROUTINE ACCEL

      IMPLICIT LOGICAL (A-Z)

      REAL DATA6,DATA4,AL,SL,ASL,
+      DATA7(1200,100),MAXSPEED,NDATA3
      INTEGER I,J,L,M,K,N,SPEDINDX,M1,M2,DESIRE,P,I1

      COMMON /A1/ AXLRATIO,MAXSPEED,ROLRAD,GF,NGEAR
      COMMON /A5/ SPEDINDX
      COMMON /A6/ DATA4(1200,200)
      COMMON /A11/ NDATA3(1200,100)
      COMMON /A13/ DATA6(1200,100)

      OPEN(UNIT = 60,FILE = 'AC1')

```

```

      OPEN(UNIT = 65,FILE = 'AC2')
C      OPEN(UNIT = 70,FILE = 'AC3')
      REWIND(60)
      REWIND(65)
C      REWIND(70)
CC      AC1 --CONTAINS SPEED AND DISTANCE FOR GRADES
CC          -- -10% TO -1% ( 10 GRADES )
CC      AC2 --CONTAINS SPEED AND DISTANCE FOR GRADES
CC          -- 0% TO +10% ( 11 GRADES )
CC      AC3 --CONTAINS ACCELARATION VALUES FOR GRADES
CC          -- -10% TO +10% ( 21 GRADES )

      DO 10 I1 = 1,100
          DATA7(1,I1) = 0.
10 CONTINUE
      L = -1
      M = 2
      N = -1
      K = 23
      M1 = 0
      M2 = 42
      P = -3
      DO 100 I = -10,10
          L = L + 2
          M = M + 1
          K = K + 1
          N = N + 8
          SL = 0.0
          M1 = M1 + 2
          M2 = M2 + 1
          P = P+4
          DO 50 J = 2,SPEDINDX,1
              AL = ((DATA6(J-1,M)+DATA6(J,M))-(DATA4(J-1,N)+
+                  DATA4(J,N)))/(DATA6(J-1,K)+DATA6(J,K))
              IF((AL .LE. 0.0001).AND.(SL .LE. 3000)) THEN
                  SL = 3000
                  DATA7(J,L) = DATA7(J-1,L)
              ELSEIF((AL .LE. 0.0001).AND.(SL .GT. 3000)) THEN
                  SL = ASL + SL
                  DATA7(J,L) = NDATA3(J,P)
              IF (SL .GT. 12000 ) THEN
                  SL = DATA7(J-1,M1)
                  DATA7(J,L) = DATA7(J-1,L)
              ENDIF
          
```



```

      ELSEIF (AL .GT. 0.0001) THEN
        ASL = (((NDATA3(J,P)**2.0)-(NDATA3(J-1,P)**2.0))
+          *.07716)/ (2.0*AL)
          IF (ASL .LT. 0) THEN
            ASL = -ASL
          ENDIF
          SL = ASL + SL
          DATA7(J,L) = NDATA3(J,P)
        ENDIF
40      DATA7(J,M1) = SL
        DATA7(J,M2) = AL
50      CONTINUE
100 CONTINUE

CC      FOR PLOTTING GRAPH
      DO 200 I = 1,SPEDINDX,1
        WRITE (60,210) (DATA7(I,J),DATA7(I,J+1),J=1,19,2)
        WRITE (65,210) (DATA7(I,J),DATA7(I,J+1),J=21,41,2)
C        WRITE (70,220) (DATA7(I,J),J=43,63,1)
210      FORMAT (22 (1X,F8.2))
220      FORMAT (21(1X,F7.3))
200 CONTINUE

      CLOSE(60)
      CLOSE(65)
C      CLOSE(70)

      CALL DECCEL

      RETURN
      END

C      This subroutine calculates the vehicle deceleration
C      up the grade, given the final tractive force avail-
C      able and the total opposing forces.
      SUBROUTINE DECCEL

      IMPLICIT LOGICAL (A-Z)

      REAL DATA6,DATA4,DL,TL,ATL,
+      DATA8(1200,100),MAXSPEED,NDATA3
      INTEGER I,J,L,M,K,N,SPEDINDX,M1,M2,P,Q
      COMMON /A1/ AXLRATIO,MAXSPEED,ROLRAD,GF,NGEAR
      COMMON /A5/ SPEDINDX

```

```

COMMON /A6/ DATA4(1200,200)
COMMON /A11/ NDATA3(1200,100)
COMMON /A13/ DATA6(1200,100)

OPEN(UNIT = 80,FILE = 'DC1')
C   OPEN(UNIT = 85,FILE = 'DC2')
REWIND(80)
C   REWIND(85)
CC  DC1 --CONTAINS  SPEED AND DISTANCE FOR GRADES
CC      --  0% TO +10% ( 10 GRADES )
CC  DC2 --CONTAINS  DECCELERATION FOR 0% TO +10%
CC      --  ( 10 GRADES )

DO 5 K = 1,21.2
    DATA8(1,K) = DATA4(SPEDINDX,1)
5 CONTINUE
DO 10 I = 2,22.2
    DATA8(1,1) = 0.0
10 CONTINUE
DO 20 J = 23,33.1
    DATA8(1,J) = 0.0
20 CONTINUE
L = -1
M = 12
N = 79
K = 33
M1 = 0
M2 = 22
Q = -3
DO 100 I = 0,10.1
    L = L + 2
    M = M + 1
    K = K + 1
    N = N + 8
    TL = 0.0
    M1 = M1 + 2
    M2 = M2 + 1
    P = 1
    Q = Q+4
    DO 50 J = SPEDINDX,2,-1
        P = P+1
        DL=((DATA4(J-1,N)+DATA4(J,N))-(DATA6(J-1,M)+
+          DATA6(J,M)))/(DATA6(J-1,K)+DATA6(J,K))
        IF((DL.LE. 0.0001).AND.(TL .LE. 3000))THEN

```

```

        TL = 3000
        DATA8(P,L) = DATA8(P-1,L)
ELSEIF((DL .LE. 0.0001).AND.(TL.GT.3000))THEN
        TL = ATL + TL
        DATA8(P,L) = NDATA3(J-1,Q)
        IF(TL .GT. 12000 )THEN
                TL = DATA8(P-1,M1)
                DATA8(P,L) = DATA8(P-1,L)
        ENDIF
ELSEIF (DL .GT. 0.0001) THEN
        ATL =(((NDATA3(J,Q)**2.0)-(NDATA3(J-1,Q)**2.0))
+         *.07716)/ (2.0*DL)
        IF (ATL .LT. 0) THEN
                ATL = -ATL
        ENDIF
        TL = ATL + TL
        DATA8(P,L) = NDATA3(J-1,Q)
ENDIF
        DATA8(P,M1) = TL
        DATA8(P,M2) = DL
50      CONTINUE
100 CONTINUE

CC      FOR PLOTTING GRAPH
DO 200 I = 1,SPEDINDX,1
        WRITE(80,210) (DATA8(I,J),J=1,22,1)
C        WRITE(85,220) (DATA8(I,J),J=23,33,1)
210      FORMAT(22 (1X,F 8.2))
220      FORMAT(11(1X,F7.3))
200 CONTINUE

        CLOSE(80)
C        CLOSE(85)

