Development of Passenger Car Equivalents for Basic Freeway Segments

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Abstract

Passenger car equivalents (PCEs) are used in highway capacity analysis to convert a mixed vehicle flow into an equivalent passenger car flow. This calculation is relevant to capacity and level of service determination, lane requirements, and determining the effect of traffic on highway operations. The most recent Highway Capacity Manual 2000 reports PCEs for basic freeway segments according to percent and length of grade and proportion of heavy vehicles. Heavy vehicles are considered to be either of two categories: trucks and buses or RVs. For trucks and buses, PCEs are reported for a typical truck with a weight to power ratio between 76.1 and 90.4 kg/kW (125 and 150 lb/hp). The weight to power ratio is an indicator of vehicle performance. Recent development of vehicle dynamics models make it possible to define PCEs for trucks with a wider variety of weight to power ratios. PCEs were calculated from the relative impact of trucks on traffic density using the simulation model INTEGRATION. The scope of this research was to evaluate PCEs for basic freeway segments for trucks with a broader range of weight to power ratios. Such results should make freeway capacity analysis more accurate for mixed vehicle flow with a non-typical truck population. In addition, the effect of high proportion of trucks, pavement type and condition, truck aerodynamic treatment, number of freeway lanes, truck speed limit, and level of congestion was considered. The calculation of PCEs for multiple truck weight to power ratio populations was not found to be different from single truck weight to power ratio populations. The PCE values were tabulated in a compatible format to that used in the *Highway Capacity Manual 2000*.

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Chapter 1. Introduction

1.1 Background

Highway capacity is expressed in passenger cars per hour per lane. This is a measure of the maximum throughput of vehicles that can be expected to pass a point on a section of highway under prevailing roadway, traffic, and control conditions. The presence of large and/or low performance vehicles in the traffic stream results in a reduction of the allowable throughput. The Highway Capacity Manual (HCM) reasons that the reduction in allowable throughput is due to the fact that heavy vehicles take up more space and more importantly that heavy vehicles have lower performance, especially on grades. Traffic volumes containing a mix of vehicle types must be converted into an equivalent flow of passenger cars using passenger car equivalents (PCEs). The procedure in the HCM allows that freeway traffic volumes containing a mix of vehicle types be adjusted by the use of a heavy vehicle factor, f_{HV}, into an equivalent flow rate of passenger cars. The heavy vehicle adjustment factor is based on the passenger car equivalence of trucks, buses, and recreation vehicles (RVs). According to the HCM 2000 (1), the heavy vehicle adjustment factor is found as

$$f_{HV} = \frac{1}{1 + P_T\left(E_T - 1\right) + P_R\left(E_R - 1\right)} \tag{1.1}$$

where P_T and P_R are the proportion of trucks/buses and RVs in the traffic stream respectively, and E_T and E_R are the PCEs for trucks/buses and RVs respectively. The HCM considers trucks and buses to have the same PCE because trucks are generally the only heavy vehicle type present in the traffic stream.

PCEs are given in the HCM 2000 for extended freeway segments as well as for specific grades. An extended freeway segment may contain a number of upgrades, downgrades, and level segments without a single uniform grade. As long as no single grade is of 3% or greater and longer than 0.4 km (0.25 mi) or no single grade is of less than 3% and longer than 0.8 km (0.5 mi), extended segment analysis may be applied. For grades that exceed these criteria, a specific grade analysis of heavy vehicles should be applied due to their significant effect on traffic flow. For extended freeway segments, PCEs are given according to the terrain type: level, rolling, or mountainous. No consideration is given as to the truck type, proportion of trucks, or freeway facility type. PCEs for specific grades however, are given with regard to percent of grade, length of grade, and proportion of heavy vehicles. In addition, the HCM 2000 provides a method for calculating PCEs on composite grades.

Level of service (LOS) is a familiar term in highway capacity analysis. This term, originally introduced in the 1965 HCM, correlates the driver's perception of operating conditions with traffic flow parameters such as density, speed, volume to capacity (v/c) ratio, and flow rate. LOS operating conditions are divided into five categories, A through E. Each of these categories represents a range of traffic flow parameters that reflect a driver's perceptions of quality of service. Quality of service includes speed, travel time, freedom to maneuver, traffic interruptions, comfort, and convenience. The HCM 2000 primarily defines LOS in terms of density; the LOS categories for basic freeway segments are provided in Table 1. These LOS categories are based on a free-flow speed of 120 km/h (75 mi/h).

Table 1. LOS categories for basic freeway segments as suggested in the HCM 2000 (1).

LOS	**Maximum Density**		**Minimum Speed**		**Maximum v/c**	**Maximum Flow Rate**
	(pc/km/ln)	**(pc/ml/ln)**	**(km/h)**	**(mi/h)**		**(pc/h/ln)**
A	7	11	120	75	0.34	820
B	11	18	120	74.8	0.56	1350
C	16	26	114.6	70.6	0.76	1830
D	22	35	99.6	62.2	0.90	2170
E	28	45	85.7	53.3	1.00	2400

1.2 Research Objectives and Research Significance

The objective of this research was to evaluate PCEs for basic freeway segments considering variables beyond the scope of the current HCM 2000. Specifically, the variables that were examined are variance in truck weight to power ratio, truck power, high proportion of trucks, pavement type and condition, truck aerodynamic treatment, number of freeway lanes, truck speed limit, and level of congestion.

An objective of this research was to verify the hypothesis that a single truck population, containing only a typical weight to power ratio, will perform the same as a multiple truck population, containing a mix of weight to power ratios. The effects of all variables on single truck population PCEs were compared with the effects of all variables on multiple truck population PCEs. Different truck populations were simulated by changing the standard deviation of weight to power ratio around the average. Variability in truck power was tested for the average single weight to power ratio truck population. It was hypothesized that PCEs will be higher for trucks with lower engine power. Another objective of this research was to verify a trend observed in the HCM 2000; that the PCE for a realistic truck population decreases with increasing proportion of trucks. In this research, an even higher proportion of trucks was examined than the limits of the HCM 2000, which considers up to 25% proportion of trucks.

Pavement type and condition have an impact on truck performance. An objective of this research was to verify the hypothesis that PCEs developed for trucks will vary by pavement type and condition. Poor pavement condition was expected to result in increased PCE values compared to the same truck population operating on good pavement condition. The development of PCEs by pavement condition could result in a capacity justification for pavement resurfacing or reconstruction. Another objective was to verify the hypothesis that truck aerodynamic treatment will have a significant effect on calculated PCEs. Both pavement type and condition as well as aerodynamic treatment affect the vehicle dynamics of the truck populations.

An objective of this research was to verify the hypothesis that trucks on freeways with more than two directional lanes will have lower PCEs than trucks on freeways with only two directional lanes. This hypothesis is based on the availability of passing being increased for freeways with more than two directional lanes. In addition, the effect of a truck lane restriction to the rightmost two lanes was considered. Another objective was to verify the hypothesis that the imposition of a truck speed limit below the speed limit of all other vehicles results in higher PCEs. Many states throughout the nation have imposed truck lane restrictions and truck speed limits. The results of this research could supply a capacity justification for or against these practices.

Lastly, it was hypothesized that increasing level of congestion will result in increasing PCEs. The prevailing traffic density represents the level of congestion on the freeway segment. As congestion increases, the amount of interaction of trucks with passenger cars and other trucks should increase. The negative aspects of this interaction were expected to result in increasing PCEs for increasing prevailing traffic density.

The significance of this research is that PCEs developed herein can be utilized to enhance the HCM 2000. Improvements to the accuracy of highway capacity analysis should increase justification for capacity improvements. PCEs developed as part of this research were tabulated in a form compatible with the current HCM 2000, with the hope that they can be incorporated into a future edition of the HCM.

1.3 Paper Layout

Chapter 2 is a literature review of previous research concerning the development of PCEs. It is organized both by subject methodology and chronologically, progressing from PCEs applied in the 1965 HCM to those applied in the current HCM 2000. The literature review is a substantial resource for anyone interested in the historical development of PCEs. Many alternative methods for calculating PCEs are presented with full references.

Chapter 3 describes the methodology for this research. It describes the approach to calculating PCEs and the parameters needed for the traffic simulation program INTEGRATION. Specific attention is given to examining the effect of the variables outlined in the research objectives.

Chapter 4 is a presentation of the results specific to single truck populations.

Chapter 5 is a presentation of the results specific to multiple truck populations.

Chapter 6 presents the conclusions and recommendations drawn from the results of this research.

Chapter 2. Literature Review

Various methods have been used to calculate PCEs throughout the evolution of highway capacity analysis. These methods have been applied both for two lane highways and multilane highways or freeways.

2.1 PCEs in the 1965 HCM

The 1965 HCM, which was the second edition of the HCM, formally introduced the concept of LOS and the definition of PCE (2). In the 1965 HCM, PCE was defined as "The number of passenger cars displaced in the traffic flow by a truck or a bus, under the prevailing roadway and traffic conditions" (3). The 1965 HCM used relative speed reduction to define PCEs for two lane highways and quantified this by the relative number of passings known as the Walker method. For multilane highways, PCEs were based on the relative delay due to trucks (4).

The relative delay due to trucks was calculated using the Walker method for two-lane highways in conjunction with gradability curves and field observations. Gradability curves relate speed distribution verses grades of specific length and percent. Steeper grades and longer grades result in a more drastic speed reduction. Cunagin and Messer (4) suggested that the gradability curve used to calculate PCEs in the 1965 HCM. was based on a truck with a weight to power ratio of 197.9 kg/kW (325 lb/hp), which was considered typical for trucks of the time. However, Roess and Messer (13) emphasized that the normal truck assumed in the 1965 HCM was of 121.8 kg/kW (200 lb/hp). Regardless of which truck was assumed, the gradability curve was eventually considered obsolete for vehicle performance calculations and was updated in subsequent years.

PCEs for multilane highways based on relative delay may be found as

$$E_T = \frac{\left(D_{ij} - D_B\right)}{D_B} \qquad [2.1]$$

where D_{ij} is the delay to passenger cars due to vehicle type *i* under condition *j* and D_B is the base delay to standard passenger cars due to slower passenger cars.

PCEs in the 1965 HCM were reported for grades of specific length and percent, proportion of trucks, and LOS grouped as A through C or D and E. As expected, the highest PCE was reported for the longest and steepest grade with the highest proportion of trucks and the lowest LOS. However, in many cases the PCE for a given grade and LOS decreased with increasing proportion of trucks. This result has been obtained by many other researchers, as mentioned later.

2.2 PCEs Based on Delay

In 1983, Cunagin and Messer (4) used an extension of the 1965 HCM method to calculate PCEs for multilane highways based on relative delay. In their approach, they used a combination of the Walker method of relative number of passings and the relative delay method. They recognized that on multilane highways, passing or overtaking vehicles are inhibited only by concurrent flow traffic. PCEs were calculated as

$$E_T = \frac{\left(OT_i / VOL_i\right)\left[\left(1/SP_M\right) - \left(1/SP_B\right)\right]}{\left(OT_{LPC} / VOL_{LPC}\right)\left[\left(1/SP_{PC}\right) - \left(1/SP_B\right)\right]} \qquad [2.2]$$

where OT_i is the number of overtakings of vehicle type *i* by passenger cars, VOL_i is the volume of vehicle type *i*, OT_{LPC} is the number of overtakings of lower performance passenger cars by passenger cars, VOL_{LPC} is the volume of lower performance passenger cars, SP_M is the mean speed of the mixed traffic stream, SP_B is the mean speed of the base traffic stream with only high performance passenger cars, and SP_{PC} is the mean speed of the traffic stream with only passenger cars.

Since at low traffic volumes faster vehicles will not likely be impeded in overtaking other vehicles, equation [2.2] was used with the omission of the bracketed expression. However at higher traffic volumes, such as near capacity, slower overtaking vehicles will impede faster vehicles. This results in queue formation in the passing lane. In their research, Cunagin and Messer applied a linear combination of equation [2.2] with and without the bracketed expression for intermediate volumes.

Cunagin and Messer examined three different grade conditions, flat, moderate, and steep. In addition, they examined proportion of trucks and volume levels corresponding to each of the five LOS categories. The PCEs developed by Cunagin and Messer increased for proportion of trucks and volume levels in flat and moderate grade conditions. However, in steep grade conditions, the PCEs decreased for increasing proportion of trucks.

2.3 PCEs in the TRB Circular 212

The TRB Circular 212 titled "Interim Materials on Highway Capacity" was published in 1980, as an effort to summarize the current knowledge in highway capacity and to identify needs for immediate research before the completion of the planned third edition of the HCM (5). PCEs reported in TRB Circular 212 were developed based on the constant v/c method. An article published by Linzer et al (6) in 1979 describes the constant v/c method, whereby PCEs are calibrated such that the mixed traffic flow will produce the same v/c ratio as a passenger car only flow.

