

IMPACT OF TIRE AND AERODYNAMIC AIDS ON TRUCK PERFORMANCE ALONG UPGRADE SECTIONS

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ABSTRACT

The paper utilizes a variable power vehicle dynamics model to validate the Highway Capacity Manual truck performance curves for a 120 kg/kW (200 lb/hp) truck equipped with radial tires, traveling on a fair asphalt surface (Pavement Serviceability Index between 1.5 and 3.0). The vehicle dynamics model is then utilized to conduct a sensitivity analysis of truck and tire characteristics on truck behavior along upgrade sections. Subsequently, considering the significant factors, truck performance curves, reflective of in-field roadway and truck characteristics, are developed. These truck performance curves are intended to enhance the HCM procedures in locating truck climbing lanes.

Key words: Truck modeling, vehicle dynamics, roadway design, truck climbing lanes, typical traveling condition.

INTRODUCTION

Mannering and Kilareski (1) suggest that “*the performance of road vehicles forms the basis for highway design guidelines and traffic analysis. For example, in highway design, determination of the length of freeway acceleration and deceleration lanes, maximum highway grades, stopping-sight distances, passing-sight distances, and numerous accident prevention devices all rely on the basic understanding of vehicle performance.*”

Truck performance along grade sections may have significant impacts on roadway throughput and efficiency depending on the roadway grade, the truck characteristics, the percentage of trucks on the roadway, and the overall level of congestion on the roadway section. Although the Highway Capacity Manual and the AASHTO Policy on the Geometric Design of Highways and Streets provide curves for predicting vehicle speeds as a function of the distance traveled and the percentage grade along a roadway section (2) (3), these curves are limited because they only consider a single truck weight-to-power (W/P) ratio of 120 kg/kW (200 lb/hp) and do not capture the effect of tire and aerodynamics aids on the truck acceleration behavior.

The objectives of this paper are two-fold. First, the paper investigates the impact of a number of vehicle-related parameters on the performance of trucks along upgrade sections. These

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parameters include the type of vehicle tires, the vehicle's aerodynamic features, the percentage mass on the tractive axle, and the vehicle's engine efficiency. This research effort complements a previous research effort that investigated the effect of roadway surface type and condition on truck acceleration behavior (4). Second, the paper expands the domain of application of the HCM and the AASHTO Policy on the Geometric Design of Highways and Streets truck performance curves by considering vehicle parameters that are deemed critical in the modeling of truck behavior along upgrade sections.

In terms of the paper layout, initially the vehicle dynamics model that is incorporated in the TRUCKSIM software and utilized to conduct the sensitivity analysis and develop the truck performance curves, is described briefly. Subsequently, the importance of enhancing the state-of-practice truck performance curves is demonstrated through a number of simple example illustrations. Subsequently, the results of the sensitivity analyses are presented followed by sample truck performance curves that were developed using the TRUCKSIM software.

VEHICLE DYNAMICS MODEL

The vehicle dynamics model that is utilized and implemented within the TRUCKSIM software was originally developed by Rakha *et al.* (5) and enhanced by Rakha and Lucic (6). It is similar to models presented by others (1, 7, 8, and 9) with additional improvements and refinements. The vehicle dynamics model computes maximum vehicle acceleration levels by computing the resultant force acting on a vehicle, as summarized in Equation 1. Given that acceleration is the second derivative of distance with respect to time, Equation 1 resolves to a second-order Ordinary Differential Equation (ODE) of the form presented in Equation 2.

The vehicle tractive effort is computed using Equation 3 with a maximum value based on Equation 4, as demonstrated in Equation 5. Equation 4 ensures that the tractive force does not exceed the maximum frictional force that can be sustained between the vehicle's tractive-axle tires and the roadway surface without the spinning of vehicle wheels. The equation demonstrates that the maximum tractive force is a function of the proportion of the vehicle mass on the tractive axle. Typical axle mass distributions for different truck types were presented by Rakha *et al.* (5).

Rakha and Lucic (6) introduced the β factor into Equation 3, in order to account for the gear shift impacts at low traveling speeds. While the variable power factor does not incorporate gear shifts explicitly, it does account for the major behavioral characteristics that result from gear shifts, namely the reductions of power. Specifically, the factor is a linear function of vehicle speed with an intercept of $1/v_0$ and a maximum value of 1.0 at v_0 (optimum speed or the speed at which the vehicle attains its full power), as demonstrated in Equation 6. The intercept guarantees that the vehicle has enough power to accelerate from a complete stop. The calibration of the variable power factor was conducted by experimenting with different truck and weight combinations to estimate the speed at which the vehicle power reaches its maximum (termed the optimum speed). The optimum speed was found to vary as a function of the weight-to-power ratio, as demonstrated in Equation 7. The details of how this relationship is derived are described by Rakha and Lucic (6).

$$a = \frac{F - R}{M} \quad [1]$$

$$\frac{d^2 x}{dt^2} = f\left(\frac{dx}{dt}, x\right) \quad [2]$$

$$F_t = 3600 \beta \eta \frac{P}{v} = \frac{K_T \beta}{v} \quad [3]$$

$$F_{\max} = 9.8066 M_{ta} \mu \quad [4]$$

$$F = \min(F_t, F_{\max}) \quad [5]$$

$$\beta = \frac{1}{v_0} \left[1 + \min(v, v_0) \left(1 - \frac{1}{v_0} \right) \right] \quad [6]$$

$$v_0 = 1164w^{-0.75} \quad [7]$$

Three resistance forces are considered in the model (1, 5, 7, and 8). First is the aerodynamic resistance, as indicated in Equations 8 and 9 where c_1 is a constant that accounts for the air density at sea level at a temperature of 15°C (59°F). Typical values of vehicle frontal areas for different truck and bus types and typical drag coefficients are provided in the literature (5).

Second is the rolling resistance, which is a linear function of the vehicle speed and mass, as indicated in Equation 10. Typical values for rolling coefficients (C_r , c_1 , and c_2), as a function of the road surface type, condition, and vehicle tires, are provided in the literature (5). Generally, radial tires provide a resistance that is 25 percent less than that for bias ply tires.