        RETURN
END

```

List of Input Variables for Model II

AXLRATIO	<i>drive axle gear ratio</i>
E	<i>altitude of vehicle operation</i>
EDAT	<i>engine data for torque and speed</i>
GDAT	<i>gear box data for different gear ratios</i>
GVW	<i>gross vehicle mass</i>
GVWR	<i>manufacturer maximum gross vehicle mass</i>
	<i>rating of powered unit</i>
HT	<i>height of the vehicle</i>
MAXSPEED	<i>maximum speed allowed on the highway</i>
NGEAR	<i>total number of gears</i>
ROLRAD	<i>rolling radius of the drive axle wheel</i>
TF	<i>tire factor</i>
VEHICLE_TYPE	<i>type of vehicle i.e. truck or RV</i>
WD	<i>width of the vehicle</i>

Note: Few variables have different notations in the Model II text as compared to the computer program. This was done to maintain simplicity in the written text. These are:

In Text	In Program
AR	AHPE
FR	FRR
GP	REAL(GRADE)
GR	GHP

GTE

TRACEFF

NTE

N_TRAC

r

ROLRAD

RR

RHP

Program Source Listing

Model II

C This subroutine calculates tractive effort available
C and the vehicle speed.

PROGRAM SAE_FTN
IMPLICIT LOGICAL (A-Z)

REAL SPEED, ENGSPEED(30), TORQUE(30), ROLRAD, LOADRAD,
+ C2, AXLRATIO, GEARATIO(20), DATA1, C1, SLIPF,
+ MAXSPEED, GVWR, GVW, N_TRAC, SLIP, FRR,
+ SPEED2, SPEED1, TF, E, FHP, AF, Z1, Z2, Z3, Z4, TRACEFF1,
+ TRACEFF, TFZ

INTEGER I, J, NGEAR, K, COUNT, M, VEHICLE_TYPE

COMMON /B1/ COUNT
COMMON /B2/ MAXSPEED
COMMON /B3/ E, Z1, Z2, Z3, Z4
COMMON /B4/ LOADRAD, GVW, GVWR, AXLRATIO, NGEAR
COMMON /B5/ DATA1(30,120)

PRINT *, ' HEAVY VEHICLE SIMULATION PROGRAM BASED ON '
PRINT *, ' SOCIETY OF AUTOMOTIVE ENGINEERS (SAE) '
PRINT *, ' '
PRINT *, ' Developed by '
PRINT *, ' '
PRINT *, ' MAYANK RASTOGI '
PRINT *, ' Carleton University, Ottawa, Canada '
PRINT *, ' August 1989 '
PRINT *, ' '
PRINT *, '*****'
PRINT *, ' '
PRINT *, ' Please Enter the Inputs '
PRINT *, ' '
PRINT *, '-----'
PRINT *, ' '
PRINT *, ' '

PAUSE

OPEN (UNIT=20, FILE='EDAT16')
OPEN (UNIT=21, FILE='GDAT8')
C OPEN (UNIT=25, FILE='CURVESA')
C OPEN (UNIT=29, FILE='CURVLOT')
REWIND (20)

```

      REWIND (21)
C      REWIND (25)
C      REWIND (29)

      COUNT = 0
      DO 10 I =1,100
          READ (20,*,END = 15) TORQUE(I),ENGSPD(I)
          COUNT = COUNT+1
10  CONTINUE

CC  TORQUE is in N-m and ENGSPD is in rpm.

15  PRINT *, 'ENTER TIRE FACTOR, TF i.e. TIRE RPM AT 1mph.'
      PRINT *, 'IF IT IS NOT KNOWN ENTER 0 BUT THEN'
      PRINT *, 'RADIUS OF TIRE SHOULD BE KNOWN'
      PRINT *, 'FOR USING DEFAULT VALUES IN CASE OF '
      PRINT *, 'TRUCKS OF ALL TYPES ENTER 1, FOR RV'
      PRINT *, 'ENTER 2 OR ELSE FOR YOUR VALUE ENTER 3'
      READ *, TFZ
          IF (TFZ .EQ. 1) THEN
              TF = 8.15
          ELSEIF (TFZ .EQ. 2) THEN
              TF = 15.56
          ELSEIF (TFZ .EQ. 3) THEN

      PRINT *, 'PLEASE ENTER YOUR VALUE'
      READ *, TF
          ENDIF
      PRINT *, 'ENTER TIRE RADIUS (rolrad) IN METRE. IT '
      PRINT *, 'IS THE VALUE OF RADIUS CALCULATED THRU TIRE '
      PRINT *, 'DESIGNATION. If TF is KNOWN, ENTER RADIUS'
      PRINT *, 'AS 0.0, ELSE ENTER THE APPROPRIATE VALUE'
      PRINT *, 'WITH EXTRA ALLOWANCE AS PER TIRE '
      PRINT *, 'DESIGNATION CALCULATIONS'
      READ *, ROLRAD
      PRINT *, 'ENTER DRIVE AXLE RATIO,(axlratio)'
      READ *, AXLRATIO
      PRINT *, 'ENTER NUMBER OF GEARS (ngear)'
      READ *, NGEAR
      PRINT *, 'ENTER MAXIMUM ALLOWABLE SPEED (maxspeed)'
      PRINT *, 'IN KMS/HR. FOR DEFAULT VALUE OF 90km/h '
      PRINT *, 'ENTER 0 OR ELSE ENTER PROPER VALUE (km/h).'
      READ *, MAXSPEED
          IF (MAXSPEED .EQ. 0) THEN

```



```

      MAXSPEED = 90.0
      ENDIF
PRINT *, 'ENTER ALTITUDE ABOVE SEA LEVEL, IN METER'
PRINT *, ' (●) FOR DEFAULT VALUE OF 150m ENTER 0'
PRINT *, '   OR ELSE ENTER YOUR VALUE'
READ *, E

      IF (E .EQ. 0) THEN
          E = 150
      ENDIF
PRINT *, 'TOTAL GROSS VEHICLE MASS (GVW) (in kg)'
READ *, GVW

PRINT *, ' MANUF. MAX. GROSS VEHICLE MASS RATING '
PRINT *, ' OF POWERED UNIT, (GVWR) (in kg), AS GIVEN'
PRINT *, ' IN TECHNICAL SPECIFICATION OR BROCHURE, '
PRINT *, ' DEPENDING UPON THE MODEL AND MAKE USED'
PRINT *, ' e.g. IN THE CASE OF LTL 9000 FORD MODEL'
PRINT *, ' (TANDEM) THIS IS 28120.0 KGS. AND FOR '
PRINT *, ' LNT 8000 MODEL (SINGLE) THIS IS 15875.0'
PRINT *, ' IF THERE IS NO INFORMATION THEN USE'
PRINT *, ' 13900.0 KGS. IN CASE OF TRACTORS WITH '
PRINT *, ' SINGLE REAR AXLE AND 25500.0 KGS. IN'
PRINT *, ' CASE OF REAR TANDEM AXLE. THESE VALUES'
PRINT *, ' ARE BASED ON AVERAGE OF ACTUAL '
PRINT *, ' CONFIGURATIONS. ALSO THIS VALUE WILL'
PRINT *, ' GENERALLY BE LESS THAN GVW'
READ *, GVWR

PRINT *, ' SPECIFY CATEGORY OF VEHICLE TO BE SIMULATED, '
PRINT *, ' i.e. ENTER 1 FOR TRUCKS AND 2 FOR RECREATIONAL'
PRINT *, ' VEHICLES i.e. (VEHICLE_TYPE)'
READ *, VEHICLE_TYPE

```

```

C-----
CC      Z1, Z2, Z3 & Z4 ARE MULTIPLYING CONVERSION FACTORS
CC      RESPECTIVELY:- FROM mph TO km/h ,
CC      FROM newton-m/s (watts) TO hp ,
CC      FROM mt TO ft AND FROM kg TO lb.
C-----

```

```

Z1 = 1.6093
Z2 = 1.3410*1.0E-03
Z3 = 3.28084
Z4 = 2.2046

```

```

      IF (TF .EQ. 0) THEN
        LOADRAD = ROLRAD/1.12
        TF = 168/ (LOADRAD*Z3*12)
      ELSEIF (TF .GT. 0.0) THEN
        LOADRAD = (168*2.54)/(TF*100)
      ENDIF
CC  LOADRAD IS THE STATIC LOADED RADIUS OF THE TIRE.