The research by Linzer et al made use of design charts resulting from microsimulation done by the Midwest Research Institute (MRI) under the direction of St John and Glauz (7) in 1976. The design chart relates the percent grade, mixed vehicle flow, and percent reference trucks to percent capacity (equivalent to v/c ratio). The PCE is formulated as

$$E_T = \frac{q_B - q_M\left(1 - P_T\right)}{q_M * P_T} \qquad [2.3]$$

where q_B is the equivalent passenger car only flow rate for a given v/c ratio, q_M is the mixed flow rate, and P_T is the proportion of trucks in the mixed traffic flow.

St John and Glauz introduced the concept of percent reference trucks to account for the variability of truck performance characteristics by truck type. This was accomplished by aggregating all truck types into a single reference truck. The Ohio Department of Transportation provides an excellent copy of the most common vehicle classification scheme on their website (20). The Federal Highway Administration (FHWA) also follows this vehicle classification scheme whereby trucks are considered to be vehicle types 5 through 13; the FHWA vehicle classification scheme is also available online (21). For any given truck population, St John and Glauz derived weight factors to compute the percent reference trucks. The derived weight factors were based on the performance of each truck type relative to the slowest speed truck. The higher the weight factor, the worse performing the subject truck is compared to the slowest speed truck. The equation for percent reference trucks is

$$Percent \quad reference \quad trucks = P_T\left(3.16 p_{10} + 1.41 p_9 + 0.14 p_8 + 0.06 p_7\right) \qquad [2.4]$$

where P_T is the total proportion of trucks and p_i is the proportion of index truck type *i* out of the total proportion of trucks.

The typical truck used in calculation of PCEs for the TRB Circular 212 by Linzer et al was of 182.7 kg/kW (300 lb/hp), slightly less than the 197.9 kg/kW (325 lb/hp) truck used in the 1965 HCM, and reflecting the increased performance of trucks since the 1960's. In addition, a light truck of 91.4 kg/kW (150 lb/hp) and a heavy truck of 213.2 kg/kW (350 lb/hp) were used to calculate PCEs. Truck performance curves were used from research conducted by Pennsylvania State University, with initial truck speed of 88.5 km/h (55 mi/h). Since the research by Linzer et al calculated PCEs for truck populations with a single weight to power ratio, the percent reference trucks method proposed by the MRI was used by assuming that only trucks of the given weight to power ratio existed.

Results of the constant v/c method for calculating PCEs indicated that PCEs did not change significantly for changes in the v/c ratio or the freeway design speed. For this reason, PCEs reported in the TRB Circular 212 were given according to percent grade, length of grade, and percent trucks just as they had been in the 1965 HCM. In addition however, PCEs were calculated for freeways with six or more lanes as well as typical freeways with four lanes. The need to calculate PCEs for different freeway sizes (number of lanes) arose from cases of high proportion trucks and/or steep grades. PCEs developed by Linzer et al exhibit a decrease for increasing percent trucks.

2.4 PCEs Based on Speed

As an extension to his research on truck performance on upgrades in 1976, St John (8) proposed a non-linear truck factor. This non-linearity addressed the successively smaller impact of trucks on the traffic stream as the proportion of trucks increased. He reasoned that as the proportion of trucks increases platoons may form and the interaction with cars may be reduced. In addition, St John asserted that the effect of multiple truck types highlights the need for a non-linear truck factor. The truck factor was based on a speed flow relationship. He introduced the concept of equivalence kernel, which accounts for the incremental effect of trucks in a traffic stream and is used to calculate PCEs.

Hu and Johnson (9) described how to use the 1965 HCM to find PCEs based on speed in a report published in 1981. According to this report, PCEs are used to convert a mixed vehicle flow into a passenger car only flow with the same operating speed. They used equation [2.3] developed by Linzer et al (6) to calculate the PCE. Operating speeds were based on the design charts obtained by research performed by the MRI, as described in the section on the TRB Circular 212. Hu and Johnson did not use specific grade adjustments, but rather developed their PCEs based on extended freeway segments.

In 1982, Huber (10) derived equation [2.3] in a different functional form to relate PCE to the flow of a passenger car only traffic stream and a mixed vehicle traffic stream. The effect of trucks is quantified by relating the traffic flows for an equal LOS. Any equivalent LOS or impedance could be chosen for the equality. If for example, density was used to define the equal LOS criteria, the flow-density relationship could be used to relate the traffic flows at an equal density value. Huber's basic equation is formulated as

$$E_T = \frac{1}{P_T}\left(\frac{q_B}{q_M} - 1\right) + 1 \qquad [2.5]$$

where P_T is the proportion of trucks in the mixed traffic flow, q_B is the base flow rate (passenger cars only), and q_M is the mixed flow rate. Huber used the assumption of equal average travel time as the measure of LOS. Equal average travel time on a one-mile segment is equivalent to the inverse of the average speed. The consequence of his assumption of equal speed is that PCEs decrease as volumes increases. A slow moving truck will have a smaller impact on the average speed when the total volume is higher. Huber found this result objectionable and suggested that equal total travel time be used as a measure of LOS. He formulated equal total travel time as the volume in vehicles per hour multiplied by the average travel time in hours per mile. By this representation, equal total travel time is equivalent to equal density because it describes equal vehicle occupancy on the roadway in vehicles per mile. The calculation of PCE by equal density is discussed later.

In 1984, Sumner et al (11) expanded the relationship described by Huber to calculate the PCE of a single truck in a mixed traffic stream, which includes multiple truck types. This calculation requires an observed base flow, mixed flow, and flow with the subject vehicles. The equal LOS or impedance measure would cut across all three flow curves. The relationship described by Sumner et al is formulated as

$$E_T = \frac{1}{\Delta P}\left(\frac{q_B}{q_s} - \frac{q_B}{q_M}\right) + 1 \qquad [2.6]$$

where ΔP is the proportion of subject vehicles that is added to the mixed flow and subtracted from the passenger car proportion, q_B is the base flow rate (passenger cars only), q_M is the mixed flow rate, and q_S is the flow rate including the added subject vehicles. Sumner et al used total travel time in terms of vehicle hours as the equal measure of LOS. In this case total travel time was applied to urban arterial roads and measured in terms of vehicle hours, which is not equivalent to density.

Using the formulation in equation [2.6], Elefteriadou et al (3) calculated PCEs for freeways, two-lane highways, and arterials in 1997 based on equal speed. The researchers also examined the impact of prevailing traffic flow, proportion of trucks, truck type (by length and weight to power ratio), length and percent grade, and number of freeway lanes in their evaluation. Their analysis was based on specific truck types, and not truck populations. The results of the analysis by Elefteriadou et al indicated that PCEs remain mostly unchanged for increasing traffic flow on freeway segments while PCEs remain unchanged or slightly increase with increasing proportion of trucks. The report did not indicate the impact of number of freeway lanes on the PCE.

In 1984, Van Aerde and Yagar (12) developed a methodology to calculate PCE based on relative rate of speed reduction. This PCE was intended for use in average speed analysis of capacity, which is unique to two lane highways. Field observations and known speed-flow relationships were used to calibrate a multiple linear regression model that estimates the percentile speed based on the free speed and speed reduction coefficients for each vehicle type. A linear speed-flow model was chosen because the speed-flow relationship within the bounds of practical operating volumes was found to be nearly linear. The multiple linear regression model is

Percentile speed = free speed + C_1*(number of passenger cars) +* C_2*(number of trucks) +* C_3*(number of RVs) +* C_4*(number of other vehicles) +* C_5*(number of opposing vehicles)* [2.7]

where coefficients C_1 to C_5 are the relative sizes of speed reductions for each vehicle type. Although this model was formulated for two lane highways with opposing traffic flow, it could be applied to multilane highways by setting the coefficient C_5 to zero. Using the speed reduction coefficients, the PCE for a vehicle type *n* is calculated as

$$E_n = \frac{C_n}{C_1} \qquad [2.8]$$

where C_n is the speed reduction coefficient for vehilce type n and C_1 is the speed reduction coefficient for passenger cars.

2.5 PCEs in the 1985 HCM

Based on the recommendations of Roess and Messer (13), PCEs in the 1985 HCM were calculated for trucks of 60.9, 121.8, and 182.7 kg/kW (100, 200, and 300 lb/hp) with 121.8 kg/kW (200 lb/hp) being considered the normal truck population. The consideration of freeway size, introduced in the TRB Circular 212, was retained in the 1985 HCM. The shift of the typical truck from 182.7 to 121.8 kg/kW (300 to 200 lb/hp) was inspired by indications that the average truck population on freeways was between 76.1 and 103.5 kg/kW (125 and 170 lb/hp). Besides this change, the approach to calculating PCE based on v/c ratio in the TRB Circular 212 remained unchanged in the 1985 HCM. Just as in the TRB Circular 212, PCEs were greatest for long steep grades, but decreased for increasing proportion of trucks.

2.6 PCEs Based on v/c Ratio

After the publication of the 1985 HCM, the constant v/c method for calculating PCE subsided. The constant v/c method was most appropriate when LOS was defined primarily in terms of v/c ratio; however, since LOS is now defined primarily by density, the constant v/c method is no longer favorable. Traffic streams with an equal v/c ratio will not necessarily have equal density and speed and therefore LOS. However, Fan (14) applied this method in 1989 to calculate PCEs for expressways in Singapore. He reasoned that although density was used to define LOS for freeways, capacity analysis performed with PCEs would still be desirable to be based on the v/c ratio. The functional form of his relationship was a multiple linear regression equation whereby the v/c ratio was related to the PCE multiplied by the observed flow of each vehicle type. The target v/c ratio to compute PCE was at 0.67 to 1.0, corresponding to LOS D or E. Fan pointed out that for capacity analysis it would be unimportant to calculate PCEs at v/c ratios well below capacity. The results of the research by Fan were PCEs for multiple vehicle types.

2.7 PCEs Based on Headways

Realizing one of the primary effects of heavy vehicles in the traffic stream is that they take up more space, headways have been used for some of the most popular methods to calculate PCEs. In 1976, Werner and Morrall (15) suggested that the headway method is best suited to determine PCEs on level terrain at low levels of service. The PCE is calculated as

$$E_T = \left(\frac{H_M}{H_B} - P_C \right) \Big/ P_T \qquad [2.9]$$

where H_M is the average headway for a sample including all vehicle types, H_B is the average headway for a sample of passenger cars only, P_C is the proportion of cars, and P_T is the proportion of trucks. In their study, Werner and Morrall used the headway method for low speed trucks and the conventional speed method of the 1965 HCM for higher speed trucks. One question arises as to use of the headway method for low speed trucks when low speeds generally occur on upgrades rather than on level terrain. The results of the study by Werner and Morrall replicated PCEs in the 1965 HCM for higher speed trucks. PCEs were categorized by percent grade, length of grade, and LOS grouped A and B, C, or D and E.

In 1982, in an article by Cunagin and Chang (16) it was revealed that the presence of trucks in the traffic stream of a freeway result in increased average headways. The largest headways involved trucks following trucks, and the headways increased for larger truck types. Seguin et al (17) formulated the spatial headway method for calculating PCEs in 1982. This method defines the PCE as the ratio of the mean lagging headway of a subject vehicle divided by the mean lagging headway of the basic passenger car and is formulated as

$$E_T = \frac{H_{ij}}{H_B} \quad [2.10]$$

where H_{ij} is the mean lagging headway of vehicle type i under conditions j and H_B is the mean lagging headway of passenger cars. The lagging headway is determined from the rear bumper of the lead vehicle to the rear bumper of the following vehicle and therefore includes the following vehicle's length.

The constant volume to capacity method, equal density method, and spatial headway method were compared in 1986 in an article by Krammes and Crowley (2). The authors concluded that the spatial headway method was most appropriate for level freeway segments. Krammes points out that the spatial headway method not only accounts for the accepted effect of trucks due to size and lower performance, but also the psychological impact of trucks on drivers of other vehicles. This impact is in the form of aerodynamic disturbances, splash and spray, sign blockage, offtracking, and underride hazard.

Spatial headway is considered to be a surrogate measure for density. Both of which reflect the freedom of maneuverability in a traffic stream. A modification to equation [2.5] put forth by Huber to calculate PCE based on flow rate allows the calculation of PCE based on headway. The equation uses the lagging headway because it is the following vehicle's perception of maneuverability that affects the PCE. Contradictory to the findings of Cunagin and Chang, the lagging headway for trucks following trucks was found to be significantly less than the lagging headway for cars following trucks. Therefore, in contrast to the recommended equation [2.10] by Seguin, Krammes and Crowley suggest that PCE should be calculated as

$$E_T = [(1 - P_T)H_{TP} + pH_{TT}] / H_P \qquad [2.11]$$

where P_T is the proportion of trucks, H_{TP} is the lagging headway of trucks following passenger cars in the mixed vehicle stream, H_{TT} is the lagging headway of trucks following trucks in the mixed vehicle stream, and H_P is the lagging headway of cars following either vehicle type in the mixed vehicle stream. An additional improvement over equation [2.10] recommended by Seguin is that the proportion of trucks is considered in equation [2.11]. Krammes and Crowley believe that an increase in the proportion of trucks will result in higher PCEs because the opportunity for interaction between cars and trucks will increase.

A drawback of the headway method is that it must be assumed that drivers are exhibiting steady state, in lane behavior. It would be hard therefore to separate the headways observed from drivers who are either not in steady state, or are not maintaining the lane (continuously following the same vehicle). Specific to multilane highways, it is less likely that cars will continue to follow trucks given the first opportunity to pass.