Third is the grade resistance, which is a function of the vehicle's total mass and the road grade, as indicated in Equation 11. The grade resistance accounts for the proportion of the vehicle weight that resists the movement of the vehicle:

$$R_a = c_1 C_d C_h A v^2 = K_a v^2 \quad [8]$$

$$C_h = 1 - 8.5 \times 10^{-5} H \quad [9]$$

$$R_r = 9.8066 C_r (c_2 v + c_3) \frac{M}{1000} = K_{r1} v + K_{r2} \quad [10]$$

$$R_g = 9.8066 M i \quad [11]$$

The vehicle dynamics model was incorporated in the TRUCKSIM software and validated by driving four trucks with different vehicle loads equipped with a Global Positioning System (GPS) that measured the vehicle speed with an accuracy of 0.1 m/s as they accelerated from a full stop at the maximum acceleration rate along the Smart Road test facility (6). The test scenarios included a total of 42 weight-to-power combinations (10 weights for 2 trucks and 11 weights for the other 2 trucks) and a combination of trucks with partial and full aerodynamic features. The model parameters were selected based on recommendations by Rakha *et al.* (5) to reflect the characteristics of the trucks in terms of their aerodynamic features, tire characteristics, and pavement conditions. Multiple repetitions were made for each weight-to-power ratio combination in order to ensure that the runs were not biased by a single observation. The final speed profile derived by the model was superimposed on the field collected GPS second-by-second speed measurements, as illustrated in Figure 1. The figure illustrates the variation in vehicle speed as a function of the traveled distance for a specific load configuration (vehicle mass of 25,120 kg and engine power of 261 kW). The results demonstrate that the state-of-the-art constant power vehicle dynamics models (1, 5, 7, and 8) produce significant errors at low speeds because the gear shifting behavior results in the vehicle operating at a power that is less than the maximum power of 261 kW (350 hp). The dips observed in the measured speed (data points on plot) are also due to the shifting of gears, as there is virtually no power transmission to the tractive axles while the clutch is activated. Alternatively, the variable power model demonstrates a very good fit to the field data. Overall, the proposed variable power vehicle dynamics model produced an error in the estimated speed that was found to be less than 10 percent. A detailed description of the validation effort is beyond the scope of this paper but is provided in the literature (6).

Rakha and Yu (4) used the vehicle dynamics model to compute the vehicle's equilibrium speed, also referred to as the vehicle crawl speed. The equilibrium speed is the maximum speed a vehicle can attain along a sustained grade section when the vehicle's acceleration is zero. By solving for the vehicle speed when the tractive force equals the summation of the resistance forces (vehicle acceleration equals zero), the equilibrium speed can be computed, as summarized in Equation 12 and 13. The computation depends upon whether or not the tractive force exceeds the maximum frictional force that can be sustained between the vehicle tires and the roadway surface. The interested reader may refer to Rakha and Yu (4) for details of the full model derivation.

Specifically, in the case that $F_{\max} \geq K_T \beta / v_0$ then Equation 12 is utilized.

$$v_m = -\frac{K_{r1}}{3K_a} + \frac{\sqrt[3]{2(-K_{r1}^2 + 3K_a c)}}{3K_a b} - \frac{b}{3\sqrt[3]{2} \cdot K_a} \quad \forall \quad F_{\max} \geq \frac{K_T \beta}{v_0} \quad [12]$$

Where:

$$b = \sqrt[3]{-27K_a^2 d - 2K_{r1}^3 - 9K_a K_{r1} c + \sqrt[2]{4(-K_{r1}^2 + 3K_a c)^3 + (-27K_a^2 d - 2K_{r1}^3 - 9K_a K_{r1} c)^2}}$$

$$c = \begin{cases} K_{r2} + R_g & v_m \geq v_0 \\ K_{r2} + R_g - \frac{K_T}{v_0} + \frac{K_T}{v_0^2} & v_m < v_0 \end{cases}$$

$$d = \begin{cases} -K_T & v_m \geq v_0 \\ -\frac{K_T}{v_0} & v_m < v_0 \end{cases}$$

Alternatively, in the case that $F_{\max} < K_T \beta / v_0$ then Equation 13 is applied.

$$v_m = \begin{cases} \frac{-K_{r1} + \sqrt{K_{r1}^2 - 4K_a(K_{r2} + R_g - F_{\max})}}{2K_a} & \forall v_m \leq \frac{K_T \beta}{F_{\max}} \\ -\frac{K_{r1}}{3K_a} + \frac{\sqrt[3]{2(-K_{r1}^2 + 3K_a f)}}{3K_a e} - \frac{e}{3\sqrt[3]{2} \cdot K_a} & \forall v_m > \frac{K_T \beta}{F_{\max}} \end{cases} \quad [13]$$

Where:

$$e = \sqrt[3]{27K_a^2 K_T - 2K_{r1}^3 - 9K_a K_{r1} f + \sqrt[2]{4(-K_{r1}^2 + 3K_a f)^3 + (27K_a^2 K_T - 2K_{r1}^3 - 9K_a K_{r1} f)^2}}$$

$$f = K_{r2} + R_g$$

Rakha and Yu (4) demonstrated the consistency between the HCM truck performance curves and the Rakha and Lucic model estimates for a full range of grades (0 to 8 percent). The paper demonstrates that the HCM truck performance curves were derived from a constant power vehicle dynamics model and thus produce significant errors at low speeds. For example, a comparison of the models demonstrated that apart from the 8 percent grade the results of the HCM and TRUCKSIM software were consistent. The reason the TRUCKSIM estimates a lower equilibrium speed for the 8 percent grade is because the equilibrium speed is less than the optimum speed of 32 km/h (v_0), and thus, the values of the constants c and d take the second form of Equation 12 (i.e. $c = K_{r2} + R_g - K_T / v_0 + K_T / v_0^2$ and $d = -K_T / v_0$). These findings are consistent with field observations (Figure 1), which have demonstrated that vehicles are unable to attain the equilibrium speeds that are proposed by a constant power model (6). Consequently, Rakha and Yu (4) demonstrated that the HCM procedures would tend to over-estimate truck equilibrium speeds when the equilibrium speed is less than the optimum speed.

EXAMPLE ILLUSTRATION

As was mentioned earlier, the variable power vehicle dynamics model has been incorporated in the TRUCKSIM software to automate the modeling of truck behavior and to assist practitioners in the design of truck climbing lanes (10). It should be noted at this point that the TRUCKSIM software solves the second order ODE, which was presented in Equation 2, numerically at a user-defined time step. The software input parameters include the pavement type and condition by altering the rolling and friction coefficients, the tire type, the altitude, the vehicle mass, vehicle power, percent mass on the tractive axle, the vehicle drag coefficient, the engine efficiency, a user specified minimum speed for the design of climbing lanes, the traffic volume and percentage trucks on various roadway segments, and the roadway free-speed (or maximum speed). The software can provide four outputs. The first output is the vehicle's acceleration, speed, position, tractive force, and resistance forces at a user-specified time step for the duration of the simulation. The second output identifies the start and end locations of truck climbing lanes (locations where the truck speed decreases below a user-specified minimum speed and where the traffic and truck volume exceeds the AASHTO thresholds). The third output is the vehicle's equilibrium speed, which is computed by solving Equation 12 and 13, as was discussed earlier. The final output is the composite equilibrium grade for a specific road section.