      E = E*Z3
      GVW = GVW*Z4
      GVWR = GVWR*Z4
      AF = (1-4.0*1.0E-05*E)
CC  AF IS THE ALTITUDE FACTOR FOR ENGINE PERFORMANCE

      DO 20 I = 1,NGEAR
        READ (21,*) GEARATIO(I)
20  CONTINUE
      IF (VEHICLE_TYPE .EQ. 1) THEN
        GOTO 25
      ELSEIF (VEHICLE_TYPE .EQ. 2) THEN
        GOTO 30
      ENDIF
30  PRINT *, 'ENTER PERCENTAGE SLIP OF THE VEHICLE RUNNING '
      PRINT *, ' GEAR, GENERALLY IT IS BETWEEN 2-6 PERCENT'
      PRINT *, ' ONLY ENTER NUMERICAL VALUE OF PERCENTAGE'
      READ *, SLIP
      SLIPF = (1-(SLIP/100.00))
      GOTO 25
25  K = 0
      DO 100 I = 1,(4*NGEAR).4
        K = K+1
        DO 90 J = 1,COUNT
          C2 = AXLRATIO*GEARATIO(K)
          SPEED = ENGSPEED(J)/(C2*TF)
          IF (VEHICLE_TYPE.EQ. 1) THEN
            GOTO 45
          ELSEIF (VEHICLE_TYPE .EQ. 2) THEN
            SPEED = SPEED*SLIPF
            GOTO 45
          ENDIF
90  CONTINUE
100 CONTINUE
CC  SPEED IS Speed IN mph
45  SPEED2 = SPEED*Z1
CC  SPEED2 IS Speed IN km/h

```

```

      SPEED1 = SPEED2 * .27777
CC  SPEED1  IS Speed  IN m/S
      TRACEFF1 = (TORQUE(J)*C2)/LOADRAD
CC  TRACEFF1 is tractive effort at sea level in Newton.
      TRACEFF = TRACEFF1*AF
CC  TRACEFF is tractive effort at given altitude in Newton.
      FHP = (1+(GVWR*2.0*1.0E-07*ENGSPD(J)))
CC  FHP is chasis frictional power in hp.
      FRR = FHP/(Z2*SPEED1)
CC  FRR is chasis frictional resistance in Newton.
      N_TRAC = TRACEFF - FRR
CC  N_TRAC  IS NET ENGINE TRACTIVE EFFORT (FORCE IN NEWTON)
CC  CORRECTED FOR ALTITUDE AND CHASIS FRICTION
      DATA1(J,I) = SPEED2
CC  DATA1 (J,I) IS Speed IN km/h
      DATA1(J,(I+1)) = N_TRAC
CC  DATA1(J,I+1) IS NET TRAC. EFF. IN NEWTONS
      DATA1(J,(I+2)) = REAL(K)
      DATA1(J,(I+3)) = GEARATIO(K)
    90      CONTINUE
    100 CONTINUE

CC  FOR WRITING IN THE RESULT FILE 'CURVES.A'
C      DO 200 I = 1,(4*NGEAR),4
C          WRITE (25,186)
C 186      FORMAT ( /, 'NEXT GEAR' , / )
C      DO 180 J = 1,COUNT
C          WRITE (25,185) (DATA1(J,M),M=I,I+3)
C 185      FORMAT (F8.3,4X,F11.2,3X,F5.2,2X,F6.2)
C 180 CONTINUE
C 200 CONTINUE
CC  FOR PLOTTING THE GRAPHS FROM FILE 'CURV.PLOT'
C      DO 250 J = 1,COUNT
C          WRITE (29,255) (DATA1(J,I),I=1,(4*NGEAR),4),
C          +              (DATA1(J,I),I=4,(4*NGEAR),4)
C 255      FORMAT ( 12(F5.1),12(F8.1))
C 250 CONTINUE

      CALL CURVFIT

      CLOSE (20)
      CLOSE (21)
C      CLOSE (25)
C      CLOSE (29)

```

STOP
END

CC NHPS -- NET ENGINE HORSE POWER AT SEA-LEVEL
CC NHPE -- NET ENGINE HORSE POWER AT GIVEN ALTITUDE
CC FHP -- CHASIS-FRICTION HORSE POWER
CC NNHP -- NET ENGINE HORSE POWER INCLUDING FHP
CC LOSSES AT GIVEN ALTITUDE

C This subroutine fits in the output of module 1 on to
C a polynomial of 10th degree and calculates engine
C tractive effort and vehicle speed for every 0.1 km/h
C of vehicle speed.

SUBROUTINE CURVFIT

IMPLICIT LOGICAL (A-Z)

REAL X(30),Y(30),W(30),R(30),EPS,C(90),A(125),
+ YFIT,YP(30),XVALU(30,20),YVALU(30,20),
+ AVALU(125,20),MAXSPEED,I1,GVW,GVWR,
+ DATA1,DATA3,Z1,Z2,Z3,Z4,
+ AXLRATIO,DIF,NX,E,WVALU(30,20),
+ LOADRAD,J1,I2,DATA2(1200,60)

INTEGER IERR,N,MAXDEG,NDEG,1,L,NDER,J,K,NGEAR,N1,M,
+ COUNT,SPEDINDX,IX

COMMON /B1/ COUNT
COMMON /B2/ MAXSPEED
COMMON /B3/ E,Z1,Z2,Z3,Z4
COMMON /B4/ LOADRAD,GVW,GVWR,AXLRATIO,NGEAR
COMMON /B5/ DATA1(30,120)
COMMON /B6/ DATA3(1200,10),SPEDINDX

C OPEN (UNIT=30,FILE='CURVES1')
C OPEN (UNIT=35,FILE='ENVE')
C REWIND (35)
C REWIND (30)
K = 0
DO 10 I = 1,(4*NGEAR),4
K = K+1
DO 5 J = 1,COUNT
WVALU(J,K) = 1.0/(DATA1(J,(I+1))**2)

3

OF/DE

3

Metrod

```

5      CONTINUE
      A(I) = 0.
10 CONTINUE
      K = 0
      DO 100 I = 1,(4*NGEAR).4
        K = K+1
        DO 15 J = 1,COUNT
          X(J) = DATA1(J,I)
          Y(J) = DATA1(J,(I+1))
          W(J) = WVALU(J,K)
15      CONTINUE
        MAXDEG = 10
        N = COUNT
        EPS = 0.
CC
        CALL POLFIT(N,X,Y,W,MAXDEG,NDEG,EPS,R,IERR,A)
CC
        DO 17 J = 1,125
          AVALU(J,K) = A(J)
17      CONTINUE
        L = NDEG
        NDER = 0.
        DO 40 J = 0,(10*MAXSPEED).1
          J1 = J/10.0000
          X(1) = J1
CC
          CALL PVALUE (L,NDER,X,YFIT,YP,A)
CC
          DATA2(J,K) = YFIT
40 CONTINUE
100 CONTINUE

C      DO 60 I = 0,(10*MAXSPEED).1
C          I1 = I/10.0000
C          X(1) = I1
C          WRITE(30,36) X(1),(DATA2(I,J),J=1,NGEAR)
C 36      FORMAT(F5.1,1X,12(E11.4))
C 60 CONTINUE
      I = -1
      I2 = -0.10000
      J = 0
      M = 0
      SPEDINDX = 0
      DO 200 K = 1,(4*NGEAR).4

```

```

210      J = J+1
      I2 = I2+0.10000
      I = I+1
      M = M+1
      IF ( I2 .GT. MAXSPEED ) GOTO 300
      SPEDINDX = SPEDINDX + 1
      IF ( I2 .LE. DATA1(1,1)) THEN
        DATA3(SPEDINDX,4) = DATA1(1,4)
        DATA3(SPEDINDX,3) = DATA1(1,3)
        DATA3(SPEDINDX,2) = DATA1(1,2)
        DATA3(SPEDINDX,1) = I2
        GOTO 210
      ELSEIF (I2 .LE. DATA1(COUNT,K)) THEN
        DATA3(SPEDINDX,4) = DATA1(J,K+3)
        DATA3(SPEDINDX,3) = DATA1(J,K+2)
        DATA3(SPEDINDX,2) = DATA2(I,J)
        DATA3(SPEDINDX,1) = I2
        GOTO 210
      ELSEIF ( ( I2 .GT. DATA1(COUNT,K)) .AND.
+         (I2 .LE. REAL(MAXSPEED))) THEN
        DATA3(SPEDINDX,4) = DATA1(COUNT,K+3)
        DATA3(SPEDINDX,3) = DATA1(COUNT,K+2)
        DATA3(SPEDINDX,2) = DATA1(COUNT,K+1)
        DATA3(SPEDINDX,1) = DATA1(COUNT,K)