2.8 PCEs Based on Queue Discharge Flow

In 2002, Al-Kaisy et al (22) published a report describing the calculation of PCE using measurements of queue discharge flow. Their hypothesis was that the effect of trucks on traffic is greater during congestion than during under saturated conditions. The congested condition is represented by queue discharge flow, where the v/c ratio is equal to one. A primary assumption of their work was that queue discharge flow capacity is constant except for the effect of trucks in the traffic stream. Al-Kaisy et al used field observations and linear programming to determine the PCE. For the case studies in their analysis, Al-Kaisy et al did not find a relationship between PCE and the proportion of trucks. However, they theorized that the PCE should decrease with increasing proportion of trucks because the interactive effect of trucks on trucks may be less than the effect of trucks on passenger cars.

2.9 PCEs Based on Density

As mentioned before, Huber (10) introduced the concept of using equal density to relate mixed flow rate and base flow rate for calculation of PCE in equation [2.5]. The drawback of Huber's computation is that it assumes the mixed vehicle flow contains passenger cars and only one type of truck. However, the formulation by Sumner et al (11) in equation [2.6] allows the calculation of the PCE of a single truck in a mixed vehicle stream including multiple truck types. As applied to freeways, density is the most common equal measure of LOS, and Webster and Elefteriadou (18) used this method to calculate PCEs for trucks in 1999. Their approach was to use simulation modeling to calculate the flow verses density relationships. Again, the researchers examined the impact of prevailing traffic flow, proportion of trucks, truck type (by length and weight to power ratio), length and percent grade, and number of freeway lanes in their evaluation. The results of the analysis by Webster and Elefteriadou indicated that PCEs increase with increasing traffic flow on freeway segments and decrease with increasing proportion of trucks and number of lanes. The most important conclusion is that truck type, as defined by length and weight to power ratio, is critical for determination of PCEs.

In 2003, Demarchi and Setti (19) published an article describing the limitations of deriving PCEs for traffic streams with multiple truck types. In an algebraic derivation, they proved that PCEs developed for a single truck type in a mixed traffic flow containing multiple truck types using equation [2.6] do not fully account for the interaction between trucks. They reasoned that considered separately, "the PCE value for the subject vehicle is normally underestimated, because the marginal impact decreases as the proportion of subject vehicles in the stream increases." Conversely, the impact of trucks already in the mixed vehicle stream is overestimated because their actual proportion should be smaller than it is prior to addition of the subject vehicles.

Demarchi and Setti suggested that a possible workaround to avoid the errors associated with calculating the PCE for each truck separately is to calculate an aggregate PCE formulated as

$$E_T = \frac{1}{\sum_i^n P_i}\left[\frac{q_B}{q_M} - 1\right] + 1 \qquad [2.12]$$

where P_i is the proportion of trucks of type i out of all trucks n in the mixed traffic flow, q_B is the base flow rate (passenger cars only), and q_M is the mixed flow rate. This equation is basically equation [2.5] put forth by Huber and modified for multiple truck types in the mixed traffic stream. This approach, using an aggregate PCE, seems to have been adopted in the 1994, 1997, and 2000 editions of the HCM. PCEs in the HCM 2000 are reported by percent grade, length of grade, and percent trucks. The PCEs exhibit a decrease for increasing proportion of trucks.

Chapter 3. Methodology

3.1 Overview

Among the methods that have been employed to calculate PCEs, the equal density method was selected for this research. A primary advantage of the equal density method is that density is used in the HCM 2000 to define LOS. Density is an indicator of freedom to maneuver in the traffic stream. In addition, density measurements are commonly made on freeways using presence type detectors. The common use of density measurements in the field makes it most practical for calculation of PCEs.

The HCM 2000 (1) defines PCE as “The number of passenger cars displaced by a single heavy vehicle of a particular type under specified roadway, traffic, and control conditions.” The PCE is also referred to as the number of passenger cars that would use the same amount of freeway capacity as a single truck or bus. It is common in this sense of the definition to equate a mixed vehicle flow to a passenger car only vehicle flow using the PCE. Equations [3.1] through [3.3] show the derivation of an aggregate PCE.

A traffic stream may contain any number of trucks of type *i*, in total amounting to *n* type trucks. Each of these truck types may be either a separate vehicle class or a distinct weight to power ratio, thus representing different vehicle sizes and performance characteristics. The flow verses density relationship may be obtained for this traffic stream by measuring the density and flow rate of a given number of simulations of the traffic stream. In a similar way, the flow verses density relationship for a traffic stream containing only passenger cars may be obtained. Figure 6 shows the flow verses density relationships for this situation.

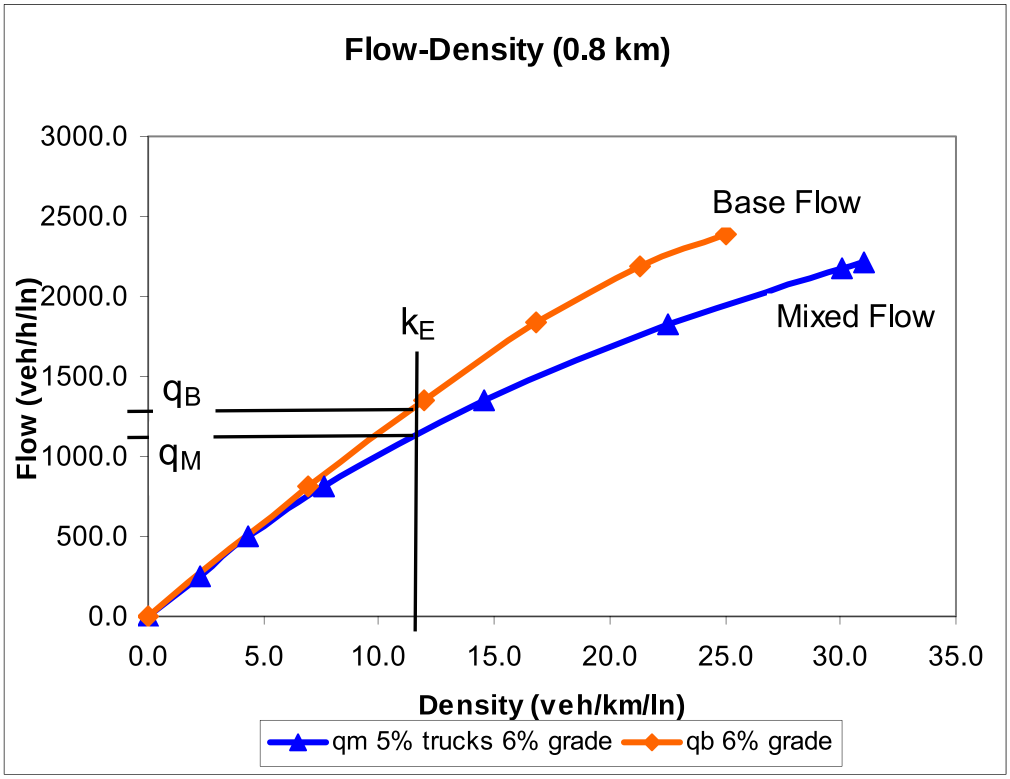

Figure 6. Flow-density relationship for a 0.8 km (0.5 mi) grade.

The flow of a passenger car only traffic stream may be related to the flow of a mixed traffic stream using an aggregate PCE and formulated as

$$q_B = \left(1 - \sum_i^n P_i\right) q_M + \sum_i^n P_i \cdot E_T \cdot q_M \qquad [3.1]$$

where q_B is the base flow rate (passenger cars only), P_i is the proportion of trucks of type i, q_M is the mixed vehicle flow rate, and E_T is the aggregate PCE.

Dividing through by q_M and subtracting 1 from each side yields

$$\frac{q_B}{q_M} - 1 = \sum_i^n P_i \left(E_T - 1\right) \qquad [3.2]$$

Finally, dividing through by $\sum_i^n P_i$ and adding 1 to each side yields

$$\frac{1}{\sum_i^n P_i}\left[\frac{q_B}{q_M} - 1\right] + 1 = E_T \qquad [3.3]$$

The general method for calculating the PCE according to equation [3.3] is as follows. First generate a flow verses density relationship for the base vehicle stream by simulating passenger cars only. Simulations of the traffic stream were obtained using the microscopic traffic simulator INTEGRATION. The simulation was conducted at 5 different flow rates, as shown in Table 1, and corresponding to the maximum service flow rate for each LOS category from the HCM 2000. Second, generate a flow verses density relationship for the mixed vehicle stream, replacing passenger cars with an equal number of trucks from the subject truck population. The proportion of trucks in this research was varied from 2 to 100 percent. Third, interpolate between observed values to obtain the base flow rate and mixed vehicle flow rate at an equal density value. Initially an equal density value of 12.4 pc/km/ln (20 pc/mi/ln), corresponding to a density at LOS C, was used. Fourth, calculate the PCE according to equation [3.3].

3.2 Variables Considered

As mentioned in the research objectives, a multitude of variables were considered, which may have an impact on the development of PCEs. The physical characteristics of the simulated network contain variables such as percent grade, length of grade, number of freeway lanes, and pavement type and condition. In addition, the simulated traffic characteristics contain variables such as flow rate, proportion of trucks, and variable truck populations. Table 2 summarizes the total number of variables which could be considered. The list of variables from Table 2 was refined for the investigative phase of the research. A smaller list of variables was created, as shown in Table 3, from which the simulations were performed. The refined list of variables made the research work load less, while still accomplishing the research objective of determining the relationships between variables. Final simulations were conducted to fill in the blanks within the data.

3.3 Plan of Research

The plan of research is summarized in the following sections.

3.3.1 Physical Network

The physical network was initially constructed using the 2, 4, and 6 percent grade and the six different length of grade variables, resulting in 18 combinations. The structure of the freeway section modeled contained two links in each chain. The first link was the subject grade, having a length that varies between 0.4 and 2.4 km (0.25 and 1.5 mi) and a grade that varies between 1 and 6 percent. The second link was always 0.11 km (0.07 mi or 370 ft) long and was used to obtain measurements of traffic flow and density. To economize simulation time, a parallel link structure was created in the simulation model. This structure is idealized in Figure 1.

Table 2. Complete list of variables considered.

	Physical Network				**Traffic Characteristics**		
	% Grade	Length of Grade (km) [mi]	# of Lanes	Pavement Type and Condition	Flow Rate (pc/h/ln)	% Trucks	Single and Multiple Truck Populations (lkg/kW) [lb/hp]
	1	0.4 [0.25]	2	Asphalt-good	820 (LOS A)	0	38.1 [62.5]
	2	0.8 [0.50]	3	Asphalt-fair	1350 (B)	2	53.3 [87.5]
	3	1.2 [0.75]		Asphalt-poor	1830 (C)	4	68.5 [112.5]
	4	1.6 [1.00]		Conc-excellent	2170 (D)	5	83.7 [137.5]
	5	2.0 [1.25]		Conc-good	2400 (E)	6	99.0 [162.5]
	6	2.4 [1.50]		Conc-poor		8	114.2 [187.5]
				Snow Covered		10	129.4 [212.5]
						15	144.6 [237.5]
						20	159.9 [262.5]
						25	Multiple w/ avg 83.7 & stdev 10%
						30	
						40	
						50	Multiple w/ avg 83.7 & stdev 20%
						60	
						70	
						80	Multiple w/ avg 83.7 & stdev 30%
						90	
						100	
# of Variables	6	6	2	7	5	18	12

Table 3. Refined list of variables considered.

