Expected Performance of Longer Combination Vehicles on Highway Grades

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ABSTRACT

Sections 138 and 415 of the Surface Transportation Assistance Act (STAA) of 1982 require the FHWA to report to Congress on the benefits and costs of a national intercity truck route network for the safe and efficient operation of longer combination vehicles (LCVs) such as the double 48-ft and the triple 28-ft combinations. The current (1984) AASHTO criteria for determining critical lengths of grades and climbing lane design for the safe and efficient operation of existing heavy (3-S2) five-axle trucks assume a gross vehicle weight-to-net horsepower (GVW/NHP) ratio of 300 lb/hp to be "representative." The objective of this paper was to investigate the expected performance of LCVs on highway grades and possible impacts on the current AASHTO design criteria. The analysis involved the application of a modified simulation model (used by earlier studies for regular five-axle trucks) under alternative hypotheses about GVW/NHP ratios, rolling resistances, and aerodynamic drag for LCVs operating on different percentage upgrades (1-9 percent grade). The research also included a limited collection of data on GVW and NHP values of actual LCVs. It was found that for LCVs, a GVW/NHP ratio between 300 and 400 would be considered normal, and a ratio above 400 could, occasionally, be observed. It was also found that critical lengths of grades up to 6 percent could be significantly less than AASHTO-recommended values depending on the percentage grade and the LCV's characteristics such as GVW/NHP ratio, rolling resistance, and aerodynamic drag. The expected difference in critical lengths could be as large as 1,060 ft on a 2 percent grade; that is, 44 percent less than the AASHTO-recommended value of 2,400 ft. In order to make specific recommendations with respect to changes in current AASHTO design criteria, actual field data for the operation of LCVs on grades have to be collected and analyzed.

Among the numerous items introduced in the Surface Transportation Assistance Act (STAA) of 1982 is the concept of the longer combination vehicle (LCV) such as the double 48-ft and the triple 28-ft truck combinations. With an overall length of 120 ft, an effective width of 102 in., and maximum axle weight of 20 kips for a single axle and 34 kips for a tandem axle, the gross vehicle weight (GVW) of these LCVs can reach approximately 130,000 lb. Although the STAA cited an upper overall length of 110 ft, fundamental considerations of configuring LCVs identified the length of 120 ft as more appropriate for these units. The current criteria for determining the critical length of grades and for providing climbing lanes, suggested in the recent (1984) AASHTO green book on geometric design policy (1), assume a weight-to-horsepower ratio of a typical 3-S2 heavy truck to be approximately 300 lb/hp. Operational tests conducted by the California Department of Transportation (Caltrans) in 1984 (2) indicate that LCVs are generally slower than are other typical heavy trucks, particularly when the weight-to-horsepower ratios are greater than 350 lb/hp.

The purpose of this paper is to gain more insight into the performance characteristics of LCVs on grades. With this understanding, the objective is then to assess the impacts that the operation of LCVs on grades might have on the current design criteria for determining the critical length of grades and for the provision of climbing lanes.

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To achieve this objective, the factors that may influence performance of vehicles on grades were reviewed, and those factors that could be relatively more important for LCVs were highlighted. This is the subject of the second section. In the third section the issue of the prediction of LCV performance on grades is addressed. This involves a discussion of existing approaches, the selection of a particular approach for the study, a detailed description of the selected approach, and the actual application of the method to LCVs. In the fourth section the focus is on the analysis of results for LCVs compared with current AASHTO criteria for the critical length of grade and climbing lane design. The fifth section includes a summary and conclusions.

FACTORS THAT INFLUENCE VEHICULAR PERFORMANCE ON GRADES

Most of the material in this section is extracted and summarized from Walton and Lee (3).

The ability of any vehicle combination to overcome any given grade is directly related to the resultant effect of two principal types of forces. These are the tractive effort forces (i.e., the pulling forces generated through the power train of the vehicle and delivered to the drive wheels) and the tractive resistance forces (i.e., the resisting forces due to inertia, internal vehicle friction, rolling, wind, grade, curvature, etc.). Each of these forces is a function of several factors related to one or more of the four principal components of the transport system. These four components are the vehicle, the roadway, the driver, and the environment. A brief description of the major influencing factors related to each of these four components follows. The factors that are expected to be relatively more influential in the case of LCVs will be highlighted.

Factors Related to the Vehicle

The vehicle is probably the most important component that may influence performance on grades. Vehicular characteristics that are most likely to affect performance are the gross vehicle weight (GVW), the power train characteristics, and the physical dimensions of the vehicle.

The GVW is no doubt a major factor. As the GVW increases, the rolling, inertial, and grade resistances increase, leading to excessive reductions of speed on grades.

The power train characteristics of the vehicle are also of prime importance. It is the weight-to-horsepower ratio that is considered to be a determining factor as far as the vehicle's performance on grades is concerned.

The physical dimensions of the vehicle that may influence its performance are side area, shape, frontal area, and number and configuration of axles. These features affect the magnitude of air resistance on the vehicle. In addition, the number and configuration of axles may affect the vehicle's inherent resistance. The influence of these features on the vehicle's performance is generally considered to be less significant than is the GVW/NHP ratio. However, in the case of LCVs, these features are expected to play, relatively, a greater role in determining the climbing capability of these particular vehicle types.

Factors Related to the Roadway

The roadway is no doubt an element that has a major influence on the vehicle's performance. The main roadway features of influence are length and steepness of grade, cross-sectional profile, horizontal alignment, and pavement type and condition.

The length and steepness of grade are the most significant factors related to the roadway. The vehicle's deceleration rate is directly dependent on the steepness of grade and the total speed reduction is primarily dependent on the length of grade.

The main cross-sectional variables are the number of lanes, the width of lanes, and the type and width of shoulders. These factors can affect the entry speed at the beginning of a grade, which is a major influencing factor on a vehicle's performance on grades. Significant variability in any of these features along the grade itself can have important effects on the vehicle's performance.

Pavement type and condition can influence operating speed and rolling resistance and, consequently, the vehicle's performance.

Factors Related to the Driver

The performance capabilities of and the ultimate speed at which a heavy vehicle can overcome a grade are, in many ways, dependent on the ability of the driver to coax the maximum pulling force from the vehicle. The training, experience, familiarity with the vehicle, and physical abilities of the driver are the main characteristics related to the driver that are most likely to affect the vehicle's performance.

Factors Related to the Environment

The major environmental factors that can influence the vehicle's performance are atmospheric conditions, traffic conditions, and land use along the roadway.

Atmospheric disturbances such as strong winds, heavy rain, dense fog, high humidity, high or low temperatures, and different altitudes will tend to adversely affect the capability of the driver and the vehicle to operate efficiently on grades. The driver will naturally tend to travel at reduced speeds and the vehicle's engine output will also tend to be reduced.

Heavy traffic volumes, high percentages of trucks and buses, and wide variability of speeds in a traffic stream will certainly have a significant detrimental effect on the performance of vehicles on grades.

As the density of abutting land use increases, the likelihood of interference caused by merging traffic attributable to adjacent activities increases. The natural reaction of the driver in these situations is to be more cautious and to reduce speed.

The relative contribution of each of these factors related to the vehicle, the roadway, the driver, and the environment can be assessed through modeling the interactions among these factors in order to predict the vehicle's performance on grades and performing sensitivity analysis for each factor in the prediction model.

The discussion in the next section should provide more insight into this issue.

PREDICTION OF PERFORMANCE OF LCVs ON GRADES

There are three major approaches to predicting the performance of vehicles on grades. These are actual field testing, econometrics modeling, and simulation modeling.

Actual field testing is no doubt the most satisfactory procedure, but it is rather laborious and expensive to conduct. In addition, the results are applicable only for the given conditions of the tests.

The econometrics modeling approach involves collecting data on actual vehicle performance, vehicle characteristics, the driver, the roadway, and the environment. These data are then used to calibrate an econometric model that relates all relevant factors to the vehicle's performance. This econometric model is then used for prediction. This approach has been used by Walton and Lee (3). They collected an extensive amount of data to study the speeds of commercial as well as recreational vehicles and developed multiple regression models for different vehicle types and sites considered in the analysis. The longest truck combination included in their analysis was the 3-S2 truck (i.e., three-axle tractor and two-axle semitrailer-truck combination). A total of 10 factors were used in their analysis. These are length of grade, percentage grade, approach speed, gross vehicle weight, vehicle horsepower, frontal area, side area, driver experience, age of driver, and age of vehicle. The roadway and environmental conditions were recorded and controlled through the selection of the test sites and times.

The major advantage of this approach is that it allows the prediction of vehicle performance for values of the variables that are different from those observed. It also allows an investigation of the relative importance of each factor. On the other hand, the results, generally, are applicable only within a certain range of values and under environmental and roadway conditions that are more or less similar to (or at least not significantly different from) those observed. For example, the GVW and the side area of LCVs will certainly be significantly greater than those used by Walton and Lee (3), and, hence, their regression model may not produce sufficiently accurate predictions for LCVs. Nevertheless, the econometrics modeling approach remains a viable alternative.

The third major method for predicting performance of vehicles on grades (i.e., the simulation modeling approach) has been used by SAE (4), St. John and Kobett (5) of the Midwest Research Institute (referred to later as the MRI study), and Abbas and May (6) of the Institute of Transportation Studies at Berkeley (referred to later as the ITS study). The simulation approach focuses on the truck's engine characteristics and decelerations (because of gravity) during gear shifts. It gives explicit consideration to gear shift delays, rolling losses, chassis losses, and aerodynamic losses. The basic assumption of the model is that the engine is employed a varying fraction of the total time.