        SPEDINDX = SPEDINDX+1
        DATA3(SPEDINDX,4) = DATA1(J,K+7)
        DATA3(SPEDINDX,3) = DATA1(J,K+6)
        DATA3(SPEDINDX,2) = DATA2(I,J+1)
        DATA3(SPEDINDX,1) = I2
        GOTO 200
      ENDIF
200 CONTINUE
300 DO 220 I = 1, SPEDINDX
      DIF = (DATA3((I+1),2) - DATA3(I,2))
      IF (DIF .LT. 0.0) THEN
        NX = DATA3(I,2)
        IX = I
        GOTO 225
      ENDIF
220 CONTINUE
225 DO 230 K = IX,1,-1
      DATA3(K,2) = NX
230 CONTINUE

```

```

C      DO 250 I = 1,SPEDINDX
C          WRITE (35,265) (DATA3(I,M),M=1,4)
C 265      FORMAT (4(F12.2))
C 250 CONTINUE

```

```

CC DATA3(I,1) is speed in km/h. DATA3(I,2) is trac. eff.
CC in newton, DATA3(I,3) is gear no. and DATA3(I,4)
CC is the gear ratio.

```

```

      CALL RESISTANCE
C      CLOSE (35)
C      CLOSE (30)

```

```

      RETURN
      END

```

```

C      This subroutine calculates the individual forces
C      opposing the vehicle motion and their total sum.

```

```

      SUBROUTINE RESISTANCE

```

```

      IMPLICIT LOGICAL (A-Z)

```

```

      REAL MAXSPEED,AHPS,AHPE,RHP,GHP,AREA,TOT,
+      DATA3,GVW,GVWR,E,
+      AXLRATIO,HT,WD,AFAR,Z1,Z2,
+      Z3,Z4,DATA4,LOADRAD

```

```

      INTEGER I,J,K,GRADE,M,SPEDINDX,NGEAR

```

```

      COMMON /B2/ MAXSPEED
      COMMON /B3/ E,Z1,Z2,Z3,Z4
      COMMON /B4/ LOADRAD,GVW,GVWR,AXLRATIO,NGEAR
      COMMON /B6/ DATA3(1200,10),SPEDINDX
      COMMON /B7/ DATA4(1200,110)

```

```

C      OPEN (UNIT=40,FILE='RESCURVE')
C      REWIND (40)

```

```

      PRINT*,'ENTER HEIGHT (HT) OF THE VEHICLES IN METER'
      READ*,HT
      PRINT*,'ENTER WIDTH (WD) OF THE VEHICLE IN METER'
      READ*,WD

```



```

HT = HT*Z3
WD = WD*Z3
AREA = (HT-.75)*WD
AFAR = ((1-(6.887*1.0E-06*E))**4.255)

I = -4
M = 1
DO 100 GRADE = -10,10,1
    I = I+5
    DO 50 K = 1,SPEDINDX
        DATA4(K,I) = DATA3(K,1)
        RHP = (((7.6+(0.09*(DATA3(K,1)/Z1))))*GVW)
        +
        /(375000)
CC    THIS IS ROLLING RESSISTANCE FORCE IN hp/mph.
        RHP = RHP/(Z2*Z1*0.27777)
        DATA4(K,I+1) = RHP
CC    THIS IS ROLLING RESISTANCE FORCE IN newton
        AHPS = (0.002*(DATA3(K,1)**2)*AREA)/(375*(Z1**2))
        AHPE = AHPS*AFAR
CC    THIS IS AIR RESISTANCE FORCE WITH ALTITUDE
CC    CORRECTION IN hp/mph.
        AHPE = AHPE/(Z2*Z1*0.27777)
        DATA4(K,I+2) = AHPE
CC    THIS IS AIR RESISTANCE FORCE WITH ALTITUDE
CC    CORRECTION IN newton.
        GHP = (GVW*REAL(GRADE))/37500
CC    THIS IS GRADE RESISTANCE FORCE IN hp/mph.
        GHP = GHP/(Z1*Z2*0.27777)
        DATA4(K,I+3) = GHP
CC    THIS IS GRADE RESISTANCE FORCE IN newton.
        TOT = RHP+AHPE+GHP
        DATA4(K,I+4) = TOT
CC    THIS IS TOTAL RESISTING FORCE IN newton.
    50    CONTINUE
    100   CONTINUE
C        DO 500 I=1,105,5
C            WRITE (40,41)
C    41    FORMAT ( /, 'NEXT GEAR'. / )
C            DO 550 J =1,SPEDINDX
C                WRITE(40,40) (DATA4(J,M),M=I,I+4)
C    40    FORMAT(5F11.2)
C    550   CONTINUE
C    500   CONTINUE

```

```

      CALL ACCEL
C      CLOSE (40)
      RETURN
      END

C      This subroutine calculates the vehicle acceleration
C      up and down the grade, given the tractive force
C      available and the total opposing forces.

```

SUBROUTINE ACCEL

```

      IMPLICIT LOGICAL (A-Z)

```

```

      REAL DATA3,DATA4,AL,SL,ASL,
+      Z1,Z2,Z3,Z4,GVW,GVWR,LOADRAD,
+      DESIRE,DATA7(1200,100),AXLRATIO,MAXSPEED

```

```

      INTEGER I,J,L,M,K,N,SPEDINDX,M1,M2,NGEAR

```

```

      COMMON /B2/ MAXSPEED
      COMMON /B3/ E,Z1,Z2,Z3,Z4
      COMMON /B4/ LOADRAD,GVW,GVWR,AXLRATIO,NGEAR
      COMMON /B6/ DATA3(1200,10),SPEDINDX
      COMMON /B7/ DATA4(1200,110)

```

```

      OPEN(UNIT = 60,FILE = 'AC  ')
      OPEN(UNIT = 65,FILE = 'AC2')
C      OPEN(UNIT = 70,FILE = 'AC3')
      REWIND(60)
      REWIND(65)
C      REWIND(70)

CC      AC1 --CONTAINS SPEED AND DISTANCE FOR GRADES
CC      -- -10% TO -1% ( 10 GRADES )
CC      AC2 --CONTAINS SPEED AND DISTANCE FOR GRADES
CC      -- 0% TO +10% ( 11 GRADES )
CC      AC3 --CONTAINS ACCELERATION VALUES FOR GRADES
CC      -- -10% TO +10% ( 21 GRADES )

```

```

      GVW = GVW/Z4
      GVWR = GVWR/Z4
      DO 10 I = 1,100
          DATA7(1,I) = 0.0
10 CONTINUE

```

```

L = -1
N = 0
M1 = 0
M2 = 42
DO 100 I = -10,10
    L = L + 2
    N = N + 5
    SL = 0.0
    M1 = M1 + 2
    M2 = M2 + 1
    DO 50 J = 2,SPEDINDX,1
        AL = ((DATA3(J-1,2)+DATA3(J,2))-(DATA4(J-1,N)+
+          DATA4(J,N)))/(GVW*2)
        IF ((AL .LE. 0.00001) .AND. (SL .LE. 3000)) THEN
            SL = 3000
            DATA7(J,L) = DATA7(J-1,L)
        ELSEIF ((AL .LE. 0.00001) .AND. (SL .GT. 3000)) THEN
            SL = ASL + SL
            DATA7(J,L) = DATA3(J,1)
            IF (SL .GT. 12000 ) THEN
                SL =DATA7(J-1,M1)
                DATA7(J,L) = DATA7(J-1,L)
            ENDIF
        ELSEIF (AL .GT. 0.00001) THEN
            ASL =(((DATA3(J,1)**2.0)-(DATA3(J-1,1)**2.0))
+          *.07716)/(2.0*AL)
            SL = ASL + SL
            DATA7(J,L) = DATA3(J,1)
        ENDIF
    40      DATA7(J,M1) = SL
           DATA7(J,M2) = AL
    50      CONTINUE
100 CONTINUE

CC  FOR PLOTTING GRAPH
    DO 200 I = 1,SPEDINDX,1
        WRITE (60,210) (DATA7(I,J),DATA7(I,J+1),J=1,19,2)
        WRITE (65,210) (DATA7(I,J),DATA7(I,J+1),J=21,41,2)
C      WRITE (70,220) (DATA7(I,J),J=43,63,1)
    210      FORMAT (22 (1X,F8.2))
    220      FORMAT (21(1X,F7.3))
    200 CONTINUE

    CALL DECCEL

```

```

CLOSE(60)
CLOSE(65)
C   CLOSE(70)
RETURN
END

C   This subroutine calculates the vehicle deceleration
C   up the grade, given the tractive force available
C   and the total opposing forces.