Rakha and Yu (4) demonstrated the consistency between the variable power vehicle dynamics model and the HCM and AASHTO procedures using consistent parameters. Rakha and Yu demonstrated that the use of a 200 lb/hp vehicle equipped with a 450 hp engine of efficiency 88 percent, equipped with aerodynamic aids and radial tires, and with a weight distribution that results in 35 percent of the total weight on the tractive axle, and traveling on a fair asphalt surface generates consistent results (5). At the same time, Rakha and Yu (4) also demonstrated, by altering the roadway characteristics differences in truck behavior are observed and, thus, the need to enhance and extend the HCM and the AASHTO procedures. This paper will investigate the impact of truck and tire characteristics on the truck performance curves.

For illustration purposes, a simple 3.2-km section of highway is considered. The grades along the section include a 2 percent upgrade over a distance of 0.8 kilometers followed by a 5 percent upgrade over 0.8 kilometers followed by a 1 percent upgrade over the remainder of the section (length of 1.6 km). Using the HCM truck performance curves the speed of the truck is estimated at 0.1-km intervals, assuming an initial truck speed of 0 and 88 km/h, as illustrated in Figure 2. Figure 2 demonstrates that the HCM procedures estimate the final truck speed to be 80.5 km/h after traveling the entire 3.2-km test section. Similarly, the final speed produced by the variable power model is 83 km/h using the HCM parameters. This results in a difference of less than 2.5 percent between the HCM procedures and the variable power vehicle dynamics model and demonstrates the consistency between the variable power model and the HCM procedures.

Subsequently, the vehicle's drag coefficient was varied to take on values of 0.58, 0.64, and 0.78, respectively to reflect a vehicle equipped with full, partial, or no aerodynamic aids. As shown, the difference in the final speed is minor. Specially, considering the acceleration scenario, the final speeds are 83.2, 82.7, and 81.4 km/h for full aerodynamic treatment, aerodynamic aids, and no aerodynamic aids. Compared to the 80.5 km/h speed estimated by the HCM procedures, the differences are less than 3.5%, which is minor. Thus, the results suggest that the performance difference due to aerodynamic aids could be omitted given that truck speeds do not reach sufficiently high values to make the aerodynamic resistance a critical factor, as will be demonstrated later.

Alternatively, Figure 3 demonstrates the impact of the vehicle tire characteristics on the truck acceleration behavior for the same 3.2-km test section. Specially, the truck final speed varies from 78 to 83 km/h for radial versus bias ply tires, which is equivalent to a 6 percent difference in the

final speed. The 80.5 km/h final speed estimated by the HCM procedures falls between 78 to 83 km/h range. At first glance, this may suggest that the difference among tire types could be ignored. However, as will be demonstrated later the tire type becomes critical at low grades (i.e. when truck speeds are high).

SENSITIVITY ANALYSIS OF VEHICLE PARAMETERS

This section first evaluates the impact of various vehicle parameters including aerodynamic features, tire type, engine efficiency, and percentage of mass on tractive axle on truck performance along upgrade sections. Depending on the results of the sensitivity analysis evaluation, the authors suggest that the HCM truck performance curves be updated accordingly. Prior to developing the truck performance curves, the base case input parameters are described followed by a description of the parameter values that were utilized to account for the various roadway and truck characteristics that were studied.

Basic Input Parameters

The basic input parameters reflected trucks equipped with full aerodynamic features given that these trucks represented the majority of trucks (55 percent of a 157 sample size) that were observed along I-81 in the state of Virginia (6). The assumption of full aerodynamic features implies the use of an aerodynamic drag coefficient of 0.58, as was described by Rakha *et al.* (5). In addition, trucks were assumed to be equipped with radial tires (97 percent of the I-81 sample). The use of radial tires implies the incorporation of rolling resistance coefficients (c_2 and c_3) of 0.0328 and 4.575, respectively. In addition, the pavement surface was assumed to be a fair asphalt surface, implying a rolling resistance factor (C_r) equal to 1.75 and a coefficient of friction of 0.5. The engine efficiency was assumed to be 88 percent with an engine power of 336 kW (450 hp) (the mean power for the I-81 sample), and a vehicle weight-to-power ratio of 120 kg/kW (200 lb/hp), which is what is used for the HCM truck performance curves, but not necessarily consistent with the truck population along the I-81 corridor. The altitude was assumed to be sea level ($C_h = 1.00$). The truck frontal area was assumed to be 10.7 m² and the percentage mass on the tractive axle was assumed to be 35 percent, as recommended by Rakha *et al.* (5). It should be noted that the vehicle engine efficiency may deteriorate with age. A characterization of engine efficiency as a function of engine age is beyond the scope of this paper. However, it is a subject worth further investigation.

Impact of Percentage Mass on Tractive Axle on Truck Performance

This section evaluates the effect of percentage of the total vehicle mass on the tractive axle on truck performance. Specifically, the percentage of mass on the tractive axle was varied to include a 25, 35, and 45 percent. The results demonstrated that the truck equilibrium speed was hardly impacted by the change in percentage of mass on the tractive axle (changes of less than 1 percent). The lack of sensitivity of the equilibrium speed to the percentage mass on the tractive axle can be attributed to the fact that this parameter only plays a role during the initial vehicle accelerations, as demonstrated in Equation 4.

Impact of Tire Type on Truck Performance

As far as vehicle tires are concerned, there are two major tire types: radial and bias ply. Table 1 illustrates the variation in the vehicle equilibrium speed as a function of four factors, namely: the engine efficiency, the vehicle drag coefficient, the tire type, and the percentage upgrade. In addition, Table 2 illustrates the percentage change in the equilibrium speed relative to the radial

tire base case scenario. The following conclusions can be made using the results of Table 1 and Table 2. First, the highest percentage change in equilibrium speed occurs when the grade is steep (8 percent). However, in these cases the equilibrium speed is low (seldom higher than 20 km/h) and thus the percentage difference is relatively high. Second, in the case of upgrades that are less than 6 percent in steepness, which is common for interstate freeways, generally the percentage change in equilibrium speed decreases as the roadway grade severity increases. Typically, the changes in the equilibrium speed are in the range from 0 to 10 percent. Consequently, it appears that the vehicle tire type could be a relative important factor in the design of truck climbing lanes.

Impact of Aerodynamic Features on Truck Performance

The study considered four aerodynamic drag factors that capture four vehicle configurations, namely a car hauler/cattle hauler, a truck not equipped with aerodynamic aids, a truck equipped with aerodynamic aids on the cab roof, and fully aerodynamic treatment. Using the equilibrium speeds of Table 1, the percentage change in the equilibrium speed relative to the base case fully aerodynamic treatment is provided in Table 3. As Table 3 shows, overall the largest change in the equilibrium speed is less than 10 percent. Second, the percentage change in the equilibrium speed decreases as the roadway upgrade increases and the vehicle equilibrium speed decreases. Specifically, the impact of the aerodynamic features becomes negligible when the grade is equal to or exceeds 4 percent. Consequently, because the design of truck climbing lanes typically occurs on relatively steep grades (greater than or equal to 4 percent), it would be reasonable to ignore the vehicle's aerodynamic features in the design of climbing lanes.