The simulation method has the advantage of capturing the vehicle's related factors in detail. Aspects of the driver's behavior are taken into consideration in "gear shift delay."

On the other hand, it is not clear how the "other" factors could be considered in the approach. Both the MRI and ITS studies have introduced modifications to the coefficient values of the SAE (4) model in order to validate the model's results with field data. The behavioral implications of these modifications are not apparent.

In this study it would have been desirable to use all three approaches in order to gain the advantages associated with each. However, because of the lack of sufficient field data on the actual performance of LCVs on grades, the approach that relies the least on field data or that is more behaviorally oriented, or both, was selected.

It is clear from the discussion of different approaches that all three methods involve the use of field data. In the econometric approach, field data were used in the calibration of the regression model, and in the simulation model the field data were used in the adjustment of SAE-recommended values of coefficients related to rolling force and aerodynamic drag.

It is not quite clear whether the difference between "calibration" and "adjustment of coefficients" is significant or not. Nevertheless, it may be argued that adjustments in the simulation model's coefficients can be achieved through a deeper understanding of the behavioral implications of the impacts of changes in the vehicle's characteristics on the rolling, chassis friction, and aerodynamic drag forces. In this case the role of field data in the use of the simulation model could be reduced significantly.

As far as the behavioral orientation of different approaches is concerned, it is obvious that the simulation model has a definite advantage. Therefore, in this study, the simulation approach has been selected. A detailed description of the approach is given followed by a discussion of the appropriate values for the model's input variables and parameters for its application to predict LCV performance on grades.

Simulation Model

The model consists of a set of performance equations that depict the capability of the truck along a straight section of roadway with a given gradient under free-flow conditions. The model focuses on the truck's engine characteristics and decelerations during gear shifts. It gives explicit consideration to gear shift delays, GVW/NHP ratios, rolling resistances, chassis friction, and aerodynamic losses. The basic assumption of the model is that the engine is employed a varying fraction of the total time.

The basic performance equation in the model calculates the vehicle's effective acceleration at a given vehicle speed taking into account the acceleration in coasting during gear shift delay. This equation may be expressed as

$$A_e = \bar{A}_p\{(\eta \cdot V)/[\eta V + S_p t_s(\bar{A}_p - \bar{A}_c)]\},\ V > V_1 \qquad (1)$$

where

- A_e = effective acceleration (ft/sec²);
- $\bar{A}_p$ = power-limited acceleration (i.e., with engine employed and vehicle at speed V); the bar indicates the use of average available net horsepower (ft/sec²);
- η = parameter dependent on the range of engine speed normally employed; typical values range between 0.33 and 0.43;
- V = vehicle speed (ft/sec);
- S_p = one times the sign of $\bar{A}_p$ (i.e., +1 or −1);
- t_s = gear shift delay (sec);
- $\bar{A}_c$ = acceleration in coasting at a vehicle speed V; the bar indicates the use of average gear ratio (ft/sec²); and
- V_1 = maximum speed in lowest speed gear ratio (ft/sec).

In Equation 1, the speed parameter (η) is defined as the ratio between maximum and minimum engine speeds in the operating range minus one. Its typical values vary between 0.33 and 0.43. A value of 0.4 was recommended and used by the MRI study. When the truck speed is less than V_1, the transmission will be in the first gear ratio. In this case the term ηV in Equation 1 is replaced by V_1.

The gear shift delay (t_s) is an important variable in the model. Its value is dependent on the driver's experience and physical condition. A value of t_s = 1.5 sec was used by SAE, MRI, and ITS.

The other two major variables in Equation 1 are the power-limited acceleration and the acceleration in coasting.

The power-limited acceleration is dependent on the GVW/NHP ratio, rolling resistances, aerodynamic drag, chassis friction losses, and highway grade. These factors, except for the gradient, are essentially related to the vehicle's characteristics including its engine, shape, weight, and physical dimensions, and their effects on the vehicle's performance will vary according to several environmental conditions such as temperature and elevation. The performance equation that gives explicit account of these factors may be expressed as

$$\begin{aligned} A_p = {} & C_{pe}\, C_1/[(GVW/NHP_s)\ (1 + C_e)] \\ & - [(C_2 + C_3V)/(1 + C_e)] \\ & - \{C_{de}\, C_4V^2/[(GVW/A)\ (1 + C_e)]\} \\ & - \{C_5R_i/[(GVW/GVW_r)\ (1 + C_e)]\} \\ & - [\underline{g}(\sin \alpha)/(1 + C_e)] \end{aligned} \qquad (2)$$

where

- A_p = power-limited acceleration (ft/sec²);
- GVW = gross vehicle weight (lb);
- NHP_s = net horsepower at sea level (hp);
- V = vehicle speed (ft/sec);
- GVW_r = rated maximum gross vehicle weight (lb);
- R_i = speed ratio (engine speed/vehicle speed) in the ith gear ratio [rmp/(ft/sec)];

A = projected frontal area (ft^2);
α = grade angle (positive for upgrade);
$\sin \alpha$ = percentage grade/100;
g = acceleration due to gravity (32.17 ft/sec^2);
C_{pe} = altitude correction factor converting sea level net horsepower to local elevation, E (ft);
= 1 = 0.00004E (for gasoline engines);
C_{de} = altitude correction factor converting sea level aerodynamic drag to local elevation, E (ft)
= (1 - 0.000006887E) **4.255; and
C_e = correction factor for engine inertia
= 14080/[(GVW/NHP) *V²].

C_1, C_2, C_3, C_4, and C_5 are coefficients reflecting the influence of different factors on the performance of the vehicle.

Acceleration in coasting (i.e., when the engine is not employed during gear shifts) is mainly influenced by rolling resistances, aerodynamic drag, and grade. In addition, chassis friction losses may be assumed to be 15 percent of the full-power value. The performance equation in coasting is, therefore, given by

$$A_c = -C_2 - C_3V - [C_{de}C_4V^2/(GVW/A)] - [(0.15)\ C_5R/(GVW/GVW_r)] - g \sin \alpha \quad (3)$$

where A_c is acceleration in coasting (ft/sec^2). To apply performance Equations 1-3 to LCVs, appropriate values for the input variables to the model, correction factors, and model coefficients have to be specified. This issue is addressed in the next subsection.

Application of the Simulation Model to LCVs

It is apparent that the results of the simulation model are quite sensitive to the values of its input variables and parameters. The input variables to the model are gear shift delay, gross vehicle weight, net horsepower, vehicle engine speed, frontal area, entry vehicle speed, and highway grade.

The gear shift delay is no doubt an important variable in the model. However, its value is not expected to be significantly different from 1.5 sec. (i.e., the value used in previous studies) in the case of LCVs because this value is related to driver characteristics, which should be more or less similar for professional truck drivers.

The GVW and NHP values of LCVs are expected to be significantly different from those of regular five-axle truck combinations. Table 1 gives typical gross weights and horsepowers of different LCV types [i.e., Rocky-Mountain doubles (RMD), turnpile doubles (TD), and turnpike triples (TT)]. From this table it is obvious that practical maximum GVW is consistently greater than 100,000 lb up to 138,000 lb. The GVW/NHP ratio could exceed 400. A ratio between 300 and 400 would be considered normal. In this analysis GVW/NHP ratios of 300, 350, and 400 were considered. It was assumed that a ratio of 300 corresponds to NHP = 315 hp and GVW = 94,500 lb, a ratio of 350 corresponds to NHP = 315 hp and GVW = 110,250 lb, and a ratio of 400 corresponds to NHP = 330 hp and GVW = 132,000 lb.

The vehicle engine speed varies with the vehicle speed in any given gear ratio. In this analysis a value of 2,000 rpm was used, which should represent an average operating engine speed (2).

The projected frontal area of a vehicle is the maximum cross-sectional area perpendicular to its direction of motion. In the case of LCVs this value was assumed to be 114 ft^2 based on a truck height of 13.5 ft and a width of 8.5 ft.

Entry vehicle speed was assumed to be 55 mph (i.e., the maximum allowable speed on freeways). The highway grade was assumed to vary between +1 and +9 percent. This should include all upgrades that may be encountered in practice. Increments of 1 percent grade are considered. Downgrades were not considered simply because the objective is related to climbing lane design criteria. The model parameters include correction factors and coefficients.

There are three correction factors in the model related to engine characteristics: two for converting sea level net horsepower and aerodynamic drag to local elevation and a third for engine inertia. These factors should not have significant effects on the model's results, particularly when it is assumed that a reasonable value of local elevation would be 1,000 ft above sea level. Therefore the formulas of the MRI study are used in the analysis.

The simulation model includes six different coefficients. These are η, C_1, C_2, C_3, C_4, and C_5 (see Equations 1-3).

The speed parameter (η) is dependent on the operating range of engine speeds in different gear ratios. Its value, as indicated earlier, varies between 0.33 and 0.43. An average value of 0.4 was used in the MRI study. In this study 0.4 was assumed to be a reasonable value to use.