	Physical Network				**Traffic Characteristics**		
	% Grade	Length of Grade (km) [mi]	# of Lanes	Pavement Type and Condition	Flow Rate (pc/h/ln)	% Trucks	Single and Multiple Truck Populations (lkg/kW) [lb/hp]
	1 2 3 4 5 6	0.4 [0.25] 0.8 [0.50] 1.2 [0.75] 1.6 [1.00] 2.0 [1.25] 2.4 [1.50]	2	Asphalt-fair	820 (LOS A) 1350 (B) 1830 (C) 2170 (D) 2400 (E)	0 5 10 25 100	83.7 [137.5] Multiple w/ avg 83.7 & stdev 30%
# of Variables	6	6	1	1	5	5	2

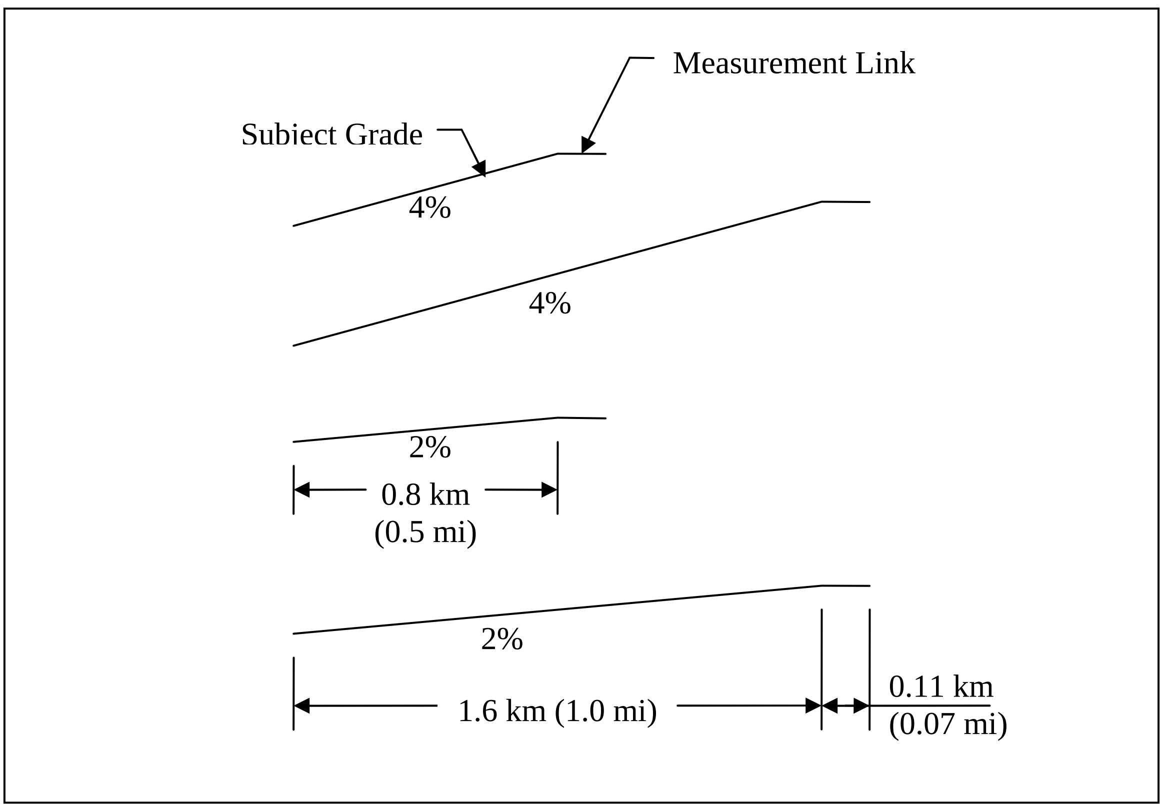

Figure 1. Idealized link structure for INTEGRATION simulations (not to scale).

Locating the flow and density measurement after the subject grade results in the worst case measurement of the effect of trucks for the up grade. Considering the first and second links as a hill, this measurement occurs at the crest of the hill. Among the 36 combinations of grade percent and length to test, the variable number of lanes as well as pavement type and condition further expands the possible combinations of the physical network. The initial physical network was comprised of only two lane freeway segments, since the examination of three lane freeway segments was conducted later. The initial physical network was also comprised of only asphalt-fair condition pavement. The examination of other pavement types was also conducted later.

3.3.2 INTEGRATION Inputs

The traffic simulator, INTEGRATION, requires a number of input variables. The free-flow speed used for this simulation was set to 120.7 km/h (75 mi/h) and the saturation flow rate per lane was set to 2400 veh/h, which is the capacity of a freeway lane according to the HCM 2000. The vehicle speed coefficient of variation was set to 0.08, a dimensionless quantity recommended based on previous research experience. The speed at capacity was set to 85.8 km/h (53.3 mi/h), which is the minimum speed corresponding to LOS E in the HCM 2000. The jam density was set to 139.8 veh/km (225 veh/mi), which is five times the density at capacity. Vehicle headways were simulated to be 100% random. The characterization of subject truck populations as well as pavement type and condition are inputs described in their respective sections below

3.3.3 Simulation Outputs

Traffic flow and density measurements were obtained as an output from the simulation on 15 minute intervals since service flow rates for determining capacity are generally based on 15 minute observations. The capability of the traffic simulator allows ten 15 minute periods to be simulated for the prescribed network size. The first interval was discarded because it may take this amount of time for trucks to reach steady flow across the final link. The remaining nine 15 minute intervals were averaged to obtain the hourly average flow rate and density on the final link. To provide a suitable sample size to overcome randomness in the results, the simulations were replicated with a different random number seed. Up to three sets of nine samples, for a total of 27 samples, were obtained from the traffic simulator.

3.3.4 Examination of the Effect of Weight to Power Ratio

A primary hypothesis of this research was that truck populations containing a single weight to power ratio perform differently than multiple truck populations containing a mix of weight to power ratios. This hypothesis was tested by comparing the PCEs calculated for a single truck population with the PCEs calculated for a multiple truck population with the same average weight to power ratio. In addition, it was hypothesized that the PCE for single truck populations varies significantly due to the weight to power ratio. Rakha and Lucic (23) found, in 2002, in a random sample of trucks at the Troutville weigh station along I-81 in Virginia that the average weight to power ratio was 79.2 kg/kW (130 lb/hp) with a standard deviation of 27.4 kg/kW (45 lb/hp). Figure 2 shows the results of the truck survey along I-81; it includes histograms of the truck weight and truck power separately as well a histogram of the truck weight to power ratio. The HCM 2000 similarly states that several studies have indicated that the average weight to power ratio is between 76.1 and 90.4 kg/kW (125 and 150 lb/hp).

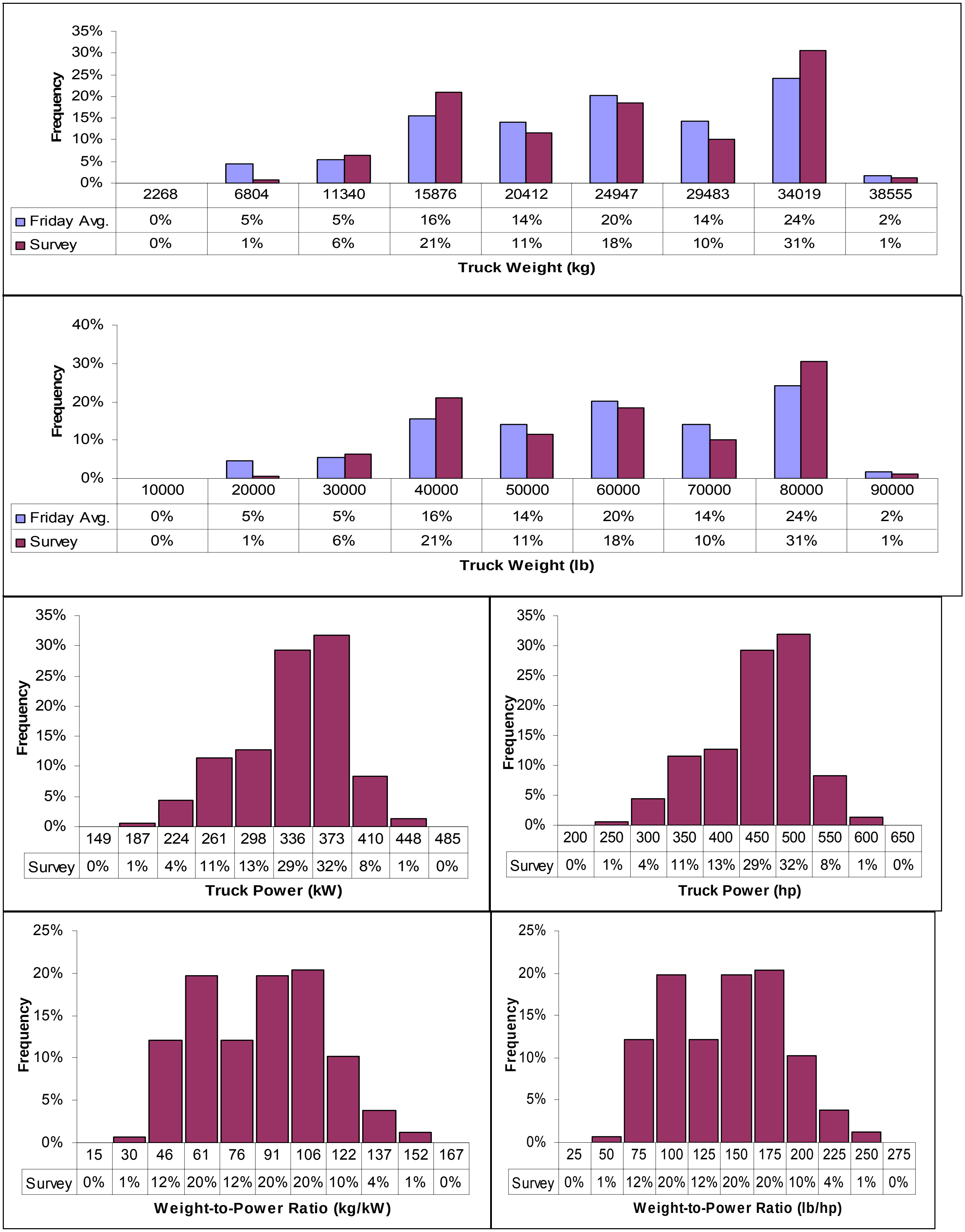

Figure 2. Truck survey results at I-81 Troutville weigh station in Virginia.

To examine the effect of weight to power ratio, the simulation was initially run using nine single truck populations. These were comprised of only a single truck type, with a weight to power ratio that ranged from 38.1 to 159.9 kg/kW (62.5 to 262.5 lb/hp) in increments of 5.2 kg/kW (25 lb/hp). This range represents the midpoint of the bins in which the I-81 truck sample results were classified. This set of simulations was carried out for 5 flow rates corresponding to the LOS flow rates. The truck proportion was tested at 5 and 10% proportion of trucks. It was not necessary in the initial investigation to create the density flow relationship over all truck proportions, nor was it necessary to change the pavement type and condition from the initial asphalt-fair pavement.

Truck performance characteristics are determined internally to the traffic simulator using vehicle dynamics models. The necessary inputs to define the truck populations were obtained from an article by Rahka et al (24) in 2001. The important vehicle dynamics values include: vehicle length of 16 m (52.5 ft), proportion of mass on tractive axle of 0.36, transmission efficiency of 0.88, drag coefficient of 0.58, frontal area of 10.7 m^2 (115.2 ft^2), first rolling resistance constant of 0.0328, and second rolling resistance constant of 4.575. It is important to note that the passenger car population in all simulations was the default passenger car used by the Environmental Protection Agency for vehicle performance and emissions modeling.

Further simulations were conducted considering more realistic truck populations that contain multiple truck weight to power ratios. This set of simulations was used to test the hypothesis that multiple truck populations perform differently than single truck populations. Multiple truck populations were created by varying the standard deviation of the truck weight to power ratio around the average weight to power ratio. Therefore a normal distribution of trucks was created. The standard deviation was varied from 0 to 40% of the average weight to power ratio. Other non-normal multiple truck populations were tested, but it was determined that the normal multiple truck population was just as accurate without being overly complicated.

3.3.5 Examination of the Effect of Engine Power

The variability of engine power within a single weight to power ratio was also considered. It was hypothesized that trucks with a lower engine power would have higher PCEs even though they may have the same weight to power ratio. This hypothesis was tested by varying the engine power from 242 to 392 kW (325 to 525 hp) in increments of 38 kW (50 hp). This range represents the midpoint of the bins in which a majority of the trucks from the I-81 truck survey were classified. The truck weight was set as necessary to obtain a weight to power ratio of 83.7 kg/kW (137.5 lb/hp). The truck weights ranged from 20,270 to 32,743 kg (44,687 to 72,187 lb), which can be observed from figure 2 to fall within the range of the most frequently observed truck weights from the survey results.

3.3.6 Examination of the Effect of Proportion of Trucks

The HCM 2000 considers proportion of trucks only up to 25 percent. However, on many freeways in the United States, the proportion of trucks exceeds 25 percent. To test the effect of high proportion of trucks, the proportion of trucks was considered in increments of 10% all the way to 100% trucks. At the lower proportion of trucks (below 25%), the percentage categories used in the HCM 2000 were matched for clarity. An objective of this research was to verify that the PCE decreases as the proportion of trucks increases. Although this trend is observed in the HCM 2000, it has not been tested at high proportion of trucks.

3.3.7 Examination of the Effect of Pavement Type and Condition

It was hypothesized that poor pavement type and condition will result in increased PCEs. The pavement type and condition for the entire network can be changed with the modification the rolling coefficient and the coefficient of friction in the vehicle dynamics input. The values of these parameters were obtained from an article on vehicle dynamics by Rahka et al (24). The simulation model was run under seven different pavement types and conditions: concrete pavement excellent condition, concrete pavement good condition, concrete pavement poor condition, asphalt pavement good condition, asphalt pavement fair condition, asphalt pavement poor condition, and snow covered. These simulations were performed on a single truck population as well as a multiple truck population. The default pavement type was asphalt pavement fair condition.

3.3.8 Examination of the Effect of Truck Aerodynamic Treatment

It was hypothesized that truck aerodynamic treatment will have a significant effect on PCEs. The aerodynamic treatment of trucks affects the vehicle drag coefficient. The default drag coefficient was 0.58. Rakha and Lucic (23) found, in 2002, in a random sample of trucks along I-81 in Virginia that 55% of trucks had full aerodynamic treatment, 15% had partial aerodynamic treatment, and 29% had no aerodynamic treatement. For these simulations, the pavement type and condition was maintained as fair asphalt, but the vehicle drag coefficient was changed to reflect the aerodynamic treatment.