Impact of Engine Efficiency on Truck Performance

The study evaluated three engine efficiency values: 0.85, 0.88, and 0.95. Using the equilibrium speeds of Table 1, the percentage change in the equilibrium speed relative to the base case engine efficiency (efficiency of 88 percent) was computed. The results demonstrate that the percentage change in the vehicle equilibrium speed increases as the roadway grade increases. This is partially because high engine efficiency provides better grade negotiation capabilities especially for higher grades. Specifically, this better grade negotiation capability becomes apparent for an 8 percent upgrade. For example, the equilibrium speeds of Table 1, demonstrate an increase in the equilibrium speed from 8 km/h to 31 km/h for an increase in engine efficiency from 85 to 95 percent for a truck equipped with radial tires traveling along an 8 percent upgrade. Accordingly, the resulting percentage changes are -27.3 percent, 0 percent, and +181.8%. The results demonstrate the significant impact of engine efficiency on truck performance along upgrade sections especially when the grade exceeds 4 percent.

Truck Performance Curves

Having completed evaluation of potential factors' impact on truck acceleration behavior, truck performance curves are provided in Figure 4 and Figure 5. Particularly, Figure 4 and Figure 5 illustrate the variation in truck performance curves for different aerodynamic aids, engine efficiencies, and tire types. It should be noted that these truck performance curves were generated using the TRUCKSIM software. Alternatively, practitioners could utilize the TRUCKSIM software to model truck performance along grade sections without the need to utilize the truck performance curves that are provided in the two figures.

In comparing the performance curves of Figure 4 and Figure 5 to the existing HCM curves, a number of conclusions can be derived. First, differences in the vehicle equilibrium speed depending on whether a vehicle is accelerating or decelerating are non-existent (which is not the case with the HCM curves). Second, the radial tire truck performance curves of Figure 4 are

similar to the HCM curves. However, noticeable differences are observed in the equilibrium speed for different tire types, especially for low road grades. For example, the equilibrium speeds are 102 and 112 km/h for bias ply and radial tires, respectively considering a drag coefficient of 0.58. This speed difference can incur significant safety impacts. Specifically, according to the AASHTO Policy on the Geometric Design of Highways and Streets, traffic safety and throughput will be greatly affected if a 16 km/h (10 mph) or greater speed reduction is expected for a typical heavy truck. Lastly, it is observed that TRUCKSIM software estimates lower equilibrium speeds in comparison to the HCM for steep road grades. For example, the HCM estimates an equilibrium speed of 27 km/h for an 8 percent grade while the TRUCKSIM software estimates an equilibrium speed of 10 km/h or less. This is attributed to the capturing of gear-shifting behavior in the TRUCKSIM software.

Additionally, the curves assume that truck speeds are only constrained by the vehicle dynamics and thus may not reflect speed limit effects on vehicle speeds. However, it should be noted that accounting for the speed limit is easily achieved by considering a maximum vehicle speed in modeling truck behavior.

EXAMPLE APPLICATION OF MODEL

In order to demonstrate the potential benefits of the TRUCKSIM software, the software was run on a sub-section of I-81. Specifically, a 45-km section of I-81 in the state of Virginia from milepost 118 to milepost 143 between Christiansburg and Roanoke was tested as part of this research effort, as illustrated Figure 6. The southbound traffic travels upgrade (from left to right), while the northbound traffic travels downgrade (from right to left). The vertical profiles for both directions are similar in many aspects except for an exceptionally high upgrade in the southbound direction in the Christiansburg exit vicinity. It should be noted that the minimum speed decreases by 8 km/h towards the end of the section (milepost 137 to 143) because the speed limit is reduced from 65 to 60 mph.

The AASHTO Policy on the Geometric Design of Highways and Streets identifies a number of criteria for locating climbing lanes. (1) The truck speed is at least 16 km/h (10 mph) less than the surrounding traffic stream speed, (2) the traffic volume on the roadway is greater than 200 veh/h, (3) the truck percentage is greater than 10 percent, and (4) inferior behavior of trucks results in a reduction in the roadway level of service (LOS). Given that the study section includes traffic and truck volumes that exceed the minimum requirements, it is sufficient to identify the locations at which the truck speed is at least 16 km/h less than the traffic stream speed in locating truck climbing lanes. It should be noted that the TRUCKSIM software considers the first three criteria in identifying the location of truck climbing lanes.

The results indicate that a significant proportion of the study section involves truck speeds below the minimum speed threshold, which was set at 16 km/h (10 mph) less than the regular traffic speed (free-speed in most cases), as summarized in Table 4. For example, in the case of bias ply tires, approximately 49 percent of the total distance traveled involves travel at a speed below the 60 mph threshold (70 mph free-speed minus the 10 mph speed differential) considering a truck with full aerodynamic treatment. This percentage decreases to 36 percent if bias ply tires are replaced for radial tires, which constitutes a reduction in the truck climbing lanes by 13 percent.

Table 4 demonstrates the following. First, in general, the climbing lane requirements are higher for the southbound versus the northbound direction of travel. Certainly, this was due to the fact that traveling along the southbound direction involves moving along more significant and sustained upgrade sections in comparison to travel in the northbound direction, as demonstrated in the vertical profile of Figure 6. Second, increasing the truck climbing lane speed threshold will result in noticeable increases in the climbing lane requirements. For example, in the southbound direction,

the percentage of distance requiring climbing lanes is 29, 36, and 50 percent for a speed threshold of 55, 60, and 65 mph, respectively; while, for the northbound direction, the values are 7, 11, and 17 percent. Third, the results indicate that a change in tire type generally results in at least a 10 percent change in the climbing lane requirements, except for some minor scenarios such as the northbound direction with a 55 mph climbing lane speed threshold. Consequently, the results clearly demonstrate the significance of the tire type on the design of climbing lanes. Finally, the results indicate that the truck's aerodynamic features and the engine efficiency have a moderate impact on the climbing lane requirements (differences are in the range of 10 percent). Consequently, we recommend that these factors be considered in the design of climbing lanes.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The paper demonstrates that the variable power vehicle dynamics model developed by Rakha *et al.* (5 and 6) produces truck acceleration behavior that is consistent with the HCM and the AASHTO Policy on the Geometric Design of Highways and Streets design procedures if identical roadway and truck characteristics are incorporated. The model offers a number of advantages over the HCM and the AASHTO procedures given that it is sensitive to roadway and truck characteristics. The paper also demonstrates that the TRUCKSIM software, which solves the second order vehicle motion ODE, can estimate vehicle speeds at a user defined time interval along a composite grade section. This tool can be of significant benefit to practitioners in identifying locations of climbing lanes along roadway segments, automating the current state-of-practice procedures, and extending the current procedures by considering factors that are not considered in the state-of-practice procedures. Furthermore, using the software, the paper extends the HCM and the AASHTO truck performance curves to cover different truck features, namely the tire type, aerodynamic features, engine efficiency, and percentage mass on the tractive axle.