The coefficients C_1, C_2, C_3, C_4, and C_5 account, respectively, for the influence of weight-to-horsepower ratio, speed-independent rolling losses, speed-dependent rolling losses, aerodynamic drag, and chassis friction losses. It should be clear that the values of these coefficients used in previous studies were validated with actual data for the performance of regular truck combinations. Indeed, the MRI study introduced significant modifications to C_3 and C_4 compared with SAE-recommended values so that the model's results may be closer to actual performance data. More specifically, C_3 was reduced to 22 percent of its SAE-recommended value (i.e., reduced from 1.982×10^{-3} to 0.44×10^{-3}) and C_4 was

TABLE 1 Typical GVW and NHP Values for LCVs

Source	LCV Type	Rated hp	NHP	Practical Maximum GVW (lb)	GVW/NHP (ratio)
Roadway (carrier)	RMD				
	TD	365	328.5	138,000	420
	TT	365	328.5	105,000	320
Western Highway Institute	RMD	350	315	100,000	317
	TD	440	396	125,000	316
	TT	350	315	106,000	337
Caltrans	RMD		304/340	107,000	314/351
	TD		340/480	123,000	360/256
	TT		304/340	111,000	365/326
Ryder/PIE (carrier)		350	315	120,000	380

reduced to 72 percent of its SAE-recommended value (i.e., reduced from 0.0317 to 0.0228). What the values of these and other coefficients for LCVs should be is an issue that is yet to be investigated through actual field experimentation with LCVs. Such an investigation is, however, beyond the scope of this paper. Therefore, "reasonable" values of coefficients for LCVs were hypothesized and a sensitivity analysis of the model's predictions under alternative hypotheses was performed.

As obvious as it may be, the model's coefficients for LCVs are expected to be generally different from those recommended by SAE (4) as well as those modified by MRI and ITS. In particular, the coefficients for rolling resistances and aerodynamic drag are expected to increase in order to reflect an increase in these losses for LCVs due to their increased number of tires and axles, additional weight, larger side areas, and increased number of combinations [see Knight (7) for a more detailed discussion of the effects of these factors for rolling and aerodynamic losses.] It was assumed that C_3 (the speed-dependent coefficient for rolling resistances) could be as high as 0.003 compared with the 1965 SAE-recommended value of 0.001982 and the MRI modified value of 0.00044. As far as the aerodynamic drag coefficient (C_4) is concerned, it was assumed that it could reach 0.04 compared with the SAE value of 0.0317 and the MRI modified value of 0.0228. The speed-independent rolling losses coefficient (C_2) was assumed to remain unchanged. The remaining coefficients (C_1 and C_5 for GVW/NHP ratio and chassis friction losses) were also assumed to be unchanged. This assumption of unchanged coefficients reflects the hypothesis that the differences between their values for LCVs and their corresponding current values in the model are expected to be relatively less significant compared with the expected differences in C_3 and C_4. The best way to verify this hypothesis is to perform actual field tests. As indicated earlier, this is not within the scope of this paper. Nevertheless, for the purpose of analysis, the hypothesis appears to be appropriate.

Table 2 gives a summary of all assumptions related to the application of the simulation model to predict performance of LCVs. The results of the application are presented and analyzed in the following section.

ANALYSIS OF RESULTS

The main objective of the analysis is to investigate the possible impacts that the operation of LCVs on grades might have on the current AASHTO criteria for determining critical length of grades and climbing lane design under alternative assumptions for rolling losses, aerodynamic drag, GVW/NHP ratio, and percentage grade.

The recent edition of the AASHTO green book (1) considers three main criteria; these are speed at entrance of grade, allowable speed reduction along the grade, and vehicle gradability. The average running speed is assumed to approximate the entry speed (e.g., a speed of 55 mph on major freeways). Allowable total reduction in speed is assumed to be 10 mph. This value is recommended primarily for safety reasons. In the 1965 AASHTO policy a 15-mph speed reduction was considered allowable, but studies in 1970 indicated that accidents involving trucks with four or more axles were 2.4 times greater for a 15-mph reduction than for a 10-mph reduction (8). The truck gradability criterion is stated as follows: "A loaded truck, powered so that GVW/NHP ratio is about 300, is representative of the size and type of vehicle normally used for design control on main highways." The relationship among speed reduction, percentage grade, and length of grade for an assumed typical heavy truck of 300 lb/hp is shown in Figure 1 (1, Figure III-30).

The four major variables of analysis are the GVW/NHP ratio (300, 350, and 400); rolling losses coefficient (C_3) (0.00044, 0.001, 0.001982, and 0.003); aerodynamic drag coefficient (C_4) (0.0228, 0.0317, and 0.04); and percentage grade (1, 2, 3, 4, 5, 6, 7, 8, and 9). The remaining variables and parameters in the simulation model are set at their appropriate values as explained in the third section and summarized in Table 2. Therefore the analysis involves 3 x 4 x 3 x 9 = 324 simulation runs. The results are summarized in the Appendix. The tables and figures of this section are essentially extracted from the raw data in the Appendix as needed for analysis. A detailed analysis of the major issues under consideration follows.

Impacts of No Change in Coefficients of Both Rolling and Aerodynamic Losses

In this case it was assumed that coefficients of both rolling and aerodynamic losses for an LCV are identical with those for a regular five-axle truck. This situation corresponds to the use of MRI modified values of C_3 and C_4. That is, $C_3 = 0.00044$ and $C_4 = 0.0228$. The results [referred to later as CTR

TABLE 2 Summary of Assumed Values of the Variables and Parameters of the Simulation Model for Application to LCVs

Variables and Parameters	Assumed Values in the Application
GVW (lb)	94,500, 110,250, and 132,000
NHP (hp)	315 and 330
GVW/NHP ratio (lb/hp)	300, 350, and 400
Entry speed (mph)	55
Percentage grade (%)	1, 2, 3, 4, 5, 6, 7, 8, and 9
Rated GVW (lb)	120,000
Vehicle frontal area (ft^2)	114
Gear shift delay (sec)	1.5
Average elevation E (ft)	1,000
Acceptable total speed reduction (mph)	10
Engine speed parameter (η)	0.4
GVW/NHP ratio coefficient (C_1)	17,693.5
Speed-independent rolling losses coefficient (C_2)	0.2445
Speed-dependent rolling losses coefficient (C_3)	0.00044, 0.001, 0.001982, and 0.003
Aerodynamic drag coefficient (C_4)	0.0228, 0.0317, and 0.04
Chassis friction losses coefficient (C_5)	0.0035387
Acceleration due to gravity (ft/sec^2)	32.2
NHP correction factor for elevation (C_{pe})	1 - 0.00004E
Aerodynamic correction factor for elevation (C_{de})	(1 - 0.000006887E) **4.255
Engine inertia correction factor (C_e)	14,080/[(GVW/NHP) *V^2]

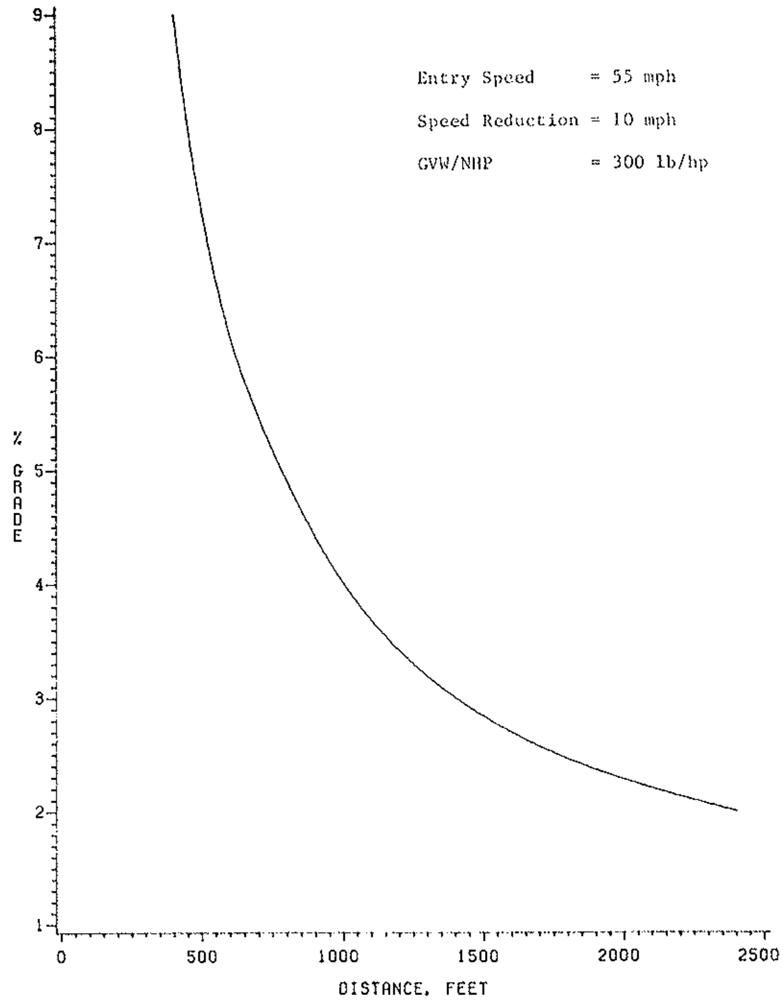

FIGURE 1 AASHTO critical lengths of grade for design assuming typical heavy truck of GVW/NHP = 300.

(i.e., Center for Transportation Research at the University of Texas at Austin)] in this case are expected to be similar to those of MRI but not identical because of differences in GVW, rated GVW, frontal area, and NHP. For the same GVW/NHP ratio, differences between CTR and MRI should be minor, and, hence, CTR results are more or less representative of regular five-axle trucks. This implies that what is essentially investigated are the impacts of differing GVW/NHP ratios on truck gradability compared with AASHTO recommendations at various percentage grades.