SUBROUTINE DECCEL

IMPLICIT LOGICAL (A-Z)

REAL DATA3,DATA4,DL,TL,ATL,
+ DATA8(1200,100),Z1,Z2,Z3,Z4,GVW,GVWR,
+ AXLRATIO,LOADRAD

INTEGER I,J,L,M,K,N,SPEDINDX,M1,M2,P,NGEAR

COMMON /B3/ E,Z1,Z2,Z3,Z4
COMMON /B4/ LOADRAD,GVW,GVWR,AXLRATIO,NGEAR
COMMON /B6/ DATA3(1200,10),SPEDINDX
COMMON /B7/ DATA4(1200,110)

OPEN(UNIT = 80,FILE = 'DC1')
C   OPEN(UNIT = 85,FILE = 'DC2')
REWIND(80)
C   REWIND(85)

CC   DC1 --CONTAINS SPEED AND DISTANCE FOR GRADES
CC   -- 0% TO +10% ( 10 GRADES )
CC   DC2 --CONTAINS DECELERATION FOR 0% TO +10%
CC   -- ( 10 GRADES )

DO 5 K = 1,21,2
    DATA8(1,K) = DATA3(SPEDINDX,1)
5 CONTINUE
DO 10 I = 2,22,2
    DATA8(1,I) = 0.0
10 CONTINUE
DO 20 J = 23,33,1
    DATA8(1,J) = 0.0

```