The major findings of this study can be summarized as follows:

1. Changing the percentage mass on the tractive axle has a minimum impact on truck performance along grade sections. Consequently, we recommend the use of a fixed value of 35 percent.
2. Tire type has a considerable impact of truck performance along grade sections. Consequently, it is recommended that this factor be considered in the design of truck climbing lanes.
3. In general the truck aerodynamic features have a minimum impact on truck performance at low speeds and have a significant impact at high speeds. Differences in climbing lane requirements in the range of 10 percent were observed for the I-81 case study.
4. In general engine efficiency has a minimum impact of truck performance at low speeds. However, the variable is critical in the design of climbing lanes for steep upgrade sections but this factor could be accounted for directly by altering the vehicle power. It should be noted that the engine efficiency may deteriorate with the vehicle and engine age. The study does not attempt to quantify the effect of vehicle age on the engine efficiency; however, it is recommended that further research be conducted in order to characterize the deterioration of engine efficiency as a function of engine age and its impact on the design of truck climbing lanes.

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VARIABLE DEFINITIONS

A	=	Vehicle frontal area (m ²)
η	=	Transmission efficiency
μ	=	Coefficient of friction between tires and pavement
a	=	The maximum vehicle acceleration (m/s ²)
$a(t_i)$	=	Vehicle acceleration at instant t_i
C_d	=	Vehicle drag coefficient
C_h	=	Altitude coefficient
C_r	=	Rolling coefficient
c_1	=	Constant (0.047285)
c_2, c_3	=	Rolling resistance coefficients
F	=	Tractive effort effectively acting on truck (N)
$F(t_i)$	=	Effective tractive force at instant t_i
F_{max}	=	Maximum tractive force
F_t	=	Tractive effort (N)
H	=	Altitude (m)
i	=	Percent grade (m/100 m)
M	=	Vehicle mass (kg)
M_{ta}	=	Vehicle mass on tractive axle (kg)
P	=	Engine power (kW)
R	=	Total resistance force, which is the sum of the aerodynamic, rolling, and grade resistance forces (N)
R_a	=	Air drag or aerodynamic resistance (N)
R_g	=	Grade resistance (N)
R_r	=	Rolling resistance (N)
v	=	Vehicle speed (km/h)
$v(t_i)$	=	Vehicle speed at instant t_i
v_0	=	Optimum speed which is the speed at which a vehicle attains maximum power (km/h)
w	=	Vehicle weight-to-power ratio (kg/kW)
x	=	Distance traveled by vehicle (m)
$x(t_i)$	=	Vehicle location along test section at instant t_i
Δt	=	Duration of time interval used for solving the ODE (in this case 1-second duration)
β	=	Vehicle power reduction factor (unitless)
v_m	=	Equilibrium speed of a vehicle (km/h)
K_T	=	Tractive force constant (kW). $K_T = 3600\eta P$
K_a	=	Aerodynamic resistance force constant. $K_a = c_1 C_d C_h A$
K_{r1}	=	Rolling resistance force speed coefficient. $K_{r1} = \frac{9.8066 \cdot C_r \cdot M}{1000} \cdot c_2$
K_{r2}	=	Rolling resistance force constant. $K_{r2} = \frac{9.8066 \cdot C_r \cdot M}{1000} \cdot c_3$
b	=	$\sqrt[3]{-27K_a^2 d - 2K_{r1}^3 - 9K_a K_{r1} c + \sqrt[2]{4(-K_{r1}^2 + 3K_a c)^3 + (-27K_a^2 d - 2K_{r1}^3 - 9K_a K_{r1} c)^2}}$
c	=	$\begin{cases} K_{r2} + R_g & v_m \geq v_0 \\ K_{r2} + R_g - \frac{K_T}{v_0} + \frac{K_T}{v_0^2} & v_m < v_0 \end{cases}$
d	=	$\begin{cases} -K_T & v_m \geq v_0 \\ -\frac{K_T}{v_0} & v_m < v_0 \end{cases}$

$$\begin{aligned} \mathbf{e} &= \sqrt[3]{27K_a^2K_T - 2K_{r1}^3 - 9K_aK_{r1}f + \sqrt[2]{4(-K_{r1}^2 + 3K_af)^3 + (27K_a^2K_T - 2K_{r1}^3 - 9K_aK_{r1}f)^2}} \\ \mathbf{f} &= K_{r2} + R_g \end{aligned}$$

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			Engine Efficiency / Drag Coefficient											
			85 percent				88 percent				95 percent			
			0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58
Tire Type / Roadway Grade	Bias ply tires	0	92	95	98	100	93	97	100	102	97	101	104	106
		2	64	65	66	66	65	66	67	68	69	70	71	72
		4	45	46	46	46	47	47	47	48	50	50	51	51
		6	34	34	34	35	35	36	36	36	38	38	38	38
		8	6	6	6	6	8	8	8	8	18	18	19	19
	Radial tires	0	99	104	108	110	101	106	110	112	105	110	114	116
		2	68	70	71	72	70	72	73	74	74	76	77	78
		4	48	48	49	49	49	50	50	50	53	53	54	54
		6	36	36	36	36	37	37	37	37	40	40	40	40
		8	8	8	8	8	11	11	11	11	29	30	31	31

Table 1: Equilibrium Speed (km/h) as a Function of Tire Type, Engine Efficiency, and Aerodynamic Aids

			Engine Efficiency / Drag Coefficient											
			85 percent				88 percent				95 percent			
			0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58
Tire Type / Roadway Grade	Bias ply tires	0	7.1%	8.7%	9.3%	9.1%	7.9%	8.5%	9.1%	8.9%	7.6%	8.2%	8.8%	8.6%
		2	5.9%	7.1%	7.0%	8.3%	7.1%	8.3%	8.2%	8.1%	6.8%	7.9%	7.8%	7.7%
		4	6.3%	4.2%	6.1%	6.1%	4.1%	6.0%	6.0%	4.0%	5.7%	5.7%	5.6%	5.6%
		6	5.6%	5.6%	5.6%	2.8%	5.4%	2.7%	2.7%	2.7%	5.0%	5.0%	5.0%	5.0%
		8	25.0%	25.0%	25.0%	25.0%	27.3%	27.3%	27.3%	27.3%	37.9%	40.0%	38.7%	38.7%
	Radial tires	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		4	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 2: Percentage Change of Equilibrium Speed as a Function of Tire Type