Table 3 gives and Figure 2 shows a comparison of critical lengths of grade between CTR and AASHTO under the preceding assumptions for different GVW/NHP ratios and percentage grades. For a GVW/NHP = 300, CTR and AASHTO values are almost identical for grades of 4 percent and greater. This confirms the earlier expectation that CTR results in this case may be representative of regular five-axle trucks. For 3 and 2 percent grades, however, CTR values are greater than AASHTO values by about 3.9 and 10 percent, respectively. This slight overestimation of gradability on lower grades could be related to the higher NHP value used in CTR compared with that of regular trucks. This can be explained by noting that the vehicle's power characteristics become predominant on lower grades because the effects of percentage grade and GVW are decreased. This implies that CTR results are conservative with respect to AASHTO-recommended values. This should, in general, strengthen the analysis and conclusions.

Looking at Table 3 and Figure 2, it is observed that as the GVW/NHP ratio and the percentage grade increase the critical lengths of grade decrease as expected. More important, the differences between CTR and corresponding AASHTO values vary (both in absolute terms and percentage-wise) according to a general trend depending on the GVW/NHP ratio and percentage grade. In general, the range of differences (absolute values and percentages) becomes wider as the percentage grade decreases and becomes narrower as the GVW/NHP increases. In other words, more variability in the results is expected on lower percentage grades and for GVW/NHP ratios closer to 300. The actual difference (in absolute terms and percentage-wise) of course increases as the GVW/NHP ratio gets further from 300 and as the percentage grade decreases. For a 2 percent grade, the critical length of grade could be less than the AASHTO value by as much as 375 ft (for GVW/NHP = 400); that is, a reduction of 16 percent from 2,400 ft. This is a significant difference. For GVW/NHP = 350, the difference could be 174 ft (i.e., a 7.3 percent reduction), which is still considered significant. At GVW/NHP = 300, the CTR value is +247 ft more than the AASHTO value (i.e., a 10 percent increase). This indicates that the difference between CTR and AASHTO values on a 2 percent grade have changed considerably from +247 to -174 ft as GVW/NHP changed from 300 to

TABLE 3 Comparison of Critical Lengths of Grade (ft) Between AASHTO and CRT Assuming No Change in Aerodynamic and Rolling Losses Coefficients (C_3 and C_4), Entry Speed = 55 mph, and Speed Reduction = 10 mph

		CTR Minimum Difference			CTR Average Difference			CTR Maximum Difference				
		GVW/NHP = 300 C_3 = 0.00044 C_4 = 0.0228 (ft)	Difference		GVW/NHP = 350 C_3 = 0.00044 C_4 = 0.0228 (ft)	Difference		GVW/NHP = 400 C_3 = 0.00044 C_4 = 0.0228 (ft)	Difference		Expected Difference Range (ft)	Expected Difference Range (%)
Grade (%)	AASHTO (ft)		Feet	Percentage		Feet	Percentage		Feet	Percentage		
1		18,000+			7,712			5,472				
2	2,400	2,647	+247	+10	2,226	-174	-7.3	2,025	-375	-15.6	+247 to -375	+10 to -16
3	1,400	1,455	+55	3.9	1,321	-79	-5.6	1,252	-148	-10.6	+55 to -148	+4 to -11
4	1,000	1,006	+6	+0.6	941	-59	-5.9	909	-91	-9.1	+6 to -91	+1 to -9
5	780	769	-11	-1.4	733	-47	-6	711	-69	-8.8	-11 to -69	-1 to -9
6	620	623	+3	+0.5	601	-19	-3	586	-34	-5.5	+3 to -34	+1 to -6
7	520	524	+4	+0.8	506	-14	-2.7	498	-22	-4	+4 to -22	+1 to -4
8	450	451	+1	+0.2	440	-10	-2.2	433	-17	-3.8	+1 to -17	+0 to -4
9	400	399	-1	-0.2	388	-12	-3	385	-15	-3.7	-1 to -15	-0 to -4

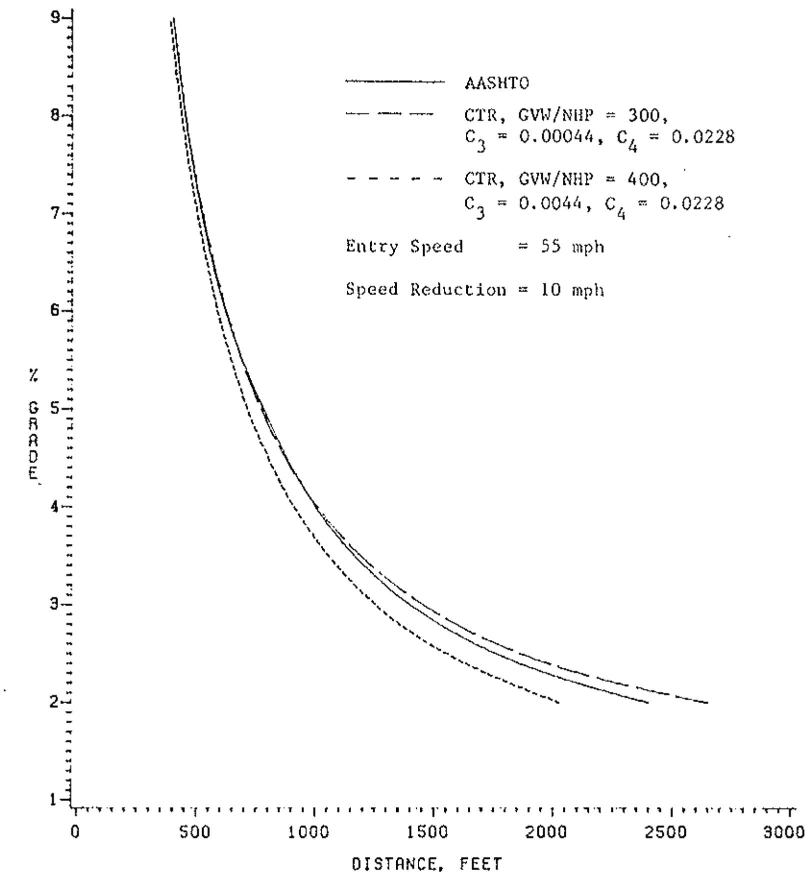

FIGURE 2 Comparison of AASHTO and CTR critical lengths of grade assuming no change in either rolling or aerodynamic losses coefficients.

350 and continued to change, but at a reduced rate, from -174 to -375 ft as GVW/NHP changed from 350 to 400, respectively. The same trend can be observed for other percentage grades as well, but the differences become less significant as the percentage grade increases.

For a 1 percent grade the variability and differences (in absolute values and percentage-wise) are expected to be extremely large. If it is assumed that the AASHTO value for a 1 percent grade is not less than 10,000 ft, it is seen that the difference could be as large as -4,528 ft. This could represent serious problems if the grade actually extended for a few miles. In practice, however, this could be a rare event.

Probably the most important conclusion to be drawn from Table 3 and Figure 2 is that even if it is assumed that LCVs would have the same aerodynamic and rolling losses coefficients as those of regular five-axle trucks, their GVW/NHP ratios, which may normally vary between 300 and 400, could result in significant reductions of critical lengths of grades compared with AASHTO design criteria. These reductions could reach 16 percent (375 ft) on a 2 percent grade, 11 percent (148 ft) on a 3 percent grade, and 9 percent (191 ft) on a 4 percent grade.

Impacts of the Increase in Coefficient of Aerodynamic Drag (C_4) Only

It was assumed that the rolling losses coefficient is unchanged (C_3 = 0.00044) while the aerodynamic

TABLE 4 Comparison of Critical Lengths of Grade (ft) Between AASHTO and CTR Assuming an Increase in Aerodynamic Drag Coefficient (C_4) Only, Entry Speed = 55 mph, and Speed Reduction = 10 mph

		CTR Minimum Difference			CTR Average Difference			CTR Maximum Difference				
Grade (%)	AASHTO (ft)	GVW/NHP = 300 C_3 = 0.00044 C_4 = 0.0317 (ft)	Difference Feet	Difference Percentage	GVW/NHP = 350 C_3 = 0.00044 C_4 = 0.0317 (ft)	Difference Feet	Difference Percentage	GVW/NHP = 400 C_3 = 0.00044 C_4 = 0.04 (ft)	Difference Feet	Difference Percentage	Expected Difference Range (ft)	Expected Difference Range (%)
1		11,697			5,604			3,888				
2	2,400	2,320	-80	-3.3	2,022	-378	-15.7	1,765	-635	-26.5	-80 to -635	-3 to -27
3	1,400	1,349	-51	-3.6	1,247	-153	-11	1,146	-254	-18	-51 to -254	-4 to -18
4	1,000	955	-45	-4.5	904	-96	-9.6	850	-150	-15	-45 to -150	-5 to -15
5	780	714	-40	-5	707	-73	-9.4	674	-106	-13.6	-40 to -106	-5 to -14
6	620	604	-16	-2.6	583	-37	-6	561	-59	-9.5	-16 to -59	-3 to -10
7	520	509	-11	-2.1	495	-25	-5	480	-40	-7.7	-11 to -40	-2 to -8
8	450	440	-10	-2.2	432	-18	-4	418	-32	-7	-10 to -32	-2 to -7
9	400	388	-12	-3	381	-19	-4.8	374	-26	-6.5	-12 to -26	-3 to -7

drag coefficient (C_4) is increased from its current value of 0.0228 in MRI to 0.04 in CTR. The SAE-recommended value is 0.0317, in the middle between the MRI and CTR values.