```

20 CONTINUE
  L = -1
  N = 50
  M1 = 0
  M2 = 22
  DO 100 I = 0,10,1
    L = L + 2
    N = N + 5
    TL = 0.0
    M1 = M1 + 2
    M2 = M2 + 1
    P = 1
    DO 50 J = SPEDINDX,2,-1
      P = P+1
      DL = ((DATA4(J-1,N)+DATA4(J,N))-(DATA3(J-1,2)+
+      DATA3(J,2)))/(GVW*2)
      IF ((DL .LE. 0.00001).AND. (TL .LE. 3000)) THEN
        TL = 3000
        DATA8(P,L) = DATA8(P-1,L)
      ELSEIF ((DL .LE. 0.00001).AND. (TL .GT. 3000)) THEN
        TL = ATL + TL
        DATA8(P,L) = DATA3(J-1,1)
        IF ( TL .GT. 12000 ) THEN
          TL = DATA8(P-1,M1)
          DATA8(P,L) = DATA8(P-1,L)
        ENDIF
      ELSEIF (DL .GT. 0.00001) THEN
        ATL = (((DATA3(J,1)**2.0)-(DATA3(J-1,1)**2.0))
+        *.07716)/(2.0*DL)
        TL = ATL + TL
        DATA8(P,L) = DATA3(J-1,1)
      ENDIF
      DATA8(P,M1) = TL
      DATA8(P,M2) = DL
    50 CONTINUE
  100 CONTINUE
CC  FOR PLOTTING GRAPH
  DO 200 I = 1,SPEDINDX,1
    WRITE(80,210) (DATA8(I,J),J=1,22,1)
    C  WRITE(85,220) (DATA8(I,J),J=23,33,1)
    210 FORMAT(22 (1X,F8.2))
    220 FORMAT(11(1X,F7.3))
  200 CONTINUE
  CLOSE(80)

```

C CLOSE(85)

RETURN
END

Appendix B

Model Inputs and Outputs

For illustration purposes, few sample outputs are included for each model.

For Model I, the inputs and outputs relate to all the cases of trucks (straight, semi-trailer and double-trailer) and recreational vehicles. Entry speed has been taken as 90 km/h for all cases. For comparison, loading levels of 120 kg/kw and 180 kg/kw in case of trucks and loading level of 40 kg/kw for recreational vehicles are included. Various other outputs with different entry speeds, loading levels and with different sets of inputs were also analysed as a part of this work.

Also, in the case of Model I, a sample output for 180 kg/kw double-trailer with the gear change delay feature, is attached. Not all grades have been reproduced for reason of clarity. It is found that the effect on terminal or crawl speeds of the vehicle is negligible, as compared to the no gear delay case.

In the case of Model II, the sample cases include, outputs for trucks (only one kind of truck as it doesn't differentiate between truck types and is only governed by loading level) and recreational vehicles. Entry speed is again 90 km/h and loading levels are the same as in Model I. Also for this model, various loading and entry speed options were analysed.

Model I

- **Input data for straight truck, semi-trailer, double-trailer and recreational vehicle (RV).**
- **Outputs**
 - **Engine curve**
 - **Performance curves with the entry speed of 90 km/h are included for the weight/power ratio of 120 and 180 kg/kw for all the three types of trucks and 40 kg/kw for recreational vehicles.**
 - **Gear change delay illustration for 180kg/kw double-trailer with the grade entry speed of 90 km/h.**

Basic Input Sheet For Straight Truck, Model I

4 Axles

Parameters	Parameter Values	
Engine		
Max. Engine Speed, <i>rpm</i>	2600	
Min. Engine Speed, <i>rpm</i>	1200	
Max. Power Rating, <i>kw(hp)</i>	156.6 (210) @ 2600 rpm	
Transmission		
Gear Ratios	17.93, 14.04, 10.96, 8.61, 6.74, 5.26, 4.11, 3.29, 2.61, 2.05, 1.60, 1.25, 1.00	
Drive Axle Ratio	4.30	
Number of Gears	13	
Vehicle		
Tire Rolling Radius, <i>m</i>	0.5235	
Weight/Power Ratio, <i>kg/kw</i>	120	180
Gross Vehicle Mass, <i>kg</i>	18784	28187
Altitude of Operation, <i>m</i>	150	
Frontal Drag Area, <i>m</i> ²	7.78	
Aerodynamic Drag Coefficient	0.43	
Static Rolling Resistance Coefficient (<i>A_d</i>)	.0095	
Dynamic Rolling Resistance Coefficient (<i>B_d</i>)	6.25×10^{-5}	
Road-Tire Adhesion Coefficient (<i>μ</i>)	0.85	

Basic Input Sheet For Semi-Trailer, Model I

6 Axles

Parameters	Parameter Values	
Engine		
Max. Engine Speed, <i>rpm</i>	1800	
Min. Engine Speed, <i>rpm</i>	1000	
Max. Power Rating, <i>kw</i> (<i>hp</i>)	231.2 (310) @ 1800 rpm	
Transmission		
Gear Ratios	10.58, 7.55, 5.39, 3.83, 2.77, 1.97, 1.41, 1.00, 0.83	
Drive Axle Ratio	3.91	
Numbe. of Gears	9	
Tire Rolling Radius, <i>m</i>	0.5235	
Weigth/Power Ratio, <i>kg/kw</i>	120	180
Gross Vehicle Mass, <i>kg</i>	27739	41608
Altitude of Operation, <i>m</i>	150	
Frontal Drag Area, <i>m</i> ²	Tractor <i>A</i> ₁ = 9.25, Semi-trailer <i>A</i> ₂ = 9.25	
Aerodynamic Drag Coefficient	Tractor <i>C</i> _{d1} = 0.51, Semi-trailer <i>C</i> _{d2} = 0.11	
Static Rolling Resistance Coefficient (<i>A</i> _d)	.0095	
Dynamic Rolling Resistance Coefficient (<i>B</i> _d)	6.25×10 ⁻⁵	
Road-Tire Adhesion Coefficient (<i>μ</i>)	0.85	

Basic Input Sheet For Double-Trailer, Model I

8 Axles

Parameters	Parameter Values	
Engine		
Max. Engine Speed, <i>rpm</i>	1800	
Min. Engine Speed, <i>rpm</i>	1200	
Max. Power Rating, <i>kw(hp)</i>	272.2 (365) @ 1800 rpm	
Transmission		
Gear Ratios	12.56, 8.32, 6.18, 4.54, 3.38, 2.46, 2.15, 1.83, 1.60, 1.34, 1.17, 1.00, 0.87	
Drive Axle Ratio	3.91	
Number of Gears	13	
Tire Rolling Radius, <i>m</i>		
0.5235		
Weight/Power Ratio, <i>kg/kw</i>	120	180
Gross Vehicle Mass, <i>kg</i>	32660	48992
Altitude of Operation, <i>m</i>	150	
Frontal Drag Area, <i>m</i> ²	Trac. <i>A</i> ₁ = 9.25, Semi. <i>A</i> ₂ = 9.25, Doub. <i>A</i> ₃ = 4.62	
Aerodynamic Drag Coefficient	Trac. <i>C</i> _{d1} = 0.51, Semi. <i>C</i> _{d2} = 0.11, Doub. <i>C</i> _{d3} = 0.11	
Static Rolling Resistance Coefficient (<i>A_d</i>)	.0095	
Dynamic Rolling Resistance Coefficient (<i>B_d</i>)	6.25×10 ⁻⁷	
Road-Tire Adhesion Coefficient (<i>μ</i>)	0.85	

Basic Input Sheet For Recreational Vehicle, Model I

Parameters	Parameter Values
Engine	
Max. Engine Speed, <i>rpm</i>	5000
Min. Engine Speed, <i>rpm</i>	1000
Max. Power Rating, <i>kw(hp)</i>	82.0 (110) @ 4500 rpm
Transmission	
Gear Ratios	3.167, 1.833, 1.240, 0.896, 0.667
Drive Axle Ratio	4.067
Number of Gears	5
Tire Rolling Radius, <i>m</i>	0.274
Weight/Power Ratio, <i>kg/kw</i>	40
Gross Vehicle Mass, <i>kg</i>	3281.0
Altitude of Operation, <i>m</i>	150
Vehicle Dimensions (Trailer), <i>m</i>	Width (<i>WD</i>) = 1.80, Height (<i>HT</i>) = 3.20
Aerodynamic Drag Coefficient	0.60
Static Rolling Resistance Coefficient (<i>A_d</i>)	.0095
Dynamic Rolling Resistance Coefficient (<i>B_d</i>)	6.25×10^{-5}
Road-Tire Adhesion Coefficient (μ)	0.85

ENGINE CHARACT. USED IN (210 kg/kw - 60 kg/kw) Straight Truck SIMULATION/ MODEL 1

ENGINE CHARACT. USED IN (210 kg/kw - 60 kg/kw) Semi-Trailer SIMULATION/ MODEL I

ENGINE CHARACT. USED IN (210 kg/kw - 60 kg/kw) Doub-Trailer SIMULATION/MODEL I

ENGINE CHARACT. USED IN (40 kg/kw) Recreational Vehicle SIMULATION/MODEL I

Straight Truck

120 kg/kw & 180 kg/kw

ACCEL. DOWNGRADE (-9% TO -1%) / W/P = 120 kg/kw (90.0 kmph) / St. - Truck / 4 Axles / MODEL I

DECEL. UPGRADE (0% TO +9%) / W/P=180 kg/kw (90.0 km/h) / St. - Truck / 4 Axles / MODEL I

ACCEL. UPGRADE(0% TO +9%)/W/P=180 kg/kw(90.0km/h)/St.-Truck/4 Axles/MODEL I

ACCEL. DOWNGRADE (-9% TO -1%) / W/P = 180 kg/kw (90.0 km/h) / St. - Truck / 4 Axles / MODEL I

Semi-Trailer
120 kg/kw & 180 kg/kw

ACCEL. UPGRADE (0% TO +9%) / W/P=120 kg/kw (90.0 km/h) / Semi-Trailer/6 Axles/MODEL I

ACCEL. DOWNGRADE (-9% TO -1%) / W/P = 120 kg/kw (90.0 km/h) / Semi-Trailer / 6 Axles / MODEL 1

ACCEL. UPGRADE (0% TO +9%) / W/P=180 kg/kw (90.0 km/h) / Semi-Trailer / 6 Axles / MODEL

ACCEL. DOWNGRADE (-9% TO -1%) / W/P = 180 kg/kw (90.0 km/h) / Semi-Trailer / 6 Axles / MODEL

Double-Trailer
120 kg/kw & 180 kg/kw

DECEL. UPGRADE (0% TO +9%) / W/P=120 kg/kw (90.0 km/h) / Doub-Trailer / 8 Axles / MODEL :

ACCEL. UPGRADE(0% TO +9%)/W/P=120 kg/kw(90.0km/h)/Doub-Trailer/8 Axles /MODEL I

ACCEL. DOWNGRADE (-9% TO -1%) / W/P = 120 kg/kw (90.0 km/h) / Doub-Trailer / 8 Axles / MODEL

DECEL. UPGRADE(0% TO +9%)/W/P=180 kg/kw(90.00km/h)/Doub-Trailer/8 Axles /MODEL

ACCEL. UPGRADE (0% TO +9%) / W/P=180 kg/kw (90.00km/h) / Doub-Trailer/8 Axles / MODEL 1