			Engine Efficiency / Drag Coefficient											
			85 percent				88 percent				95 percent			
			0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58
Tire Type / Roadway Grade	Bias ply tires	0	8.0%	5.0%	2.0%	0.0%	8.8%	4.9%	2.0%	0.0%	8.5%	4.7%	1.9%	0.0%
		2	3.0%	1.5%	0.0%	0.0%	4.4%	2.9%	1.5%	0.0%	4.2%	2.8%	1.4%	0.0%
		4	2.2%	0.0%	0.0%	0.0%	2.1%	2.1%	2.1%	0.0%	2.0%	2.0%	0.0%	0.0%
		6	2.9%	2.9%	2.9%	0.0%	2.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.3%	5.3%	0.0%	0.0%
	Radial tires	0	10.0%	5.5%	1.8%	0.0%	9.8%	5.4%	1.8%	0.0%	9.5%	5.2%	1.7%	0.0%
		2	5.6%	2.8%	1.4%	0.0%	5.4%	2.7%	1.4%	0.0%	5.1%	2.6%	1.3%	0.0%
		4	2.0%	2.0%	0.0%	0.0%	2.0%	0.0%	0.0%	0.0%	1.9%	1.9%	0.0%	0.0%
		6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.5%	3.2%	0.0%	0.0%

Table 3: Percentage Change of Equilibrium Speed as a Function of Truck Aerodynamic Features

a. Northbound Direction

		Engine Efficiency 85%				Engine Efficiency 88%				Engine Efficiency 95%			
		0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58
Min. Speed 55 mph	Bias ply	17	14	11	10	15	13	10	10	12	10	9	8
	Radial	11	9	8	7	10	9	7	7	9	7	6	5
Min. Speed 60 mph	Bias ply	32	24	20	17	27	21	17	16	21	16	14	12
	Radial	18	14	12	11	16	12	11	11	13	11	10	10
Min. Speed 65 mph	Bias ply	51	44	35	29	48	38	29	27	38	29	23	22
	Radial	34	24	19	18	29	22	18	17	22	18	15	14

b. Southbound Direction

		Engine Efficiency 85%				Engine Efficiency 88%				Engine Efficiency 95%			
		0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58	0.96	0.78	0.64	0.58
Min. Speed 55 mph	Bias ply	49	46	43	42	47	44	41	38	43	38	33	32
	Radial	41	34	32	31	38	32	30	29	32	29	27	26
Min. Speed 60 mph	Bias ply	65	59	52	51	62	55	50	49	55	49	46	45
	Radial	51	47	43	40	49	45	40	36	45	38	34	33
Min. Speed 65 mph	Bias ply	81	78	70	66	79	74	65	63	72	64	57	54
	Radial	67	59	53	51	63	54	51	50	56	50	47	44

Table 4: Percentage Distance Requiring Climbing Lanes along the I-81 Study Section

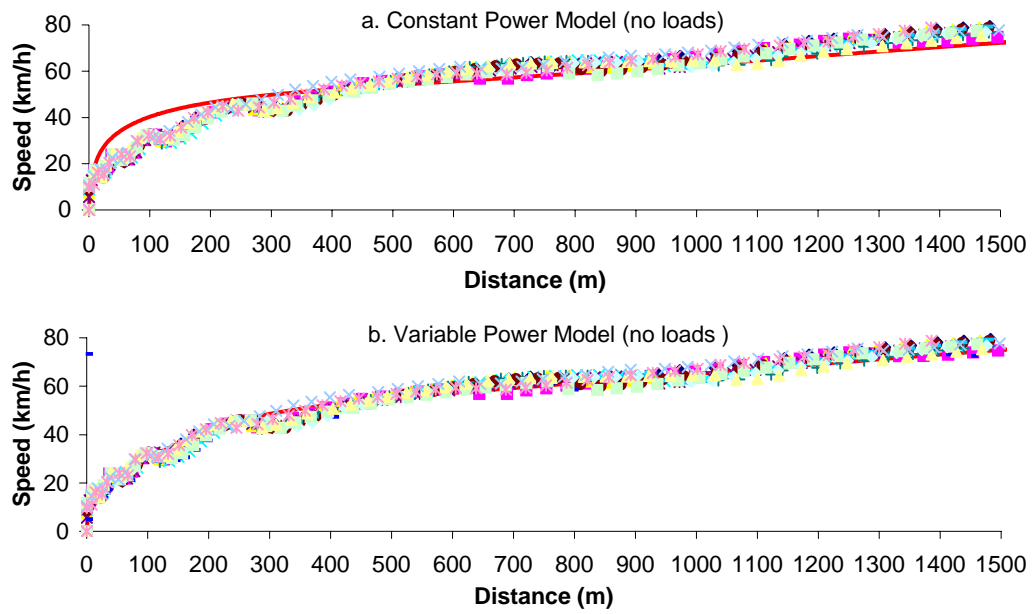


Figure 1: Sample Speed Profile Validation of Vehicle Dynamics Model (NTC-350 Engine) (Source: Rakha and Lucic (4))