3.3.9 Examination of the Effect of Three Lane Segments

It was hypothesized that PCEs for freeways with more than two directional lanes will be lower than PCEs for freeways with only two directional lanes. To examine this hypothesis, the number of lanes was increased from two to three. This change was applied to a single truck as well as a multiple truck population. It was also of interest to examine the effect of lane restrictions. Simulations were conducted with a lane restriction in effect, which limited trucks to the two rightmost lanes. This lane restriction was instituted in the form of a lane bias, which made the leftmost lane appear to trucks to operate slower than the other lanes.

3.3.10 Examination of the Effect of Truck Speed Limit

It was hypothesized that the imposition of a speed limit on trucks will increase the PCEs. The default PCE was calculated with no separate speed limit for trucks. However, in many states the truck speed limit is regulated to as much as 24.1 km/h (15 mi/h) below the speed limit for other vehicles. This lowers the speed of trucks approaching a grade and thus increases the effect of the grade on trucks. For the default simulations, the speed limit for all vehicles was 112.6 km/h (70 mi/h). The actual vehicle speeds for this case were limited to 8 km/h (5 mi/h) above the speed limit. For the truck speed limit simulations, a speed limit was imposed on trucks at 88.5 km/h (55 mi/h).

3.3.11 Examination of the Effect of Level of Congestion

It was hypothesized that increasing level of congestion will result in increasing PCEs. It has already been established that simulations will be conducted at 5 different traffic flow rates, corresponding to the LOS categories shown in Table 1. However, simulation at these 5 flow rates does not in itself quantify the effect of level of congestion. The effect of level of congestion is considered in the equal density value that is used to calculate the PCE. As mentioned in section 3.1, an equal density value of 12.4 pc/km/ln (20 pc/mi/ln), corresponding to density at LOS C, was used initially. To examine the effect of level of congestion, the equal density values used to calculate PCE were varied in increments of 3.1 pc/km/ln (5 pc/mi/ln) from 9 to 25 pc/km/ln (15 to 40 pc/mi/ln). An important note is that the effect of prevailing traffic volume can be examined without further simulations.

3.4 Data Analysis

The simulation results were used to calculate the PCE following the methodology described in section 3.1. In simulations to test the effect of weight to power ratio, proportion of trucks, or level of congestion, the calculated PCE was compared with the HCM 2000. In simulations to test the effect of pavement type and condition, aerodynamic treatment, three lane segments, or truck speed limit, the calculated PCE was compared with the default simulation PCEs. The default simulation was a single truck population with a weight to power ratio of 83.7 kg/kW (137.5 lb/hp), operated on fair asphalt pavement with full aerodynamic treatment and no separate truck speed limit. Percentage differences that exceeded 10% were considered significant for investigation. If no significant difference existed, the variable was considered to have no impact on the development of PCEs.

Chapter 4. Results for Single Truck Populations

4.1 Background

A simplified method for determining the PCE of trucks in a traffic stream is to assume that all trucks have the same characteristics. A realistic truck population may contain any number of trucks with different operating characteristics. Even if all trucks on the highways had the same engine power, which they do not, there would still be differences in the trucks. Loaded trucks have a higher weight to power ratio than empty trucks. Trucks also have variability in the type of aerodynamic features used. Many interstate, long-haul, trucks employ full aerodynamic features to permit the maximum acceleration. Still others may employ partial or no aerodynamic treatments.

Although variability does exist in realistic truck populations, using only a single truck population is a popular way to simplify calculations. This method has been applied in many previous research studies. This was especially popular before the mainstream use of computer simulators because the interaction between trucks was not as clearly known. Simplifying assumptions had to be made to make use of field data, for which the exact truck population was unknown. Even today, the HCM 2000 provides PCEs that were calibrated from a mix of trucks that ranged within the average truck weight to power ratio. This population may be a simplification of a realistic truck population, but it has been determined accurate enough for meaningful results. Simplifications and generalizations are common and useful practices in traffic engineering to make work more efficient.

In this research, single truck populations were defined to have different weight to power ratios. This not only represents the variability in engine power, but also the difference between loaded and unloaded trucks. Nine different weight to power ratios were used, ranging from 38.1 to 159.9 kg/kW (62.5 to 262.5 lb/hp) in increments of 5.2 kg/kW (25 lb/hp). These truck populations represented the midpoint of the survey bins from the random truck survey along I-81 in Virginia (23). One objective of the single truck population tests was to determine how significant the impact of truck weight to power ratio is. The single truck population that most closely matched the PCEs provided in the HCM 2000 was chosen for further investigative research. The variability of the single truck population by length and percent grade was used to validate the chosen population. Further variables for investigation included engine power, proportion of trucks, pavement type and condition, aerodynamic treatment, three lane segments, truck speed limit, and level of congestion.

The variables selected for the single truck population investigations were used to verify the hypotheses of this research. It was first hypothesized that truck weight to power ratio has a significant effect on the PCE. In accordance with this hypothesis, it was expected that the PCE for single truck populations with a low weight to power ratio will be much less than the PCE for single truck populations with a high weight to power ratio. Section 4.3 presents the results of the variability of the PCE by truck weight to power ratio. It was also hypothesized that variability in engine power within the same weight to power ratio would significantly affect the PCE. Trucks with low engine power were expected to have higher PCEs than trucks with high engine power but the same weight to power ratio. Section 4.6 presents the results of the variability of the PCE by engine power. It was hypothesized that the PCE for a single truck population decreases with increasing proportion of trucks. This relationship exists in the current HCM 2000, but it was examined for a higher proportion of trucks in this research. Section 4.7 presents the results of the variability of PCE by proportion of trucks. Another hypothesis of this research was that pavement type and condition significantly influence the PCE. It was expected that poor pavement would result in higher PCEs in comparison to the same single truck population on better pavement. The results of the variability of PCE by pavement type and condition are presented in section 4.8.

It was hypothesized that truck aerodynamic treatment would significantly affect the PCE. Single truck populations with only partial or no aerodynamic treatment were expected to have higher PCEs than single truck populations with full aerodynamic treatment. Section 4.9 presents the results of the variability of PCE by truck aerodynamic treatment. Another hypothesis of this research was that PCEs for three lane freeway segments would be much lower than PCEs for two lane freeway segments. The results of the variability of PCE for three lane segments are presented in section 4.10. It was hypothesized that the institution of a truck speed limit below the speed limit of other vehicles would result in significantly higher PCEs. The results of the variability of PCE for a truck speed limit are presented in section 4.11. A final hypothesis of this research was that the level of congestion will significantly affect the calculated PCE. Under this hypothesis, it was expected that increasing levels of congestion will result in increasing calculated PCEs for the same single truck population. Section 4.12 presents the variability of PCE by level of congestion. Section 4.13 presents an examination of the combined effects of the variables on the calculated PCE. Whereas the preceding sections of this chapter examine the effect of the variables independently, the combined effects of the variables is a more complicated issue.

4.2 Speed-Flow-Density Relationships

The first task in the traffic simulations was to obtain speed, flow, and density data. These data were used to construct the speed-flow-density relationships. The data were only collected for the uncongested flow regime. Figure 3 shows the speed-flow-density relationships for the base vehicle flow on a 0.8 km (0.5 mi) grade. Separate curves were plotted for the different percent grades, 2, 4, and 6%. It can be observed that the speed-flow-density relationships for passenger cars are the same regardless of the different percent grades. The observed relationships between speed, flow, and density are as would be expected for freeway segments in the uncongested flow regime.

The speed-flow-density relationships were also constructed for the mixed traffic, passenger cars and a single truck population. Figure 4 shows the speed-flow-density relationships for a single truck population of 83.7 kg/kW (137.5 lb/hp) on a 0.8 km (0.5 mi) grade. Separate curves were plotted for different proportion of trucks, 5 and 10% as well as the different percent grades. The stated proportion of trucks was chosen because 5% is low enough to have high PCE values for comparisons and 10% is close, although below, the actual proportion of trucks observed on many freeways. A separate speed, flow, or density relationship could be plotted for each combination of the roadway and traffic characteristics. It was decided to focus on these roadway and traffic characteristics for the 0.8 and 1.6 km (0.5 and 1.0 mi) grades for most of this research.

The speed-flow-density relationships are a primary tool to proof check the simulation results. These relationships are also useful in the calculation of the PCE, although not graphically. The mixed vehicle flow-density relationship in figure 4 illustrates that for an equal density value, flow decreases with increasing proportion of

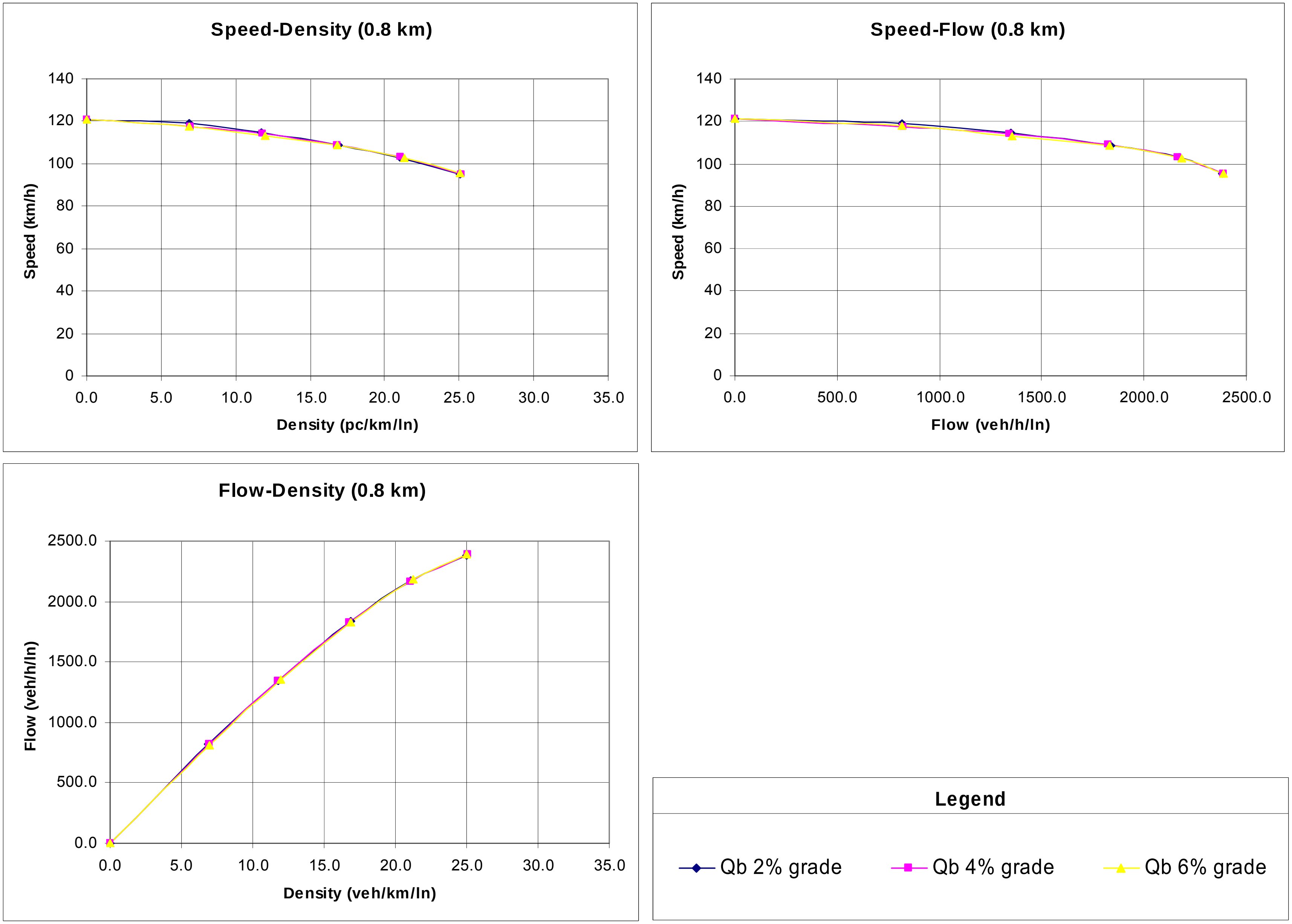

Figure 3. Speed-flow-density relationships, base vehicle flow.