ACCEL. DOWNGRADE (-9% TO -1%) / W/P = 180 kg/kw (90.00 km/h) / Doub-Trailer / 8 Axles / MODEL

Recreational Vehicle

40 kg/kw

Gear Change Delay Example

Double-Trailer 180 kg/kw

DECEL. UPGRADE (0%, 3%, 6%, 9%) / DOUB-TRAILER / 8 AXLES / W/P = 180kg/kw, With Gear Delay

ACCEL. UPGRADE (0%, 3%, 6%, 9%) / DOUB-TRAILER / 8 AXLES / W/P = 180kg/kw, With Gear Delay

Model II

- **Input sheets for trucks and recreational vehicles (RV).**
- **Outputs**
 - **Engine curve**
 - **Performance curves with grade entry speed of 90 km/h, for 120 and 180 kg/kw loading levels in case of trucks and 40 kg/kw for recreational vehicles.**

Basic Input Sheet For Truck, Model II

120 kg/kw Category

Parameters	Parameter Values
Engine	
Max. Engine Speed, <i>rpm</i>	2200
Min. Engine Speed, <i>rpm</i>	1400
Max. Power Rating, <i>kw(hp)</i>	179.0 (240) @ 2200 rpm
Transmission	
Gear Ratios	9.01, 5.27, 3.25, 2.04, 1.36, 1.00
Drive Axle Ratio	3.91
Number of Gears	6
Tire Factor (<i>rpm/mph</i>)	8.15
Weight/Power Ratio, <i>kg/kw</i>	120
Gross Vehicle Mass, <i>kg</i>	21476
Altitude of Operation, <i>m</i>	150
Vehicle Dimensions, <i>m</i>	Width (<i>WD</i>) = 2.43 Height (<i>HT</i>) = 3.81

Basic Input Sheet For Truck, Model II

180 kg/kw Category

Parameters	Parameter Values
Engine	
Max. Engine Speed, <i>rpm</i>	1800
Min. Engine Speed, <i>rpm</i>	1000
Max. Power Rating, <i>kw (hp)</i>	231.2 (310) @ 1800 rpm
Transmission	
Gear Ratios	10.58, 7.55, 5.39, 3.83, 2.77, 1.97, 1.41, 1.00, 0.83
Drive Axle Ratio	4.30
Number of Gears	9
Tire Factor (<i>rpm/mph</i>)	8.15
Weight/Power Ratio, <i>kg/kw</i>	180
Gross Vehicle Mass, <i>kg</i>	41611
Altitude of Operation, <i>m</i>	150
Vehicle Dimensions, <i>m</i>	Width (<i>WD</i>) = 2.43 Height (<i>HT</i>) = 3.81

Basic Input Sheet For Recreational Vehicle, Model II

Parameters	Parameter Values
Engine	
Max. Engine Speed, <i>rpm</i>	5000
Min. Engine Speed, <i>rpm</i>	1000
Max. Power Rating, <i>kw(hp)</i>	82.0 (110) @ 4500 rpm
Transmission	
Gear Ratios	3.167, 1.833, 1.240, 0.896, 0.667
Drive Axle Ratio	4.067
Number of Gears	5
Tire Factor (<i>rpm/mph</i>)	15.56
Weight/Power Ratio, <i>kg/kw</i>	40
Gross Vehicle Mass, <i>kg</i>	3281
Altitude of Operation, <i>m</i>	150
Vehicle Dimensions, <i>m</i>	Width (<i>WD</i>) = 1.80 Height (<i>HT</i>) = 3.20

ENGINE CHARACTERISTICS USED IN (120 kg/kw & 60 kg/kw) TRUCK SIMULATION / MODEL II

ENGINE CHARACTERISTICS USED IN(210 kg/kw & 180 kg/kw)TRUCK SIMULATION /MODEL II

ENGINE CHARACTERISTICS USED IN 40 kg/kw RECREATIONAL VEHI. SIMULATION / MODEL II

Truck
120 kg/kw

Truck
180 kg/kw

Recreational Vehicle

40 kg/kw

ACCEL. DOWNGRADE(-9% TO -1%) / W/P=40 kg/kw (90.0km/h) / Rec. Vehicle / MODEL II

Appendix C

Vehicle Weights and Dimensions

In February of 1988, the Council of Ministers of Transportation and Highway Safety endorsed a Memorandum of Understanding (37) designed to improve uniformity in regulations covering weights and dimensions of commercial vehicles, operating between provinces and territories and on a nationwide highway system in Canada.

As a matter of fact, more and more operators will now try to obtain the vehicles complying to these regulations, as then they could not only operate within their province (where regulations might be more liberal) but also interprovincially. As such, it is justified to represent our representative vehicle according to this document. The next few pages, follow the dimensions and weights of different categories of trucks.

- Semi-trailer
- A-Train Double
- B-Train Double
- C-Train Double

Dimensions

Weights

MAXIMUM GROSS COMBINATION WEIGHTS

3 axles:	23 700 kg.
4 axles:	31 600 kg.
5 axles:	39 500 kg.
6 axles:	46 500 kg.

Single Axle:
Max 9100 kg.

Tandem Axle:
Max 17 000 kg.

Tridem Axle:
Max 24 000 kg.

Single Axle:
Max 9100 kg.

Tandem Axle:
Max 17 000 kg.

Max 5500 kg.

Parameter	Limit
-----------	-------

DIMENSIONS**Tractor:**

Tractor wheelbase	Maximum 6.2 m
Tandem Axle Spread	Minimum 1.2 m/Maximum 1.85 m
Interaxle Spacing	Minimum 3 m

Semitrailer:

Length	Maximum 14.65 m
Wheelbase:	
Single or Tandem Axle Group	Minimum 6.5 m to Maximum 12.5 m
Tridem Axle Group	Minimum 9.5 m to Maximum 12.5 m
Kingpin Setback	Maximum 2.0 m radius
Effective Overhang	Maximum 35% of wheelbase
Tandem Axle Spread	Minimum 1.2 m/Maximum 1.85 m
Tridem Axle Spread	Minimum 2.4 m/Maximum 3.7 m
Track Width	Minimum 2.5 m/Maximum 2.6 m

Overall Length	Maximum 23 m
Overall Width	Maximum 2.6 m
Overall Height	Maximum 4.15 m

WEIGHTS**Axle Weights:**

Steering Axle	Maximum 5500 kg
Single Axle (dual tires)	Maximum 9100 kg
Tandem Axle:	
Tandem Axle Spread 1.2 m - 1.85 m	Maximum 17 000 kg
Tridem Axle:	
Tridem Axle Spread 2.4 m - less than 3.0 m	Maximum 21 000 kg
Tridem Axle Spread 3.0 m - less than 3.6 m	Maximum 23 000 kg
Tridem Axle Spread 3.6 m to 3.7 m	Maximum 24 000 kg

Interaxle Spacings:

Single Axle - Tandem Axle	Minimum 3 m
Tandem Axle - Tandem Axle	Minimum 5 m
Tandem Axle - Tridem Axle	Minimum 5.5 m

Gross Vehicle Weight	Maximum 46 500 kg
----------------------	-------------------

Dimensions

Weights

MAXIMUM GROSS COMBINATION WEIGHTS

5 axles:	39 700 kg.
6 axles:	47 600 kg.
7 axles:	53 500 kg.
8 axles:	53 500 kg.

*Note: Second trailer limited to a maximum weight of 16 000 kg. or weight of lead trailer, whichever is lower.

Parameter

Limit

DIMENSIONS

Tractor:

Tractor wheelbase
Tandem Axle Spread
Interaxle Spacing

Maximum 6.2 m
Minimum 1.2 m/Maximum 1.85 m
Minimum 3 m

Lead Semitrailer:

Trailer wheelbase
Kingpin Setback
Tandem Axle Spread
Hitch Offset
Track Width

Minimum 6.5 m
Maximum 2.0 m radius
Minimum 1.2 m/Maximum 1.85 m
Maximum 1.8 m
Minimum 2.5 m/Maximum 2.6 m

Full Trailer or Second Semitrailer:

Trailer wheelbase
Tandem Axle Spread
Track Width

Minimum 6.5 m
Minimum 1.2 m/Maximum 1.85 m
Minimum 2.5 m/Maximum 2.6 m

Box Length

Maximum 18.5 m

Overall Length

Maximum 23 m

Overall Width

Maximum 2.6 m

Overall Height

Maximum 4.15 m

WEIGHTS

Axle Weights:

Steering Axle
Single Axle
Tandem Axle

Maximum 5500 kg
Maximum 9100 kg
Maximum 17 000 kg

Sum of Axle Weights of Full Trailer or
Second Semitrailer

Maximum 16 000 kg or the weight
of the lead trailer whichever
is less.

Interaxle Spacings:

Single Axle - Single Axle
Single Axle - Tandem Axle
Tandem Axle - Tandem Axle

Minimum 3 m
Minimum 3 m
Minimum 5 m

Gross Vehicle Weight

Maximum 53 500 kg

Dimensions

Weights

MAXIMUM GROSS COMBINATION WEIGHTS

5 axles:	40 700 kg.
6 axles:	48 600 kg.
7 axles:	56 500 kg.
8 axles:	62 500 kg.

Category 3: B Train Configuration Summary

Parameter	Limit
DIMENSIONS	
Tractor:	
wheelbase	Maximum 6.2 m
Tandem Spread	Minimum 1.2 m/Maximum 1.85 m
Interaxle Spacing	Minimum 3 m
First Semitrailer:	
wheelbase	Minimum 6.5 m
kingpin Setback	Maximum 2.0 m radius
Tandem Axle Spread	Minimum 1.2 m/Maximum 1.85 m
Tridem Axle Spread	Minimum 2.4 m/Maximum 3.0 m
Second Semitrailer:	
wheelbase	Minimum 6.25 m
Tandem Axle Spread	Minimum 1.2 m/Maximum 1.85 m
Distance from Front of Lead Trailer to Rear of Second Trailer	Maximum 20 m
Overall Length	Maximum 23 m
Overall Width	Maximum 2.6 m
Overall Height	Maximum 4.15 m
Track Width:	
Trailers	Minimum 2.5 m/Maximum 2.6 m
WEIGHTS	
Axle Loads:	
Steering Axle	Maximum 5500 kg
Single Axle	
(dual tires)	Maximum 9100 kg
Tandem Axle	Maximum 17 000 kg
Tridem Axle	
Spread 2.4 m to less than 3.0 m	Maximum 21 000 kg
Spread 3.0 m	Maximum 23 000 kg
Interaxle Spacings:	
Single - Single	Minimum 3 m
Single - Tandem	Minimum 3 m
Tandem - Tandem	Minimum 5 m
Tandem - Tridem	Minimum 5.5 m
Gross Combination Weight	Maximum 62 500 kg

Dimensions

Weights

MAXIMUM GROSS COMBINATION WEIGHTS

5 axles:	39 700 kg.
6 axles:	47 600 kg.
7 axles:	53 500 kg.
8 axles:	53 500 kg.