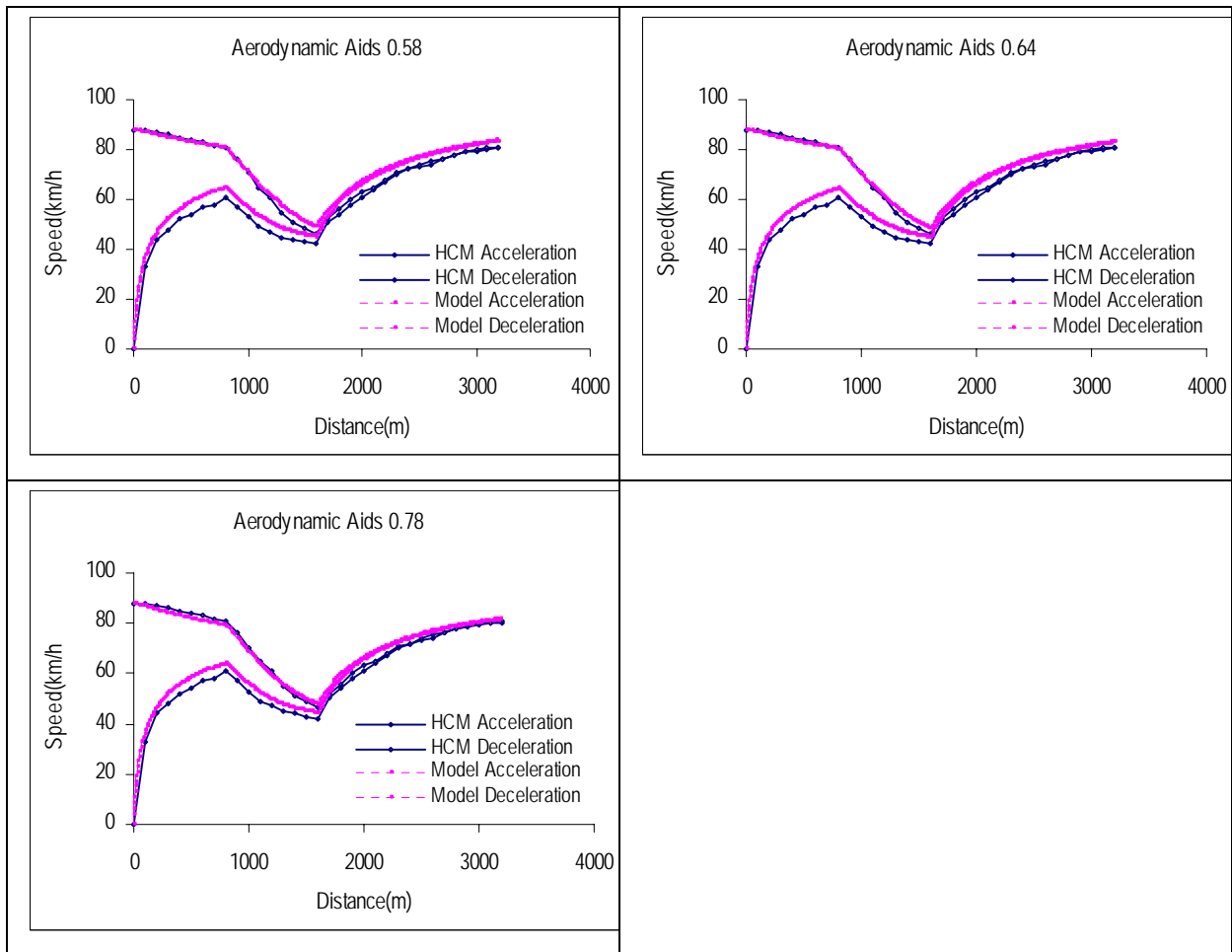


Figure 2: Impact of Aerodynamic Aids on Truck Speed Profile

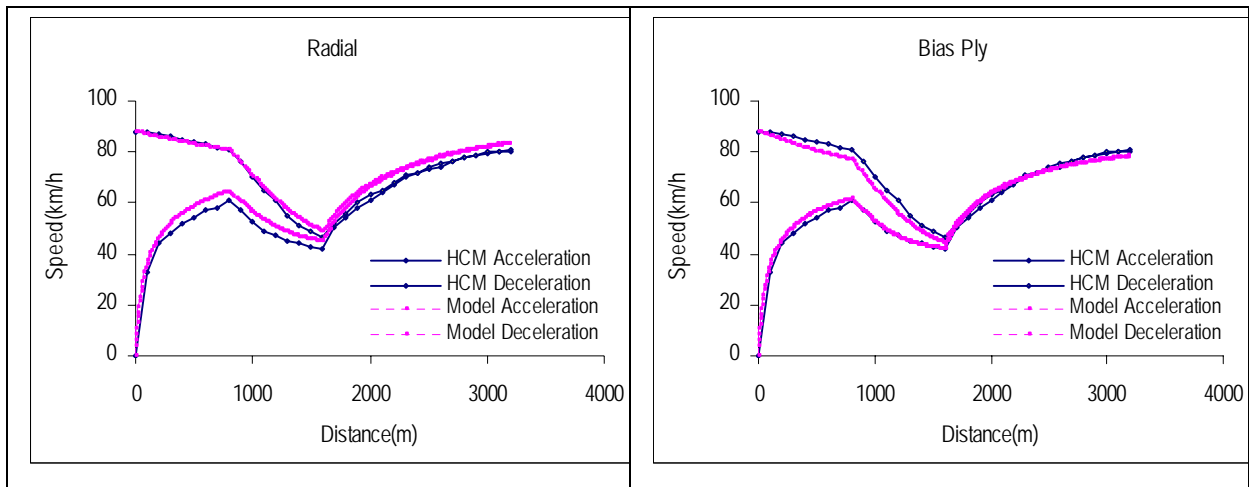


Figure 3: Impact of Truck Tire on Truck Speed Profile

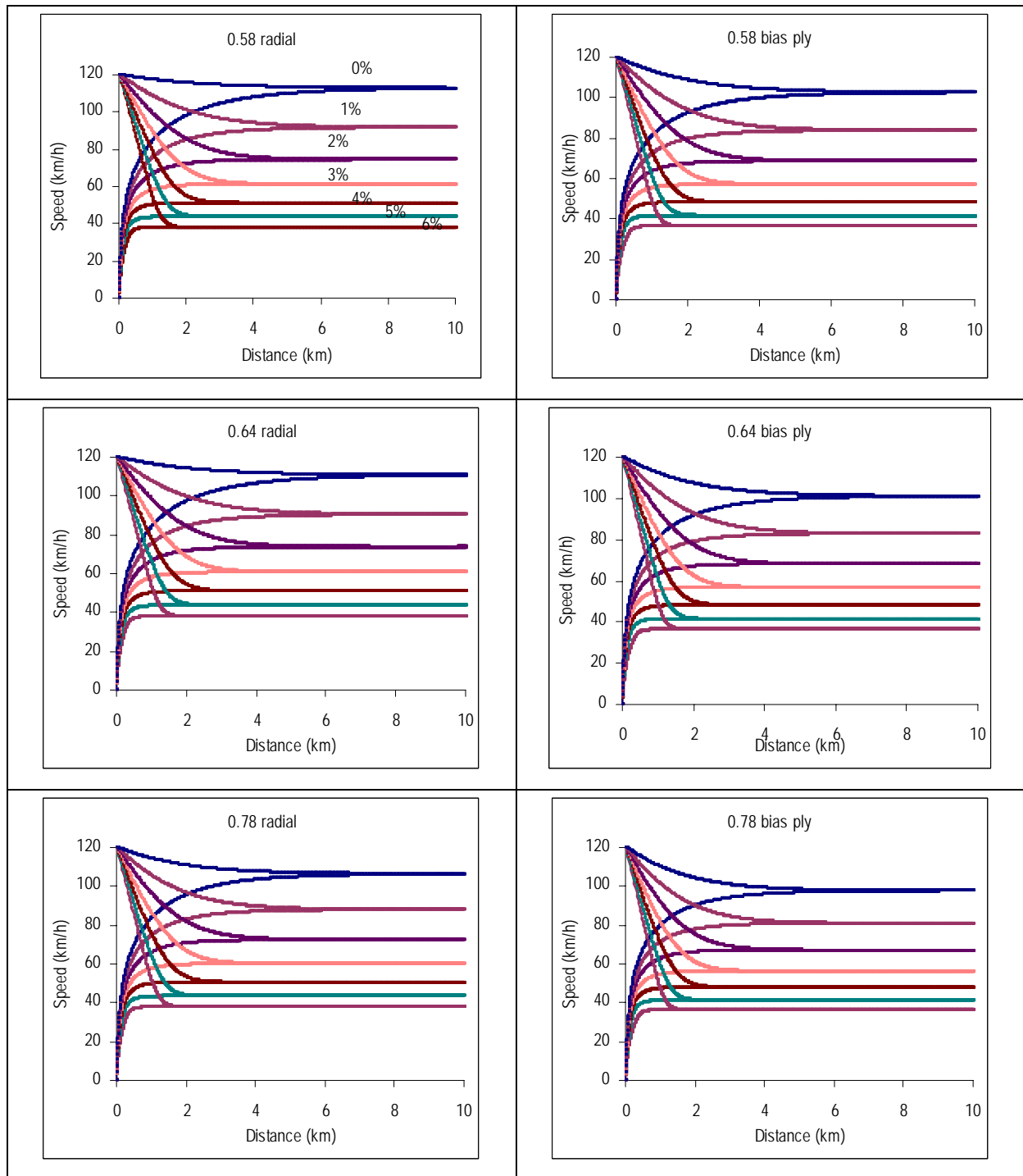