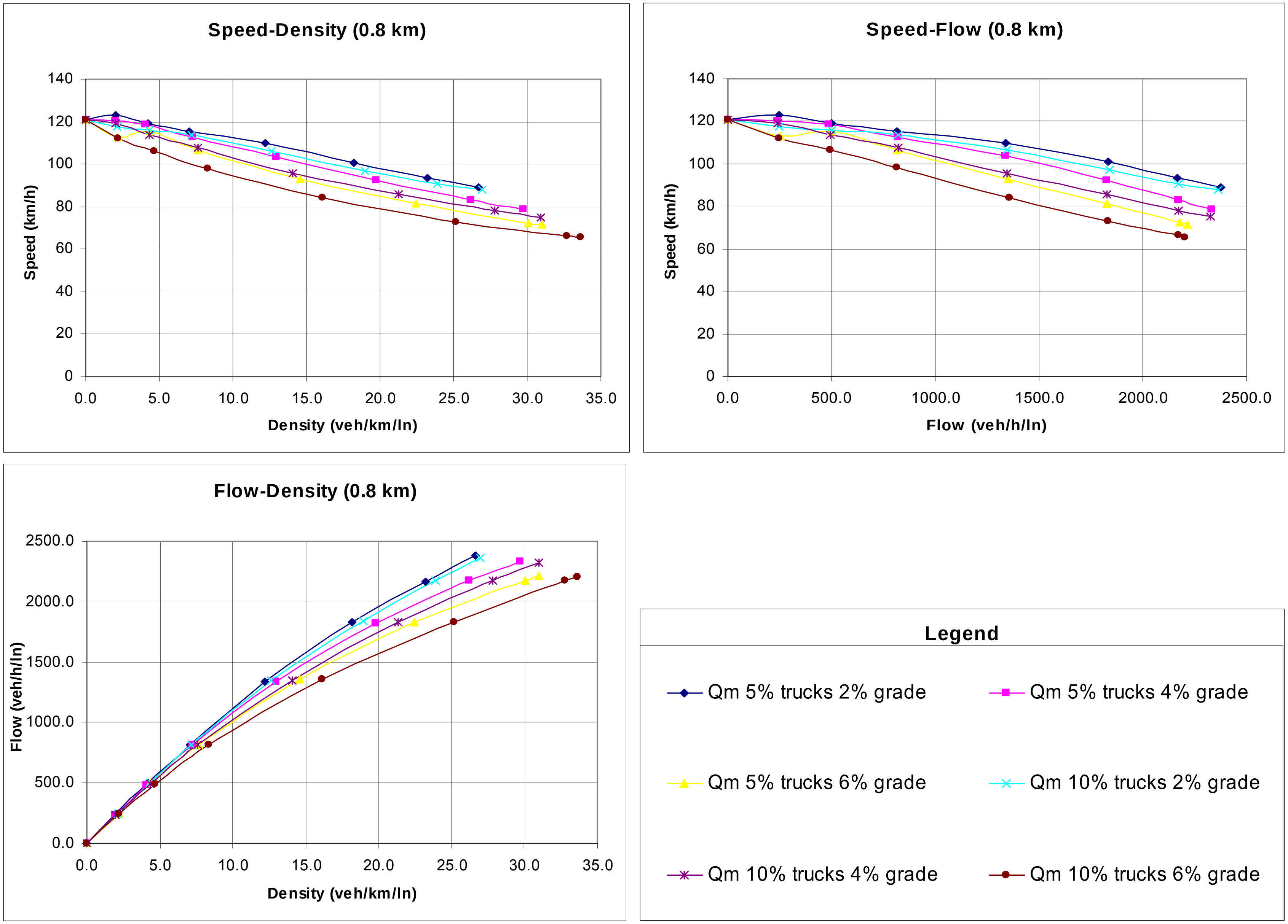

Figure 4. Speed-flow-density relationships, mixed vehicle flow single truck population of 83.7 kg/kW (137.5 lb/hp).

trucks or percentage grade. This trend is also observed in the speed-density and speed-flow relationships at equal values of density and flow respectively. The general trends observed in the mixed vehicle speed-flow-density relationships are as would be expected for freeway segments in the uncongested flow regime.

4.3 Variability of PCE by Weight to Power Ratio

The weight to power ratio of the single truck populations was found to have a significant effect on the calculated PCE; percentage differences between different populations exceeded 10%. The PCE of trucks was computed for each truck population at an equal density value of 12.4 pc/km/ln (20 pc/ml/ln), corresponding to LOS C. Figure 5 shows the predicted PCE for specific grade length and percent combinations plotted against the corresponding weight to power ratio. There is much less variability in the predicted PCE for short and mildly sloped grades as compared to long and steeply sloped grades. The PCE for a 0.8 km (0.5 mi), 2% grade ranges from 1.5 to 3.0; however, the PCE for a 1.6 km (1.0 mi), 6% grade ranges from 2.0 to 8.0. For the same slope grade, the PCE and variability of PCE is higher for longer grades. This means that the effect of the weight to power ratio in truck populations is more pronounced for longer grades.

The 83.7 kg/kW (137.5 lb/hp) truck population most closely matches the PCE provided in the HCM 2000 across all of the grade length and percent combinations. This weight to power truck population usually intersects or is very near to the horizontal line in figure 5 which represents PCEs in the HCM 2000. The 83.7 kg/kW (137.5 lb/hp) truck population confirms the assertion made in the HCM 2000 that the PCEs provided therein were calculated for a truck population with an average weight to power ratio between 76.1 and 90.4 kg/kW (125 and 150 lb/hp). This observation also validates the

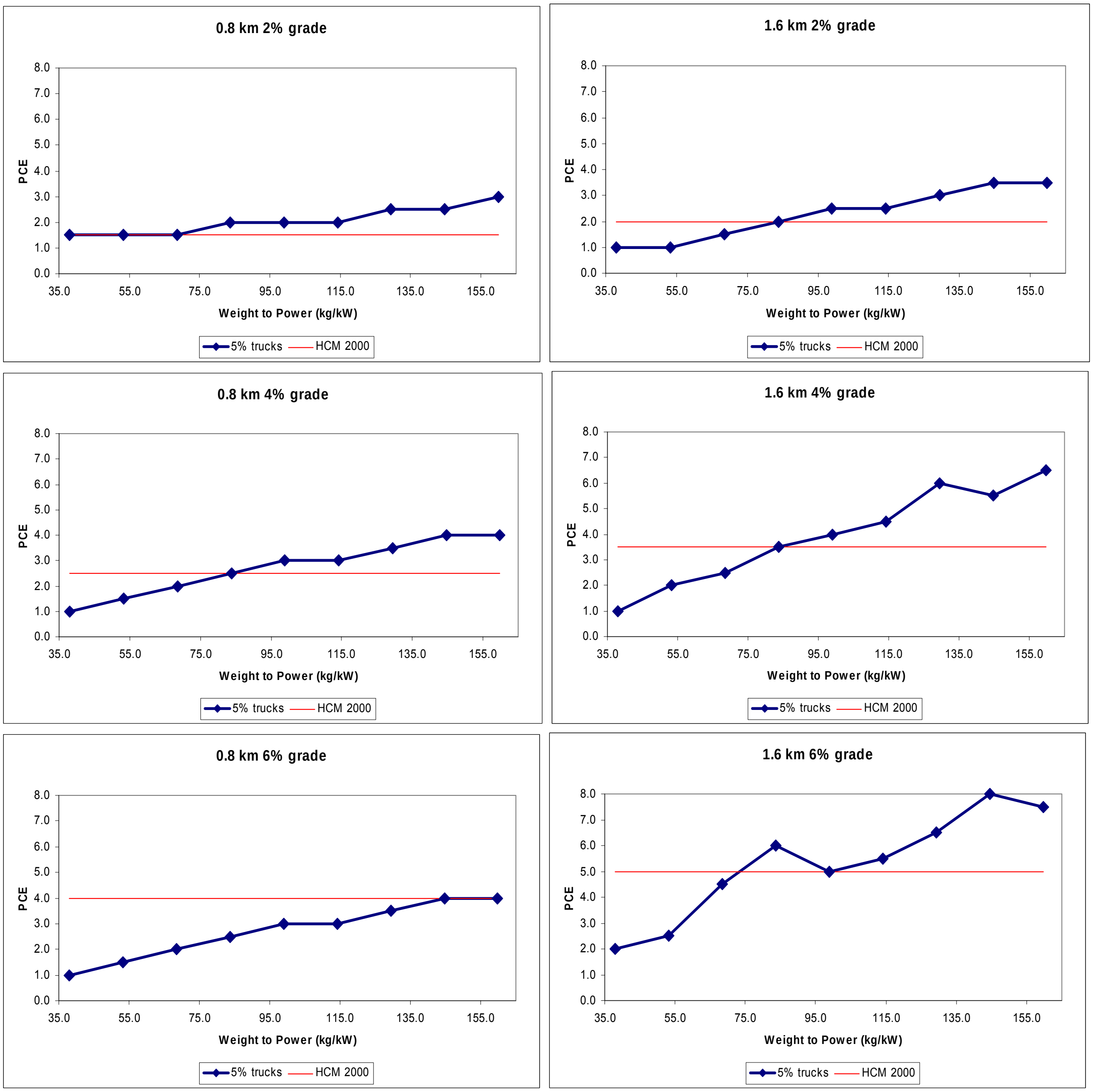

Figure 5. PCE variability by weight to power ratio for selected grades and LOS C congestion.

PCE calculation procedure used in this research because it accurately replicates the PCEs provided in the HCM 2000. Further investigations in this research focused on truck populations with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp). Table 4 shows the calculated PCEs for the average single truck population.

The PCE calculated for different weight to power ratio single truck populations provides sufficient evidence to suggest that weight to power ratio significantly affects the PCE. The PCEs calculated for two single truck populations were compared with the PCEs calculated for the average weight to power ratio single truck population. The first single truck population had a weight to power ratio of 68.5 kg/kW (112.5 lb/hp) and represents a lighter than average weight to power ratio truck population. This weight to power ratio is slightly below the range of 76.1 to 90.4 kg/kW (125 to 150 lb/hp) that the HCM 2000 is said to represent. The second single truck population had a weight to power ratio of 106.6 kg/kW (175 lb/hp) and represents a heavier than average weight to power ratio truck population. These two truck populations were selected because they represent potential realistic truck populations that are lighter and heavier than the average truck population.

The ratio of the examined truck population PCE to the average truck population PCE was calculated for comparison. Table 5 shows the calculated ratio of the PCEs for these two truck populations. It can be observed that for the lighter than average single truck population, the PCE is on average a fraction of 0.8 of the average single truck population PCE for 5% trucks. However, as the percentage of trucks increases, the ratio becomes closer to 1.0, which no longer represents a significant difference. For the heavier than average single truck population, the PCE is on average a fraction

Table 4. PCEs for trucks and buses on upgrades, average single truck population 83.7 kg/kW (137.5 lb/hp) and LOS C congestion.

Upgrade (%)	Length (km)	Length (mi)	E_T												
			Percentage of Trucks and Buses												
			2	4	5	6	8	10	15	20	25	30	40	50	60
	0.40	0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	0.80	0.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	1.21	0.75	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
1	1.61	1.00	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	2.01	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	2.41	1.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	3.22	2.00	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	0.40	0.25	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	0.80	0.50	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	1.21	0.75	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2	1.61	1.00	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	2.01	1.25	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	2.41	1.50	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	3.22	2.00	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	0.40	0.25	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	0.80	0.50	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	1.21	0.75	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
3	1.61	1.00	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	2.01	1.25	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	2.41	1.50	3.5	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5
	3.22	2.00	4.0	3.0	3.5	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5
	0.40	0.25	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	0.80	0.50	3.0	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5
	1.21	0.75	3.5	2.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
4	1.61	1.00	4.0	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0
	2.01	1.25	4.5	3.5	4.0	3.5	3.5	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0
	2.41	1.50	4.5	4.0	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0
	3.22	2.00	5.0	4.0	4.5	4.0	3.5	3.5	3.0	2.5	2.5	2.5	2.0	2.0	2.0
	0.40	0.25	3.5	2.5	2.5	2.5	2.0	2.5	2.0	2.0	2.0	2.0	2.0	2.0	1.5
	0.80	0.50	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.5	2.0	2.0	2.0
	1.21	0.75	5.5	4.0	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0
5	1.61	1.00	5.5	4.5	4.0	4.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0
	2.01	1.25	6.5	5.0	4.0	4.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.0
	2.41	1.50	6.5	5.0	5.0	4.5	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0
	3.22	2.00	7.5	5.0	5.5	5.0	4.5	4.0	3.5	3.0	3.0	3.0	2.5	2.5	2.0
	0.40	0.25	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	0.80	0.50	4.5	4.5	4.5	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.5	2.5	2.0
	1.21	0.75	7.5	5.5	5.5	5.0	4.5	4.0	3.5	3.5	3.0	3.0	2.5	2.5	2.5
6	1.61	1.00	7.0	6.0	6.0	6.0	5.0	4.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5
	2.01	1.25	8.5	6.5	6.0	6.0	5.0	4.5	4.0	3.5	3.5	3.0	3.0	2.5	2.5
	2.41	1.50	8.5	7.0	6.5	5.5	5.5	5.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5
	3.22	2.00	9.0	6.5	6.5	6.0	5.5	5.0	4.5	3.5	3.5	3.5	3.0	2.5	2.5
	0.40	0.25	5.0	5.0	4.5	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5	2.5	2.0
	0.80	0.50	8.0	7.5	7.0	6.5	5.5	5.0	4.5	4.0	3.5	3.5	3.0	3.0	2.5
	1.21	0.75	8.0	7.5	7.5	7.0	6.0	5.5	4.5	4.0	4.0	3.5	3.5	3.0	3.0
8	1.61	1.00	9.0	8.0	8.0	7.0	6.0	5.5	5.0	4.5	4.0	4.0	3.5	3.0	3.0
	2.01	1.25	9.5	8.0	8.0	7.0	6.0	6.0	5.0	4.5	4.0	4.0	3.5	3.0	3.0
	2.41	1.50	10.0	8.0	8.0	7.5	6.5	6.0	5.0	4.5	4.0	4.0	3.5	3.0	3.0
	3.22	2.00	10.5	9.5	8.5	7.5	6.5	6.0	5.0	4.5	4.5	4.0	3.5	3.0	3.0

Table 5. Ratio of PCE for light and heavy single truck populations to PCE for average single truck population.