* Note: Second trailer limited to a maximum weight of 16 000 kg.
or weight of lead trailer, whichever is lower.

Category 4: C Train Double

Parameter	Limit
DIMENSIONS	
Tractor:	
Tractor wheelbase	Maximum 6.2 m
Tandem Axle Spacing	Minimum 1.2 m/Maximum 1.85 m
Interaxle Spacing	Minimum 3 m
First Semitrailer:	
Tractor wheelbase	Minimum 6.5 m
Kingpin Setback	Maximum 2.0 m radius
Tandem Axle Spread	Minimum 1.2 m/Maximum 1.85 m
Hitch Offset	Maximum 1.8 m
Track width	Minimum 2.5 m/Maximum 2.6 m
Second Semitrailer:	
Trailer wheelbase	Minimum 6.5 m
Tandem Axle Spread	Minimum 1.2 m/Maximum 1.85 m
Track width	Minimum 2.5 m/Maximum 2.6 m
Box Length	Maximum 18.5 m *
C-Dolly:	
Drawbar Length	Maximum 2.4 m
Overall Length	Maximum 23 m
Overall width	Maximum 2.6 m
Overall Height	Maximum 4.15 m
WEIGHTS	
Axle Weights:	
Steering Axle	Maximum 5500 kg
Single Axle	Maximum 9100 kg
Tandem Axle	Maximum 17 000 kg
Sum of Axle Weights of Second Semitrailer	Maximum 16 000 kg or the weight of the lead trailer, whichever is less *
Interaxle Spacings:	
Single Axle - Single Axle	Minimum 3 m
Single Axle - Tandem Axle	Minimum 3 m
Tandem Axle - Tandem Axle	Minimum 5 m
Gross Vehicle Weight:	Maximum 53 500 kg *
(*) Subject to review upon implementation of compliance standard for C Converter Dollies	

Appendix D

Technical Data and Details

1. Trucks

In order to simulate a realistic and practical truck, every effort was made to select the proper power-train combinations i.e. proper engine and transmission combinations, which are being practically sold through the dealer networks.

It was decided to use two typical Ford models for simulation purposes. Power-train combinations were obtained from a Ford dealer and the respective engine and transmission details from the *Fleet Owner's Directory*. Engine and transmission details for the simulation runs are already given in appendix B. Enclosed here are:

- 1) Commonly used power train combinations as given by Ford Motor Company for truck models *LTL-9000* and *LNT-8000*. *LTL-9000* is used for heavy (180 kg/kw and 210 kg/kw) truck modelling and *LNT-8000* is used for medium and lightly loaded trucks (60 kg/kw and 120 kg/kw).

These combinations have been ascertained after having personnel discussions with the truck dealers in the Ottawa-Hull Region. It is also recognised that depending upon the area of operation and type of commodity, choices might differ.

LTL - 9000

Engine (HP @ rpm)	Transmission	Axle Ratio
270 @ 2100	RTX-11613	4.10
300 @ 2100	RTX-11609B	4.30
300 @ 2100	RTX-11609B	3.91
310 @ 1800	RTX-11609B	4.30
310 @ 1800	RTX-11609B	3.91
365 @ 1800	RTX-14613	3.91
400 @ 1800	RTO-14613	4.30
400 @ 1800	RTO-14613	3.91
425 @ 2100	RTO-14715	4.30
425 @ 2100	RTO-14715	3.91
425 @ 2100	RTO-14715	3.91

LTN - 8000

Engine (HP @ rpm)	Transmission	Axle Ratio
210 @ 2400	RT-6613	4.30
240 @ 2400	RT-6613	4.88
240 @ 2400	RT-6613	4.30
240 @ 2400	FS-6106	3.91
270 @ 2400	RT-7608LL	4.88
270 @ 2400	RT-7608LL	4.30

These transmissions have a code representation given by each gear manufacturer. Basically the last two digits in the code give the number of gear ratios available, third digit from the last gives the design level and the rest one or two digits ($\times 100$) in the beginning give the torque handling capacity of the transmission box, in lb-ft.

The power train combinations given by these were mostly followed. Only exceptions are, where it was not possible to get exact engine characteristics. In such cases engine characteristics curves were used having the same horsepower, but marginally different *rpm* value at peak power rating.

Other vehicle details and dimensions were also checked with the company brochures acquired from the dealers and manufacturers.

2. Recreational Vehicles

In the case of recreational vehicles, it was found that a typical combination which poses problems on highways is a normal sedan car, towing travel trailers or boat trailers, etc.

The dealers and manufacturers contacted were Ford Motors, Hyundai, General Motors, Mazda Canada, Chrysler Canada, Volvo Canada and Honda Canada Ltd.

Out of the information received from these sources and supplementing it with recreational vehicle dealers in the Ottawa region, the Hyundai Sonata model was considered for the recreational vehicle simulation.

- Details of 'Hyundai Sonata' engine and transmission are already included in appendix B.

Appendix E

Truck Power, Weight and Dimension Questionnaire

To have current and first-hand information from the truckers, a detailed questionnaire was sent out to several trucking companies (truck operators) within Ontario. The information collected from these is contained in Tables 4.1 and 4.2 and Figures 4.1 and 4.2.

A sample of the questionnaire used is enclosed. Also enclosed in the questionnaire (Part C) were the details of different truck configurations as per appendix C, for the operators to identify the truck types being used.

Questionnaire

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Part A:

Fleet characteristics data are essential for our research. Please complete the following tables for your existing and future (planned) fleet.

Gross weight (Kg.)	No. of axles	Vehicles in your fleet		Installed Horsepower HP	General Comment
		Number	Percent		

(a) Existing Fleet

63,000	> 8				
58,000	7 or 8				
53,500	7 or 8				
52,500	6				
46,500	6				
43,500	5				
42,000	5				
39,000	5				
Light Weight	< 5				
Other					

(b) Future Planned Fleet

63,000	> 8				
58,000	7 or 8				
53,500	7 or 8				
52,500	6				
46,500	6				
43,500	5				
42,000	5				
39,000	5				
Light Weight	< 5				
Other					

Please complete the following questions for your typical runs (if applicable). This information will help us to study the extent of "cube-out" and "weight-out" experience.

For typical LTL runs:

% of cubic capacity used -----. % of permitted "gross weight" used -----.

For typical TL runs:

% of cubic capacity used -----. % of permitted "gross weight" used -----.

For "other" operations: (please specify) -----

% of cubic capacity used -----. % of permitted "gross weight" used -----.

Part B:

Information requested here will enable us to simulate vehicle speed performance under different highway geometric conditions (e.g., grades).

For your typical vehicles, please provide as much information as is convenient.

Tractor:

Model name ----- Model No. ----- Series -----

Engine:

Model name ----- Model No. ----- Series -----

Number of cylinders ----- Displacement -----cubic inch

Rated horsepower -----bhp at -----rpm.

Maximum torque -----lb.ft. at -----rpm.

Transmission:

Model name ----- Model No. ----- Series -----

Type: Automatic ---- or Manual -----

If automatic, maximum torque ratio:

Gear ratio	High	Low	Gear ratio	High	Low
1			6		
2			7		
3			8		
4			9		
5			10		

Drive Axle:

Model name ----- Model No. ----- Series -----

Type: Single reduction ----- or Double reduction -----

Gear reduction ratio -----

Tire:

Make: ----- Size ----- Inflation pressure -----psi

Aerodynamic Enhancement Device:

Device on tractor: Model name ----- Model No. ----- Series -----

Device on trailer: Model name ----- Model No. ----- Series -----

Part C:

Please complete for your typical vehicles only. This information is required for the study of aerodynamic, rolling and grade resistances on trucks and combination vehicles. Your answers can be shown on the attached sheets. For vehicle types that are not covered by the attached sheets, please add drawings/sketches and notes, if convenient.

In case you are not able to complete Part C, we will be grateful to receive this questionnaire with answers to other questions (i.e., Parts A and B) noted.

(Part C is the same as pages 241-248 of appendix C.)

END

1 9/0 2/9 1

FIN