In Table 4 and Figure 3 the critical lengths of grade obtained from CTR are compared with those of AASHTO, under the previously stated assumptions, for different GVW/NHP ratios and percentage grades. The CTR values are consistently less than the corresponding AASHTO results, as expected. The discrepancies become more and more significant as the percentage grade decreases. For a 2 percent grade the difference could reach 27 percent, and it is about 16 percent on the average. In absolute terms, the expected maximum difference is 635 ft and the expected average is about 378 ft. These are indeed extremely large differences. For a 1 percent grade (Figure 3) the difference is expected to reach about 10 times that for a 2 percent grade. For higher grades, up to 5 or even 6 percent, significant differences could still be observed. The expected maximum differences are 254 ft (18 percent), 150 ft (15 percent), 106 ft (14 percent), and 59 ft (10 percent) for grades of 3, 4, 5, and 6 percent, respectively. On the average (that is, for GVW/NHP = 350 and C_4 = 0.0317), expected differences are 378 ft (16 percent), 153 ft (11 percent), 96 ft (9.6 percent), and 73 ft (9.4 percent) for grades of 2, 3, 4, and 5 percent, respectively. The differences between CTR and AASHTO results become less significant for grades of 7 percent and more or GVW/NHP ratios closer to 300, or both.

Probably the most important conclusion that could be extracted from Table 4 and Figure 3 is that if it

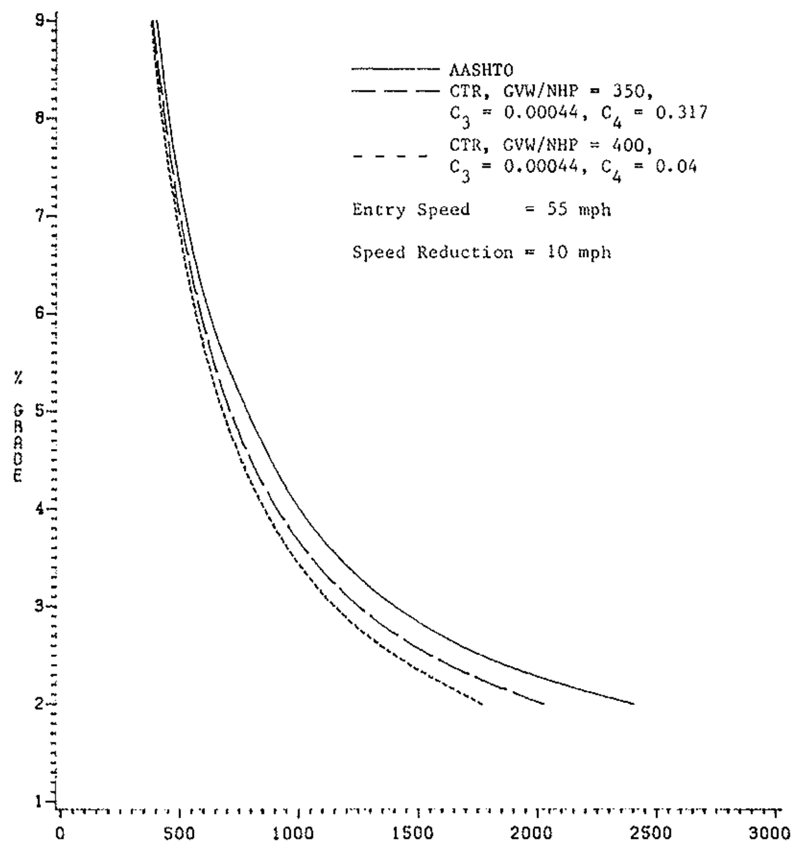

FIGURE 3 Comparison of AASHTO and CTR critical lengths of grade assuming an increase in aerodynamic drag coefficient (C_4) only.

is assumed that the aerodynamic drag coefficient (C_4) for LCVs is increased by about 75 percent of its MRI modified value, gradability results could be quite different from AASHTO design criteria. The reductions of critical lengths of grades could reach 27 percent for a 2 percent grade (an absolute difference of 635 ft). Significant differences could be expected for grades of up to 5 or even 6 percent and for GVW/NHP ratios around or greater than 350.

Impacts of the Increase in Rolling Resistances Coefficient (C_3) Only

In this case it was assumed that the aerodynamic drag coefficient is unchanged (C_4 = 0.0228) while the rolling losses coefficient (C_3) is increased from its current value of 0.00044 in the MRI study to 0.003 in CTR. Within this range a value of 0.001 (between MRI and SAE) and the SAE-recommended value of 0.001982 were considered.

In Table 5 and Figure 4 the critical lengths of grade obtained from the CTR study are compared with those of AASHTO, under the previously stated assumptions, for different GVW/NHP ratios and percentage grades. The trend of the CTR results in this subsection is similar to that in the preceding subsection, as expected. The CTR results are consistently less than those of AASHTO, and the differences between CTR and AASHTO increase as the percentage grade decreases and, of course, as the GVW/NHP ratio gets further above 300. The rate of increase, however, decreases as the GVW/NHP ratio increases.

Compared with those of Table 4 and Figure 3, the

TABLE 5 Comparison of Critical Lengths of Grade (ft) Between CTR and AASHTO Assuming an Increase in Rolling Losses Coefficient (C_3) Only, Entry Speed = 55 mph, and Speed Reduction = 10 mph

		CTR Minimum Difference			CTR Average Difference			CTR Maximum Difference				
		GVW/NHP = 300, C_3 = 0.001, C_4 = 0.0228	Difference		GVW/NHP = 350, C_3 = 0.001982, C_4 = 0.0228	Difference		GVW/NHP = 400, C_3 = 0.003, C_4 = 0.0228	Difference		Expected Difference Range	Expected Difference Range
Grade (%)	AASHTO (ft)	(ft)	Feet	Percentage	(ft)	Feet	Percentage	(ft)	Feet	Percentage	(ft)	(%)
1		15,898			4,091			2,750				
2	2,400	2,397	-3	-0	1,747	-653	-27	1,488	-912	-38	-3 to -912	-0 to -38
3	1,400	1,375	-25	-2	1,156	-244	-17	1,025	-375	-27	-25 to -375	-2 to -27
4	1,000	966	-34	-3.4	857	-143	-14.3	780	-220	-22	-34 to -220	-3 to -22
5	780	747	-33	-4.2	678	-102	-13	630	-150	-19	-33 to -150	-4 to -19
6	620	608	-12	-2	564	-56	-9	531	-89	-14	-12 to -89	-2 to -14
7	520	513	-7	-1.3	480	-40	-7.7	458	-62	-12	-7 to -62	-1 to -12
8	450	443	-7	-1.5	421	-29	-6.4	403	-47	-10	-7 to -47	-1 to -10
9	400	392	-8	-2	374	-26	-6.5	359	-41	-10	-8 to -41	-2 to -10

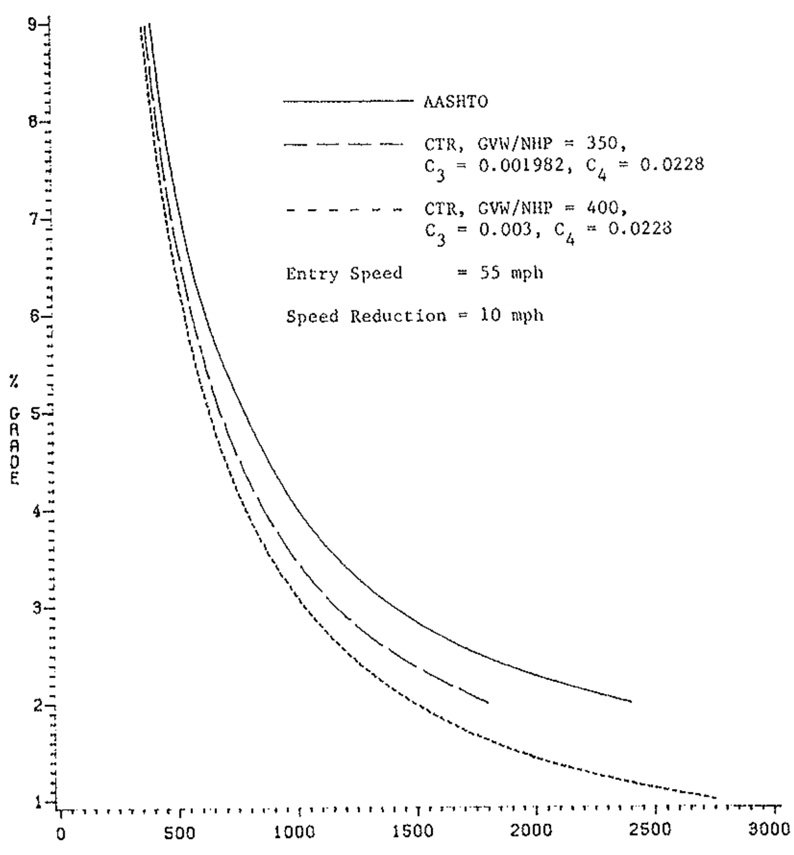

FIGURE 4 Comparison of AASHTO and CTR critical lengths of grade assuming an increase in rolling losses coefficient (C_3) only.

differences in Table 5 and Figure 4 are considerably greater. This is because the assumed values of C_3 in Table 5 imply more variability than do the assumed values of C_4 in Table 4.