Upgrade (%)	Length (km)	Length (mi)	Ratio to Average Single Truck PCE, 83.7 kg/kW (137.5 lb/hp)							
			Light Truck Pop. 68.5 kg/kW (112.5 lb/hp)				Heavy Truck Pop. 106.6 kg/kW (175 lb/hp)			
			Percentage of Trucks and Buses							
			5	10	25	100	5	10	25	100
2	0.40	0.25	1.0	1.0	1.0	0.7	1.3	1.0	1.0	1.0
	0.80	0.50	0.8	1.0	1.0	0.7	1.3	1.3	1.3	1.0
	1.21	0.75	0.8	1.0	1.0	0.7	1.3	1.3	1.3	1.0
	1.61	1.00	0.8	1.0	1.0	0.7	1.3	1.7	1.3	1.0
	2.01	1.25	0.8	1.0	1.0	0.7	1.3	1.7	1.3	1.0
	2.41	1.50	0.5	1.0	1.0	0.7	1.3	1.7	1.3	1.3
4	0.40	0.25	1.0	1.0	0.8	1.0	1.3	1.3	1.0	1.0
	0.80	0.50	0.8	0.8	1.0	1.0	1.4	1.2	1.3	1.0
	1.21	0.75	0.8	0.7	1.0	1.0	1.5	1.2	1.5	1.3
	1.61	1.00	0.7	0.8	0.8	1.0	1.6	1.3	1.4	1.3
	2.01	1.25	0.8	0.8	0.8	1.0	1.3	1.3	1.4	1.3
	2.41	1.50	0.8	0.8	0.8	1.0	1.4	1.3	1.4	1.7
6	0.40	0.25	0.8	1.0	1.0	1.0	1.2	1.2	1.5	1.3
	0.80	0.50	0.8	0.9	1.0	0.8	1.3	1.3	1.6	1.0
	1.21	0.75	0.8	0.9	0.8	0.8	1.3	1.4	1.5	1.0
	1.61	1.00	0.8	0.8	0.8	0.8	1.3	1.2	1.5	1.0
	2.01	1.25	0.8	0.8	0.7	0.8	1.3	1.2	1.3	1.0
	2.41	1.50	0.8	0.7	0.9	0.8	1.2	1.2	1.4	1.0
		average =	0.8	0.9	0.9	0.8	1.3	1.3	1.4	1.1

of 1.3 of the average single truck population PCE for 5 or 10% trucks. The largest ratio of the PCE occurs for 25% trucks, at an average of 1.4. These ratios could be used as a scale factor to multiply the average single truck population PCEs by. This could account for the effect of lower or higher weight to power ratio single truck populations.

4.4 Variability of PCE by Length of Grade

The PCE was observed to increase as the length of grade increased. This trend exists in the PCEs provided in the HCM 2000, and it was observed for the truck population with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp). The variability of PCE by length of grade was used to validate the PCE calculation procedure used in this research because length of grade is a major determining factor in the PCEs provided in the HCM 2000. The PCEs provided in the HCM 2000 are given for a range of grades between 0.40 and 2.41 km (0.25 and 1.5 mi). The range of grades considered for this research was extended to 0.40 to 9.65 km (0.25 to 6 mi) for illustrative purposes. Figure 6 shows the variability of the PCE over this range of grade lengths for 5 and 10% trucks. It is encouraging that the trends observed from the results of this research are similar to the trends observed in the HCM 2000.

A primary observation from figure 6 is that the PCE changes more drastically by length of grade for steeper grades. This trend is sensible, and closely ties into the variability of the PCE by percent grade. In addition, it can be observed that the PCE and variability in PCE is higher for the 5% proportion of trucks as compared to 10% proportion of trucks. This diminishing effect of the proportion of trucks was a major reason for choosing to examine such a low proportion of trucks in this research. It is clear that at low percent grades, the PCE changes very little from one grade length to the next.

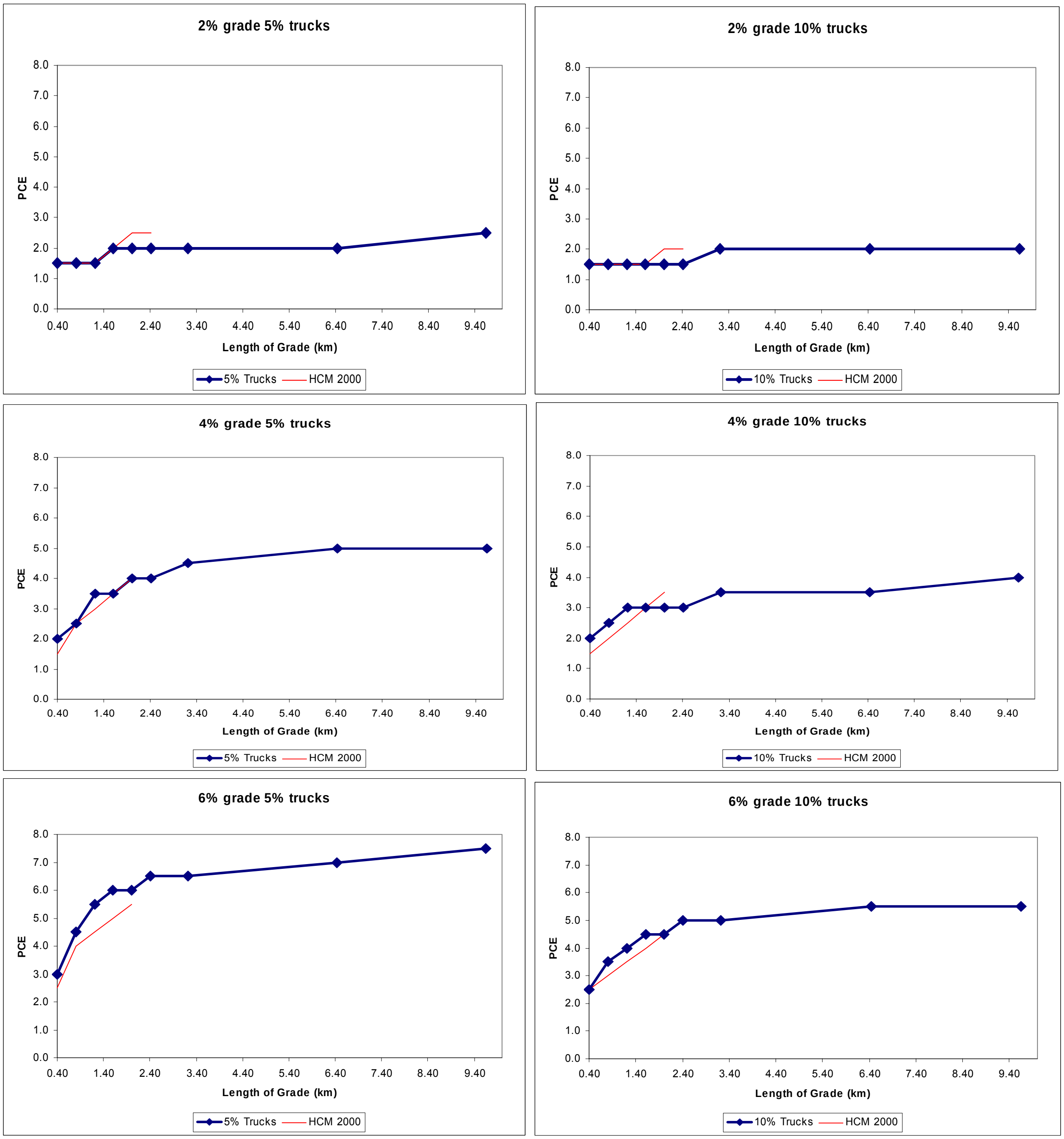

Figure 6. PCE variability by length of grade for average single truck population, 83.7 kg/kW (137.5 lb/hp) and LOS C congestion.

This is illustrated by the almost constant value of PCE over all lengths of grade for 2% grades. However, for steeper grades the change in PCE between successive lengths of grades up to 3.22 km (2 mi) increased by an average of 0.6. For grades longer than 3.22 km (2 mi) up to 9.65 km (6 mi), the PCE did not increase by very much if at all.

4.5 Variability of PCE by Percent Grade

The PCE was observed to increase as the percent grade increased. This trend was also used to validate the selected truck population because it is a determining factor used in the PCEs provided in the HCM 2000. The PCEs provided in the HCM 2000 only range between 1 and 6%; however, grades up to 8% were tested in this research for investigative purposes. Figure 7 shows the variability of the PCE over percent grades ranging from 1 to 8%. It is clear that the single truck population with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp) closely matches the trend in PCEs from the HCM 2000. The curves in Figure 7 only apply to the 5% proportion of trucks because this proportion trucks shows more variability in PCE than 10% proportion of trucks. It can be observed, regardless of the length of grade, that the PCE for 1% grades is always around 1.5. For longer grades, the PCE varies more dramatically by percent grade, creating a larger range of PCE values for the longest grades. The average difference in PCE from one percent grade to the next is 0.6. A uniform incremental increase does not truly exist however. In fact, the change in PCE from 1% to 2% grade is always less incrementally than the change in PCE from 5% to 6% grade. This illustrates the detrimental effect of steep grades on heavy vehicles. Since the PCEs calculated for 8% grades are larger than the PCEs for 6% grades, it must not be assumed that PCEs for

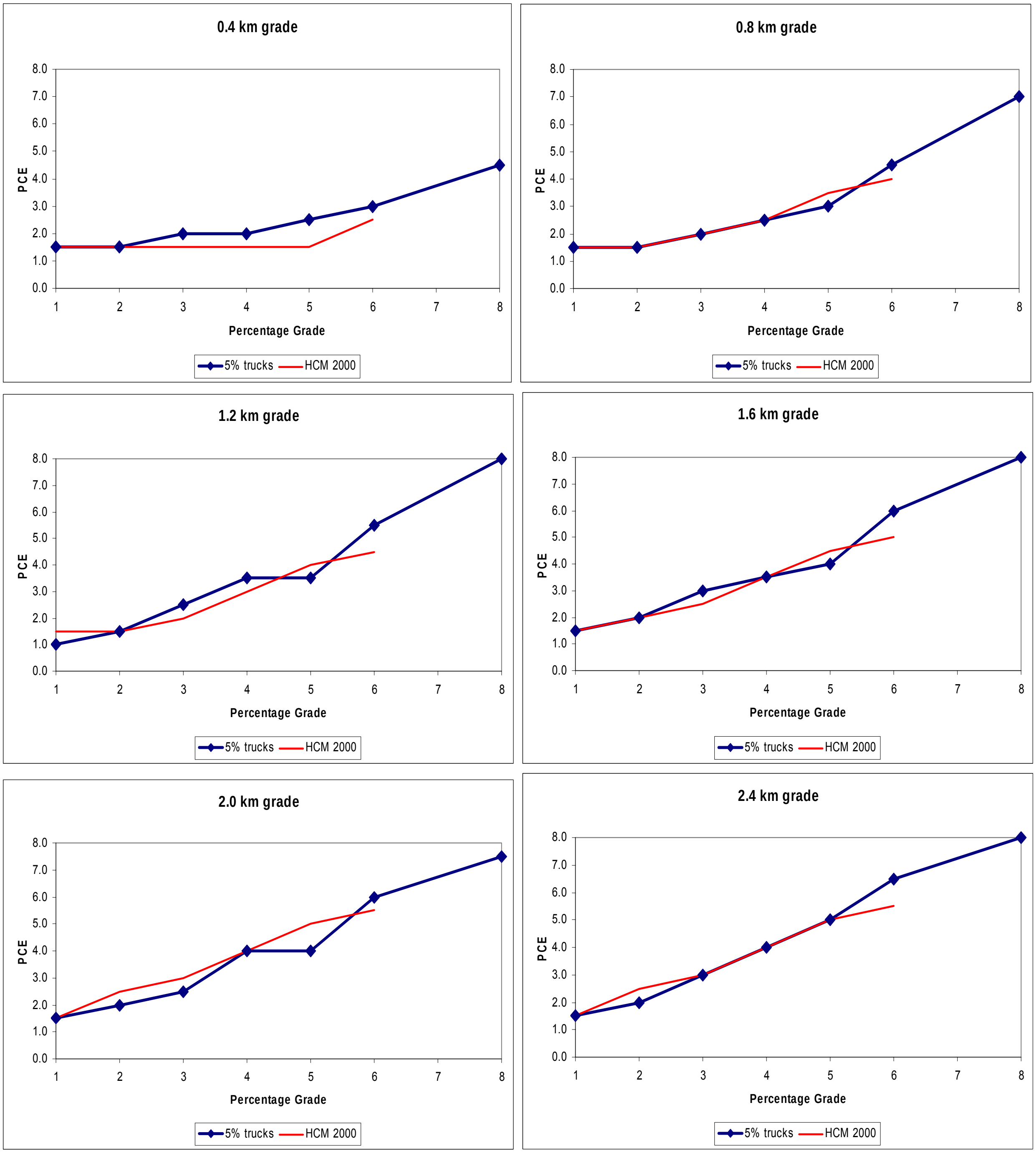

Figure 7. PCE variability by percentage grade for average single truck population, 83.7 kg/kW (137.5 lb/hp) and LOS C congestion.

grades beyond the range of the HCM 2000 are constant, but rather that they continue to increase with percent grade.