Figure 4: Truck Performance Curves (Different Aerodynamic Aids and Tire Types)

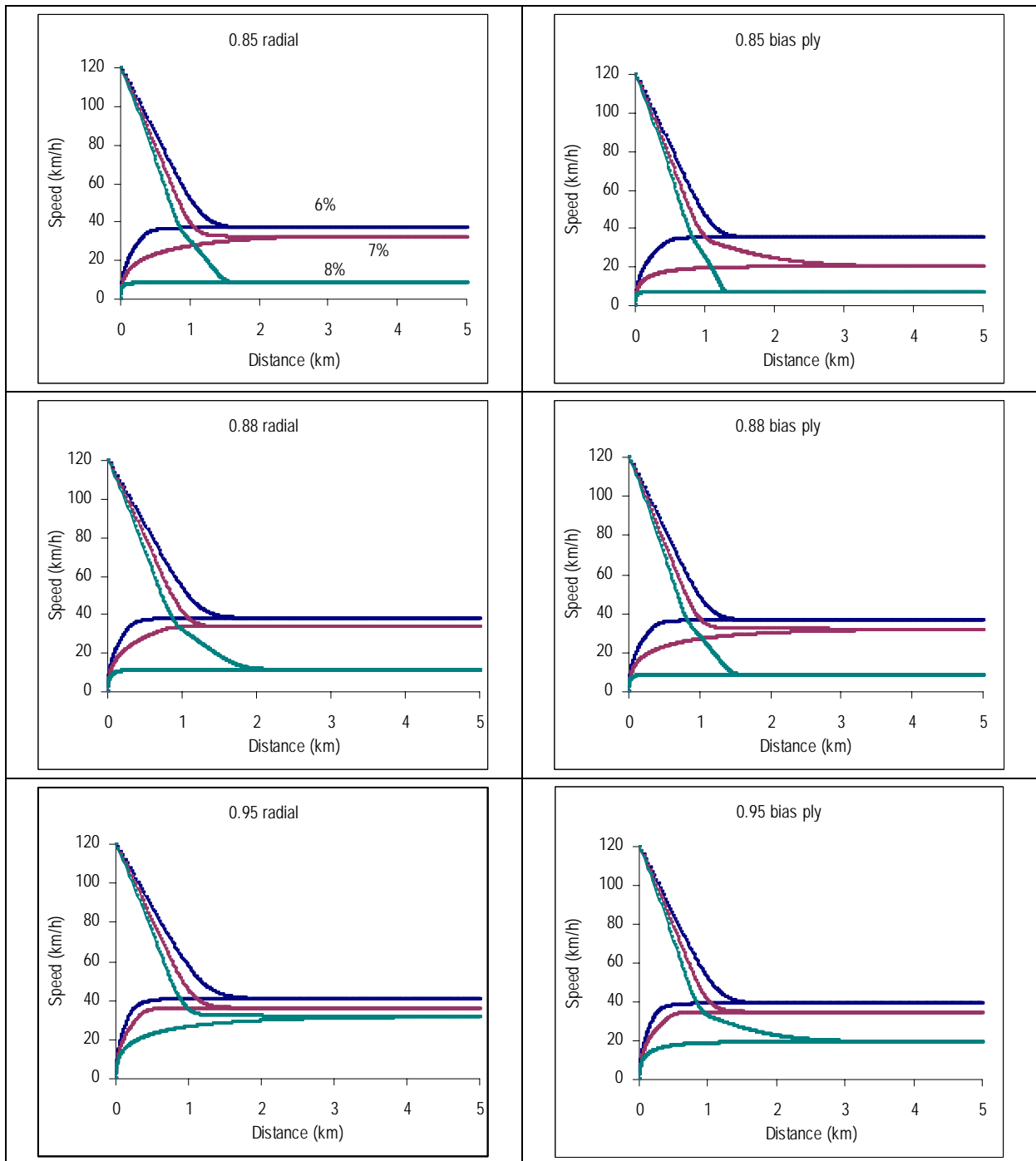


Figure 5: Truck Performance Curves (Different Engine Efficiencies)

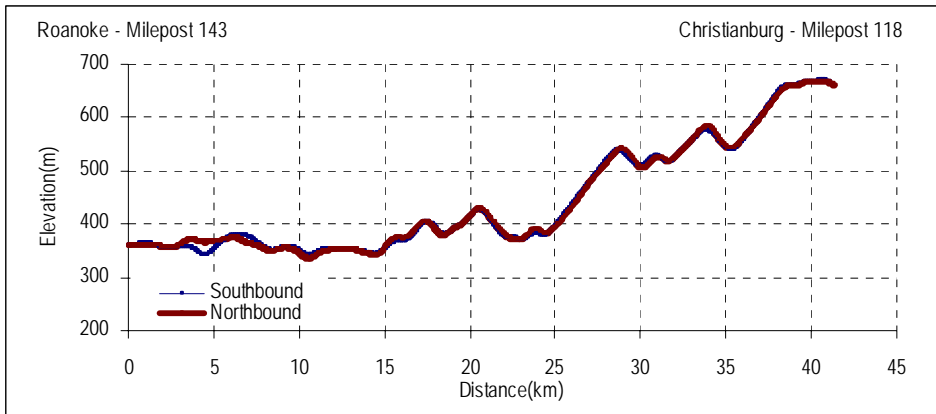


Figure 6: I-81 Test Section Vertical Profile