Looking at the last two columns of Table 5, the differences between CTR and AASHTO could reach 38 percent (912 ft), 27 percent (375 ft), 22 percent (220 ft), 19 percent (150 ft), and 14 percent (89 ft) for grades of 2, 3, 4, 5, and 6 percent, respectively. On the average (for GVW/NHP = 350 and C_3 = 0.001982), expected differences are about 27 percent (653 ft), 17 percent (244 ft), 14 percent (143 ft), and 13 percent (102 ft) for grades of 2, 3, 4, and 5 percent, respectively. These expected maximum as well as average differences, which range between 912 and 90 ft for grades of 2 through 5 percent and GVW/NHP ratios 400 to 350, are certainly significant and should have strong impacts on the current AASHTO criteria, if it turns out that indeed the rolling losses coefficient for LCVs should be adjusted to the assumed values.

Impacts of Increases in Both Rolling and Aerodynamic Losses Coefficients (C_3 and C_4)

In this subsection it was assumed that coefficients C_3 and C_4 are increased from their current values in the MRI study to reflect the expected increases in aerodynamic and rolling resistances for LCVs compared with regular five-axle trucks. This is the basic underlying assumption of the analysis.

Table 6 gives and Figure 5 shows a comparison of AASHTO criteria and CTR results under alternative

TABLE 6 Comparison of Critical Lengths of Grade (ft) Between CTR and AASHTO Assuming Increases in Coefficients of Both Rolling and Aerodynamic Losses (C_3 and C_4), Entry Speed = 55 mph, and Speed Reduction = 10 mph

		CTR Minimum Difference			CTR Average Difference			CTR Maximum Difference				
		GVW/NHP = 300, C_3 = 0.001, C_4 = 0.0317	Difference		GVW/NHP = 350, C_3 = 0.001982, C_4 = 0.0317	Difference		GVW/NHP = 400, C_3 = 0.003, C_4 = 0.04	Difference		Expected Difference Range	Expected Difference Range
Grade (%)	AASHTO (ft)	(ft)	Feet	Percentage	(ft)	Feet	Percentage	(ft)	Feet	Percentage	(ft)	(%)
1		7,078			3,440			2,288				
2	2,400	2,124	-276	-11.5	1,658	-742	-31	1,342	-1,058	-44	-276 to -1,058	-11 to -44
3	1,400	1,283	-117	-8.4	1,101	-299	-21.4	952	-448	-32	-117 to -488	-8 to -32
4	1,000	919	-81	-8.1	824	-176	-17.6	740	-260	-26	-81 to -260	-8 to -26
5	780	718	-62	-8	659	-121	-15.5	604	-176	-23	-62 to -176	-8 to -23
6	620	590	-30	-5	549	-71	-11.5	509	-111	-18	-30 to -111	-5 to -18
7	520	498	-22	-4	469	-51	-10	443	-77	-15	-22 to -77	-4 to -15
8	450	432	-18	-4	414	-36	-8	392	-58	-13	-18 to -58	-4 to -13
9	400	385	-15	-3.8	366	-34	-8.5	348	-52	-13	-15 to -52	-4 to -13

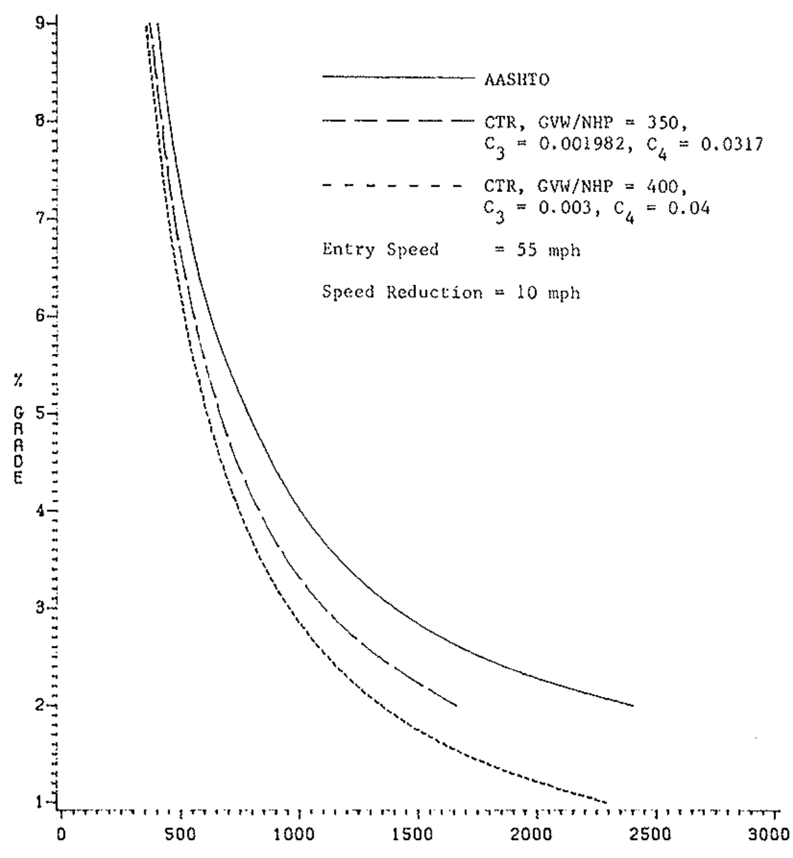

FIGURE 5 Comparison of AASHTO and CTR critical lengths of grade assuming increases in both rolling and aerodynamic losses coefficients (C_3 and C_4).

assumptions for C_3 and C_4 for different GVW/NHP ratios and percentage grades. The trend of CTR results is, again, similar to that encountered in preceding subsections. In this subsection, however, the differences between AASHTO and CTR results are becoming extremely large because both coefficients were allowed to increase simultaneously.

Looking at Table 6, the differences in critical lengths of grades between CTR and AASHTO ranges from 11 to 44 percent (276 to 1,058 ft), 8 to 32 percent (117 to 448 ft), and 8 to 26 percent (81 to 260 ft) for grades of 2, 3, and 4 percent, respectively. This indicates that even the expected minimum differences (for GVW/NHP = 300, $C_3 = 0.001$, and $C_4 = 0.0317$) for lower grades are significant. Of course, the expected maximum differences (for GVW/NHP = 400, $C_3 = 0.003$, and $C_4 = 0.04$) are quite large for grades of up to 6 percent and are still significant for higher grades. The expected average differences (for GVW/NHP = 350, $C_3 = 0.001982$, and $C_4 = 0.0317$) are quite high for grades of up to 5 percent and are still significant for higher grades.

These results indicate that differences between critical lengths of grades for LCVs and AASHTO-recommended values could be as large as 44 percent (1,058 ft) for a 2 percent grade depending on the values of aerodynamic and rolling losses coefficients and GVW/NHP ratios of these LCVs. This "extreme" difference is expected to decrease for grades of more than 2 percent and GVW/NHP ratios below 400.

SUMMARY AND CONCLUSIONS

The current AASHTO (1) criteria for determining critical lengths of grades and climbing lane design for the safe and efficient operation of heavy vehicles assumes a GVW/NHP ratio of a typical five-axle (3-S2) truck to be about 300 lb/hp. Operational tests conducted by Caltrans (2) indicate that LCVs such as double 48-ft and triple 28-ft truck combinations with an overall length of 120 ft and an effective width of 102 in. are generally slower than other typical five-axle trucks, particularly when GVW/NHP ratios are greater than 350.

The main objective of this paper was to gain more insight into the performance of LCVs on highway grades and to investigate the possible impacts that the operation of LCVs on grades might have on the current AASHTO design criteria.

To achieve this objective the factors that may influence performance of vehicles on grades were reviewed and the relatively more important factors for LCVs were highlighted. The issue of the prediction of the performance of LCVs on grades was then addressed. This involved discussion of existing approaches, selection of a particular approach for the study, detailed description of the selected approach, and actual application of the approach to LCVs. The results of the application were analyzed in view of the current AASHTO criteria.

The major conclusions of this paper may be stated as follows:

1. The practical maximum GVW for LCVs is consistently greater than 100,000 lb up to 138,000 lb. NHP ranges between 300 and 330 hp and could exceed 400 hp. A GVW/NHP ratio between 300 and 400 lb/hp would be considered normal and could, occasionally, exceed 400.

2. The larger side area of LCVs should increase their aerodynamic drag. The increased GVW and number of tires for LCVs should increase their rolling resistances. These increased aerodynamic and rolling resistances could be considerable. The rolling losses coefficient (C_3) in the simulation model could increase from its current value of 0.00044 (the MRI modified value) to 0.003. The aerodynamic drag coefficient (C_4) could increase from its MRI modified value of 0.0228 to 0.04. Actual representative values for LCVs can only be obtained from actual field tests.

3. If it is assumed that the rolling and aerodynamic coefficients (C_3 and C_4) are unchanged from their current MRI values for regular five-axle trucks, the results (CTR) of critical lengths of grades (assuming entry speed = 55 mph and speed reduction = 10 mph) at GVW/NHP = 300 are almost identical with the corresponding AASHTO values for grades of 4 percent and more, as expected. For 3 and 2 percent grades, however, the CTR values are greater than the AASHTO values by about 3.9 and 10 percent, respectively. This slight overestimation of gradability on lower grades can be explained by noting that effects of percentage grade and GVW tend to decrease on lower grades, where the effects of the vehicle's power capabilities become predominant, and that the net horsepower used in the analysis (NHP = 315 hp) is indeed higher than the value for regular trucks with the same GVW/NHP = 300 ratio. This implies that CTR results are conservative with respect to AASHTO criteria. This should strengthen the analysis.

4. In the comparison between critical lengths of grades obtained from CTR and the corresponding AASHTO values, a certain trend for the differences depending on the GVW/NHP ratio and the percentage grade was observed. Of course the differences increase as the GVW/NHP ratio increases, but the rate of increase of differences decreases for higher GVW/NHP ratios. As the percentage grade increases, the differences decrease both in absolute value and percentage-wise. In other words, more variability in the results is expected on lower percentage grades and for GVW/NHP ratios closer to 300.

5. Under the assumption of no change in rolling and aerodynamic losses coefficients for LCVs compared with regular five-axle trucks, the critical lengths of grades can still be significantly less than AASHTO criteria. For GVW/NHP = 400, these reductions could reach 16 percent on a 2 percent grade (from 2,400 to 2,025 ft), 11 percent on a 3 percent grade (from 1,400 to 1,252 ft), and 9 percent on a 4 percent grade (from 1,000 to 909 ft).

6. Assuming that the rolling losses coefficient is unchanged ($C_3 = 0.00044$) while the aerodynamic drag coefficient (C_4) is increased from its current MRI value of 0.0228 to 0.04, more significant differences between CTR and AASHTO could be observed. Expected maximum reductions (for GVW/NHP = 400 and $C_4 = 0.04$) are 27 percent (635 ft), 18 percent (254 ft), 15 percent (150 ft), 14 percent (106 ft), and 10 percent (59 ft) for grades of 2, 3, 4, 5, and 6 percent, respectively. Expected average reductions in critical lengths of CTR compared with AASHTO (for GVW/NHP = 350 and $C_4 = 0.0317$) are 16 percent (378 ft), 11 percent (153 ft), 9.6 percent (96 ft), and 9.4 percent (73 ft) for grades of 2, 3, 4, and 5 percent, respectively. In other words, under the previously stated assumptions, gradability results for LCVs could be quite different from those of AASHTO.

7. Assuming that the aerodynamic drag coefficient is unchanged ($C_4 = 0.0228$) while the rolling resistances coefficient (C_3) is increased from its MRI value of 0.00044 to 0.003, the differences between CTR and AASHTO become more and more dramatic. Expected differences could be as much as 38 percent (912 ft), 27 percent (375 ft), 22 percent (220 ft), 19 percent (150 ft), and 14 percent (89 ft) for grades of 2, 3, 4, 5, and 6 percent, respectively. On the average (for GVW/NHP = 350 and $C_3 = 0.001982$), expected differences are about 27 percent (653 ft),

17 percent (244 ft), 14 percent (143 ft), and 13 percent (102 ft) for grades of 2, 3, 4, and 5 percent, respectively.

8. Assuming that both rolling and aerodynamic coefficients (C_3 and C_4) are increased from their MRI values to reflect the expected increases in rolling and aerodynamic resistances for LCVs compared with regular five-axle trucks, the resulting reductions in critical lengths of grades could be extremely high. Expected reductions of CTR compared with AASHTO critical lengths could be as high as 44 percent (1,058 ft), 32 percent (448 ft), 26 percent (260 ft), 23 percent (176 ft), and 18 percent (111 ft) for grades of 2, 3, 4, 5, and 6 percent, respectively. Expected minimum differences corresponding to GVW/NHP = 300, C_3 = 0.001, and C_4 = 0.0317 are still significant for lower grades. These differences are 12 percent (278 ft), 8.4 percent (117 ft), and 8.1 percent (81 ft) for 2, 3, and 4 percent grades, respectively.

9. Reductions of critical lengths for grades of 7 percent and greater could be at most 77 ft (15 percent), 58 ft (13 percent), and 52 ft (13 percent) on grades of 7, 8, and 9 percent, respectively.

10. The variability in the results for a 1 percent grade is enormous. Estimated critical length reductions could reach about 75 percent. The absolute values for critical lengths are, however, quite large in most cases. On the basis of the hypothesized results in this paper, as long as the length of a 1 percent grade is less than 2,500 ft, the performance of LCVs should be satisfactory in the majority of situations.

In summary, the CTR results indicate that critical lengths of grades for LCVs could be less than the AASHTO design values by as much as 1,058 ft on a 2 percent grade (44 percent less than the recommended 2,400 ft) for GVW/NHP = 400, C_3 = 0.003, and C_4 = 0.04. This extreme difference is expected to decrease for grades of more than 2 percent, GVW/NHP ratios below 400, C_3 values below 0.003, and C_4 values less than 0.04.

Notice that in the analysis no attempt was made to recommend specific values for "representative" LCVs. Instead, a sensitivity analysis was performed within certain "reasonable" ranges of values for GVW/NHP ratios, percentage grades, C_3 coefficients, and C_4 coefficients. The message conveyed through this analysis is that the operation of LCVs on grades could indeed have serious implications for the current AASHTO criteria for determining critical lengths of grade and climbing lane design. To make specific recommendations in this regard, actual field experimental data on the performance of different LCV types (such as turnpike doubles, turnpike triples, and Rocky-Mountain doubles) on grades have to be collected and analyzed. These field tests may consider, in addition to straight upgrades, operation along loop ramps at major interchanges. Operation on loop ramps is influenced by the combined effects of grade and curvature. Of course, the entry speed at loop ramps is considerably less than 55 mph. This combination of factors could have serious adverse consequences as far as the operation of LCVs is concerned unless appropriate changes in existing geometric design practices, if deemed necessary, are undertaken.

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APPENDIX --SIMULATION RESULTS

TABLE A-1 CTR Critical Lengths of Grades for GVW/NHP = 300

% Grade				GVW = 94500 lb			NHP = 315		GVW/NHP - 300			
	C_3 = 0.00044			C_3 = 0.001			C_3 = 0.001982			C_3 = 0.003		
C_4 →	0.0228	0.0317	0.04	0.0228	0.0317	0.04	0.0228	0.0317	0.04	0.0228	0.0317	0.04
1	--	11697.3	6597.4	15899.0	7078.7	5078.7	6173.2	4556.0	3685.8	4165.1	3391.5	2892.2
2	2647.1	2320.1	2080.1	2397.2	2124.5	1920.8	2056.3	1852.4	1695.8	1791.4	1634.6	1514.0
3	1455.2	1349.1	1264.8	1375.1	1283.2	1206.3	1258.0	1177.6	111.7	1155.7	1086.3	1031.3
4	1006.9	955.5	911.5	966.9	919.1	878.7	908.1	864.3	830.9	853.2	816.4	783.5
5	769.6	740.1	714.3	747.6	718.2	692.5	710.9	685.1	663.0	677.8	652.3	633.7
6	623.3	604.8	586.4	608.6	590.1	571.9	583.1	568.0	549.9	560.9	546.0	531.3
7	524.5	509.8	498.5	513.5	498.9	487.7	495.2	484.0	472.9	480.3	465.8	456.1
8	451.4	440.3	432.7	444.0	433.0	425.4	432.7	421.8	414.3	418.2	410.6	399.9
9	399.8	389.0	381.6	392.5	385.1	377.7	381.6	374.2	366.8	370.6	363.3	359.3

TABLE A-2 CTR Critical Lengths of Grades for GVW/NHP = 350

% Grade				GVW = 350			NHP = 315		GVW/NHP = 350			
	C_3 = 0.00044			C_3 = 0.001			C_3 = 0.001982			C_3 = 0.003		
C_4 →	0.0228	0.0317	0.04	0.0228	0.0317	0.04	0.0228	0.0317	0.04	0.0228	0.0317	0.04
1	7712.5	5604.3	4494.2	5793.7	4550.5	3800.5	4091.9	3440.1	2999.5	3153.7	2755.7	2465.9
2	2266.8	2022.3	1861.7	2048.4	1873.2	1734.5	1797.1	1658.5	1552.2	1593.1	1483.6	1395.8
3	1321.6	1248.0	1185.5	1259.1	1189.5	1130.9	1156.9	1101.6	1050.4	1069.1	1021.2	977.3
4	941.9	904.9	871.7	908.8	872.1	842.5	857.3	824.3	795.0	806.2	780.2	754.5
5	733.3	707.7	689.0	711.4	689.3	670.7	678.4	659.8	641.4	648.8	630.4	612.2
6	601.4	583.2	568.5	586.8	572.0	557.3	564.7	550.0	535.5	542.7	528.1	517.0
7	506.4	495.3	487.6	498.8	487.8	476.8	480.7	469.7	462.1	465.8	454.9	447.4
8	440.3	432.8	425.4	433.0	425.5	418.1	421.8	414.4	407.0	407.4	400.0	396.0
9	389.0	381.7	377.7	381.8	377.8	370.6	374.2	366.9	363.0	363.3	359.4	352.2

TABLE A-3 CTR Critical Lengths of Grades for GVW/NHP = 400

% Grade				GVW = 132,000			NHP = 330		GVW/NHP = 400			
	C_3 = 0.00044			C_3 = 0.001			C_3 = 0.001982			C_3 = 0.003		
C_4 →	0.0228	0.0317	0.04	0.0228	0.0317	0.04	0.0228	0.0317	0.04	0.0228	0.0317	0.04
1	5472.8	4519.6	3888.8	4486.5	3829.3	3369.8	3423.0	3027.8	2733.9	2750.2	2488.6	2288.4
2	2025.4	1882.4	1765.2	1879.2	1754.6	1652.1	1664.0	1565.1	1484.4	1488.7	1411.5	1342.1
3	1252.7	1194.1	1146.2	1194.1	1142.6	1098.5	1106.0	1058.6	1021.7	1025.5	985.3	952.2
4	909.0	876.2	850.3	876.2	846.9	824.5	828.3	802.6	780.5	780.8	758.7	740.1
5	711.6	693.1	674.9	693.1	674.8	659.9	660.3	645.4	630.7	630.9	616.1	604.8
6	586.9	572.4	561.3	572.4	561.2	550.1	550.4	539.3	531.6	531.8	520.8	509.9
7	499.0	488.1	480.6	488.1	480.5	473.1	473.3	465.8	485.4	458.5	451.0	443.7
8	433.1	425.7	418.5	425.7	418.4	414.5	414.6	407.3	403.4	403.5	396.3	392.4
9	385.2	378.0	374.2	378.0	374.1	367.0	367.1	363.3	359.5	359.6	355.8	348.7

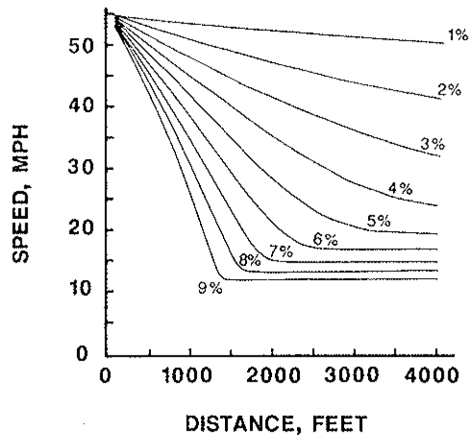

FIGURE A-1 Speed-distance profile for GVW = 94,500 lb, NHP = 315 hp, C_3 = 0.00044, C_4 = 0.0228, and GVW/NHP = 300.

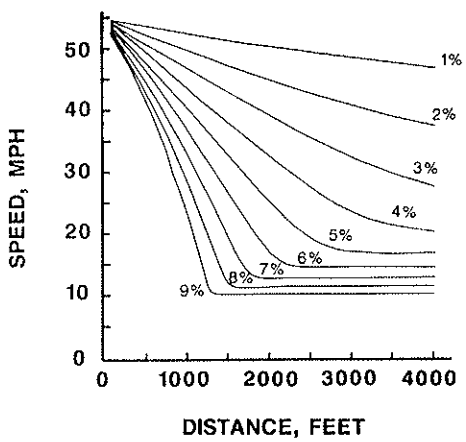

FIGURE A-2 Speed-distance profile for GVW = 110,250 lb, NHP = 315 hp, C_3 = 0.00044, C_4 = 0.0317, and GVW/NHP = 350.

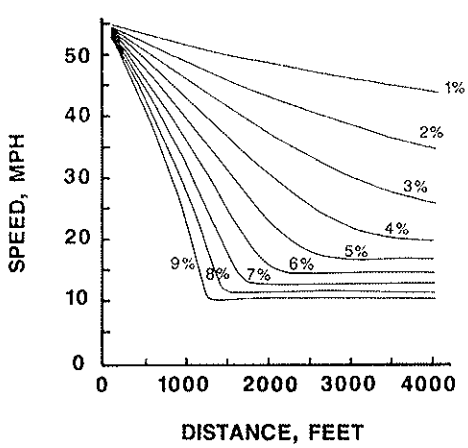

FIGURE A-3 Speed-distance profile for GVW = 110,250, NHP = 315 hp, C_3 = 0.001982, C_4 = 0.0317, and GVW/NHP = 350 (expected average).

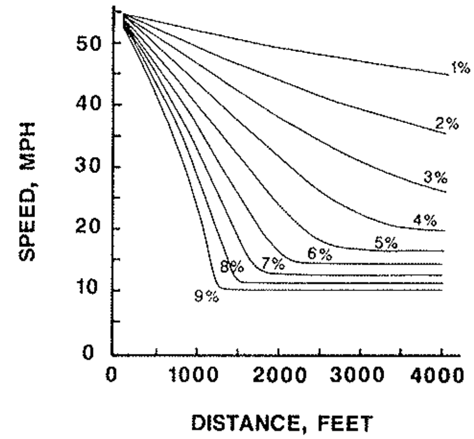

FIGURE A-4 Speed-distance profile for GVW = 110,250 lb, NHP = 315 hp, C_3 = 0.001982, C_4 = 0.0228, and GVW/NHP = 350.

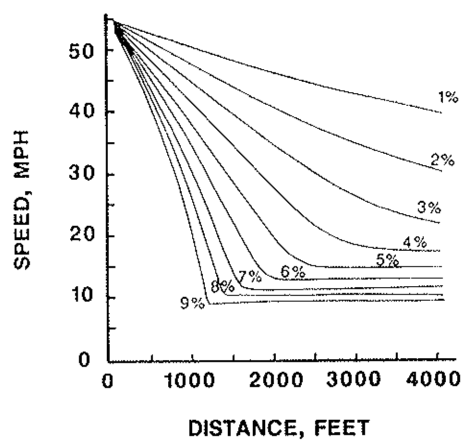

FIGURE A-5 Speed-distance profile for GVW = 132,000 lb, NHP = 330 hp, C_3 = 0.003, C_4 = 0.04, and GVW/NHP = 400 (expected worst).

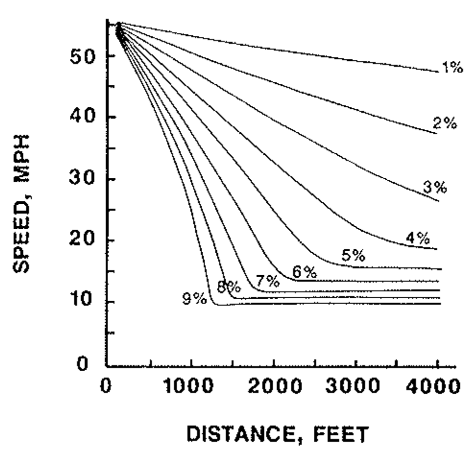

FIGURE A-6 Speed-distance profile for GVW = 132,000 lb, NHP = 330 hp, C_3 = 0.00044, C_4 = 0.0228, and GVW/NHP = 400.

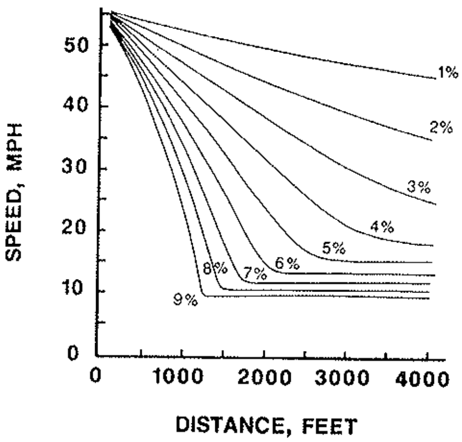

FIGURE A-7 Speed-distance profile for GVW = 132,000 lb, NHP = 330 hp, C_3 = 0.00044, C_4 = 0.04, and GVW/NHP = 400.

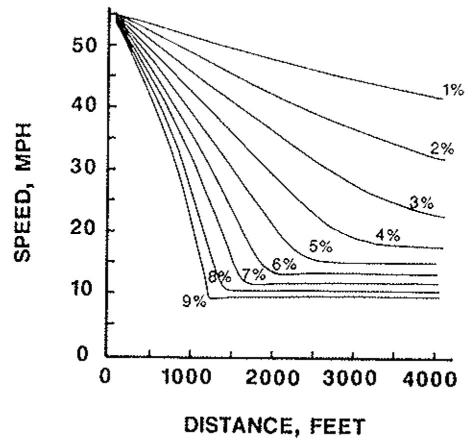

FIGURE A-8 Speed-distance profile for GVW = 132,000 lb, NHP = 330 hp, C_3 = 0.003, C_4 = 0.0228, and GVW/NHP = 400.

Influence of the Geometric Design of Highway Ramps on the Stability and Control of Heavy-Duty Trucks

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ABSTRACT

A research study is described in which accidents experienced by tractor-semitrailers on expressway ramps were found to depend largely on the interaction between highway geometrics and vehicle dynamic behavior. The accident rates of tractor-semitrailers on expressway ramps in five states were scanned to select 14 individual ramps that exhibited an unusual incidence of serious accidents involving these vehicles. The geometrics of each ramp were fully defined in a computer simulation in such a way that the dynamic behavior of example tractor-semitrailers could be examined. The results of combined study of accident data, simulated vehicle response, and geometric details of ramp design are presented. The findings of the study indicate that the maneuvering limits of certain trucks are quite low relative to those of automobiles so current practice in ramp design leaves an extremely small margin for control of heavy vehicles. The primary design issues are embodied in the nominal side friction factor achieved at each curve, the transition geometry, and the layout and signing of curve segments in order to assure that truck speeds are suitably reduced for negotiating small-radius curves.

The geometric design of highway ramps is guided by the design policy of AASHTO (1). These policies provide specific guidance on the relationships among curve radius, superelevation, transition sections, vehicle speeds, and other details that control ramp design. For a given anticipated ramp layout, there exists a range of variations, which are allowed within the design policy, in each design parameter. In the real world, ramps that are in service around

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