4.6 Variability of PCE by Engine Power

Engine power was only found to significantly affect the PCE for a low engine power single truck population; the percentage difference in the PCE was as much as 13%. This partially confirms a hypothesis of this research. However, it was not only expected that PCEs will be higher for low engine powers, but also that PCEs will be lower for high engine powers. Five different engine powers were tested in this research, representing a range of engine powers observed in the truck survey along I-81 in Virginia. The truck weight corresponding to each engine power was set so that the weight to power ratio of the trucks remained 83.7 kg/kW (137.5 lb/hp). Table 6 shows the variability of the PCE for the different truck powers as a percentage difference compared to the PCE for the default truck power. The default truck power for this research was 354 kW (475 hp) representing the 75^{th} percentile truck power in the survey.

The lowest truck power simulated was 242 kW (325 hp) representing the 10^{th} percentile truck power in the survey. From table 6 it can be observed that the PCEs for 10% proportion of trucks for this truck power were significantly higher (13%) than the PCEs for the average single truck population with the default engine power. However, the PCEs at 5, 25, and 100% proportion of trucks were not significantly higher (6%) than the PCEs for the average single truck population. The other truck powers simulated represented the 22^{nd}, 45^{th}, 75^{th}, and 95^{th} percentile truck powers from the truck survey. For the 22^{nd} percentile truck power, the PCEs were again significantly different only for 10% proportion of trucks. For the 45^{th} and 95^{th} percentile truck powers, none of the PCEs

Table 6. Percentage difference in calculated PCE for different engine powers compared to 75th percentile engine power 354 kW (475 hp).

Upgrade (%)	Length (km)	Length (mi)	% Error From 75th Percentile Power, 354 kW (475 hp)														
			10th Percentile Power, 242 kW (325 hp)				22nd Percentile Power, 280 kW (375 hp)				45th Percentile Power, 317 kW (425 hp)				95th Percentile Power, 392 kW		
			Percentage of Trucks and Buses														
			5	10	25	100	5	10	25	100	5	10	25	100	5	10	25
2	0.40	0.25	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	0%	0%	0%	0%	0%	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	1.21	0.75	0%	33%	0%	0%	0%	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	1.61	1.00	0%	33%	0%	0%	0%	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	2.01	1.25	0%	33%	0%	0%	0%	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	2.41	1.50	0%	33%	0%	0%	0%	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%
4	0.40	0.25	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	20%	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	1.21	0.75	33%	0%	25%	0%	17%	0%	0%	0%	17%	0%	0%	0%	17%	0%	0%
	1.61	1.00	14%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-20%
	2.01	1.25	0%	17%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	2.41	1.50	13%	0%	0%	0%	0%	17%	0%	0%	0%	17%	0%	0%	0%	0%	0%
6	0.40	0.25	0%	20%	25%	0%	0%	20%	0%	0%	0%	20%	0%	0%	0%	0%	0%
	0.80	0.50	0%	14%	20%	0%	11%	0%	20%	0%	0%	14%	0%	0%	0%	0%	20%
	1.21	0.75	0%	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	1.61	1.00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-8%	0%	0%
	2.01	1.25	0%	11%	0%	0%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-14%
	2.41	1.50	0%	0%	0%	0%	-8%	0%	0%	0%	-8%	-10%	0%	0%	-8%	0%	0%
		average =	6%	13%	4%	0%	2%	11%	1%	0%	0%	2%	0%	0%	0%	0%	-1%

were significantly different from the PCEs calculated for the average single truck population.

4.7 Variability of PCE by Proportion of Trucks

The proportion of trucks in the traffic stream was found to have a significant effect on the calculated PCE only at low proportion of trucks. This trend is especially truefor longer and steeper grades. Figure 8 shows the variability of the PCE over proportion of trucks ranging from 2% to 100%. The PCE table in the HCM 2000 only provides PCEs for up to 25% proportion of trucks. It can be observed that the PCE is highest for low proportion trucks, and that the PCE decreases and levels off as the proportion trucks increases. The PCE past 60% trucks shows very little variability.

The variability in PCE for proportion of trucks between 25 and 60% provides significant evidence that the PCE table in the HCM 2000 should be expanded to include up to 60% trucks. If one were to assume that on a 1.6 km (1 mi), 6% grade, the PCE for 60% trucks was equal to that for 25% trucks, the PCE would be 3.0 as calculated in this research. However, the calculated PCE for 60% trucks on such a grade is actually 2.5. The relative difference of 0.5 in the PCE seems small, but is actually 20% larger than it should be. If the freeway traffic volume is assumed to be 3000 veh/h over two lanes, the proportion of the traffic that is trucks would be 1800 veh/h. Using the PCE of 3.0 would result in an estimate of the equivalent throughput of passenger cars as 6600 pc/h. However, using the PCE of 2.5 would result in an estimate of the equivalent throughput of passenger cars that is 16% lower, as 5700 pc/h.

The observed decreasing trend in PCE with increasing proportion of trucks confirms a hypothesis of this research. An explanation for this observed trend is that as

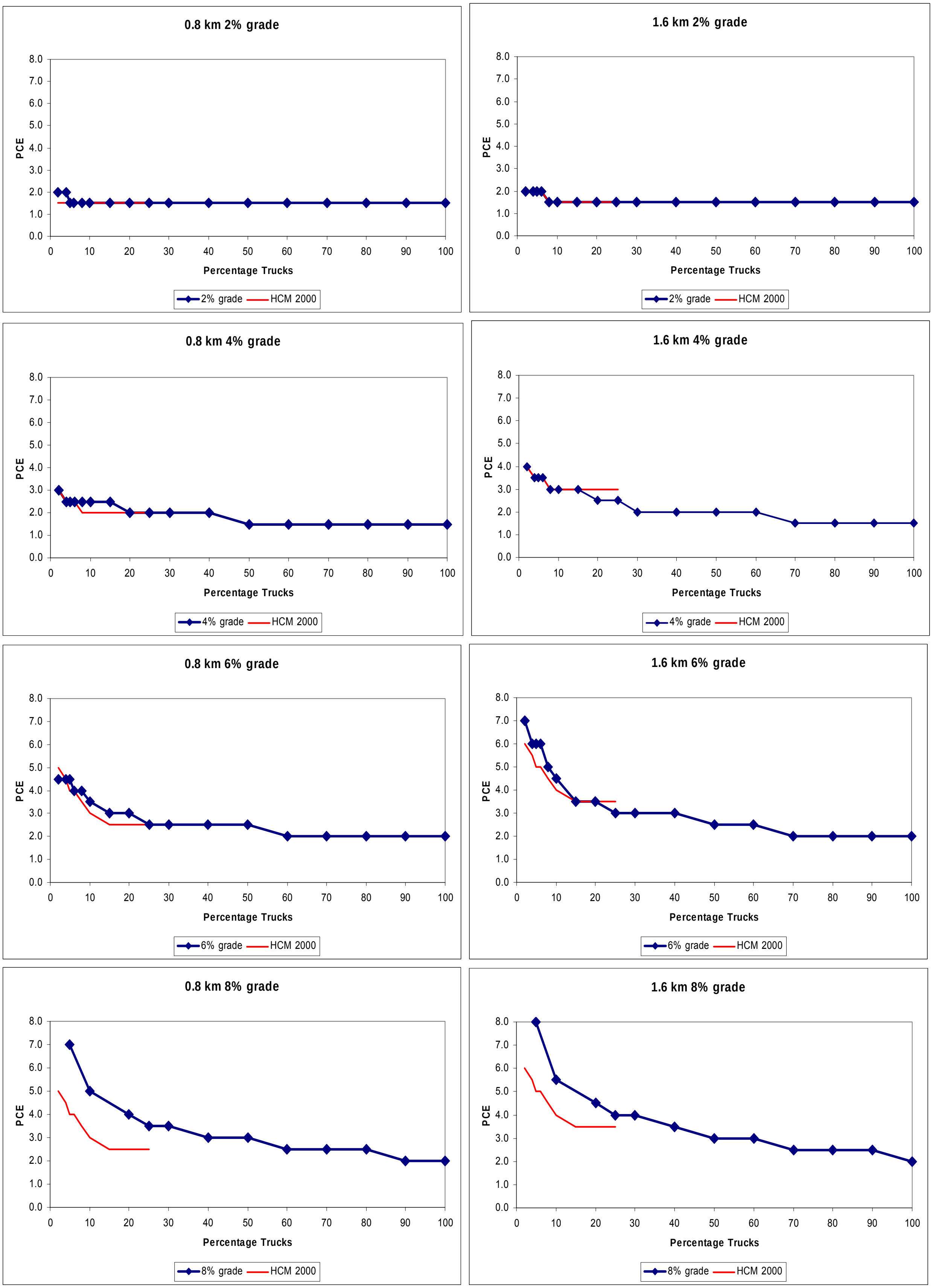

Figure 8. PCE variability by proportion of trucks for average single truck population, 83.7 kg/kW (137.5 lb/hp) and LOS C congestion.

the proportion of trucks increases, the interaction of trucks with cars decreases because trucks will form platoons climbing the grade. The interaction of trucks with trucks is negligible since the trucks perform the same, having the same weight to power ratio. Providing PCEs that apply for proportion of trucks beyond 25% is desirable since the proportion of trucks on many freeway segments currently exceeds 25% at times.

4.8 Variability of PCE by Pavement Type and Condition

Pavement type and condition was found to have a significant effect on the calculated PCE, with percentage differences exceeding 10%. This confirms a hypothesis of this research. The pavement type and condition affects the rolling coefficient and pavement friction coefficient. These vehicle dynamics coefficients affect the maximum acceleration of all vehicles and especially trucks. The default pavement type for simulations in this research was asphalt in fair condition. This is a reasonable to slightly conservative estimate for the pavement condition for many interstate freeway segments.

The PCE of trucks was calculated for six additional pavement types and conditions. The calculated PCE for these different pavement types and conditions for the truck population with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp) is shown in table 7. Table 8 shows the variability of the PCE for these different pavement types and conditions calculated as the percent difference in PCE from the default pavement type. Poor asphalt and poor concrete pavement always had higher or equal PCEs as compared with fair asphalt. The PCE for both poor pavement types was on average 9% higher than for the fair asphalt. However, the effect of the poor pavement types was even more severe for a lower proportion of trucks such as 5 or 10% trucks. The PCE for poor asphalt pavement at 10% trucks averaged 17% higher than the PCE for fair

Table 7. PCEs for trucks and buses on upgrades with different pavement types, average single truck population 83.7 kg/kW (137.5 lb/hp) and LOS C congestion.

Upgrade (%)	Length (km)	Length (mi)	E_T																						
			Asphalt Poor				Concrete Poor				Asphalt Good				Concrete Good				Concrete Excellent				Snow Covered		
			Percentage of Trucks and Buses																						
			5	10	25	100	5	10	25	100	5	10	25	100	5	10	25	100	5	10	25	100	5	10	25
2	0.40	0.25	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	5.5	3.5	2.0
	0.80	0.50	2.0	2.0	1.5	1.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	5.5	3.5	2.0
	1.21	0.75	2.0	2.0	1.5	1.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	5.5	3.5	2.0
	1.61	1.00	2.0	2.0	1.5	1.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	5.5	3.5	2.0
	2.01	1.25	2.0	2.0	1.5	1.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	5.5	3.5	2.0
	2.41	1.50	2.0	2.0	1.5	1.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	5.5	3.5	2.0
4	0.40	0.25	2.5	2.0	2.0	1.5	2.5	2.0	2.0	1.5	2.0	2.0	2.0	1.5	2.0	2.0	2.0	1.5	2.0	2.0	1.5	1.5	5.5	3.5	2.0
	0.80	0.50	3.0	3.0	2.0	1.5	3.0	2.5	2.0	1.5	2.5	2.5	2.0	1.5	2.5	2.5	2.0	1.5	2.5	2.0	2.0	1.5	5.5	3.5	2.0
	1.21	0.75	4.0	3.0	2.5	1.5	3.5	3.0	2.5	1.5	3.0	2.5	2.0	1.5	3.5	2.5	2.0	1.5	3.0	2.5	2.0	1.5	5.5	3.5	2.0
	1.61	1.00	4.0	3.5	2.5	1.5	4.0	3.0	2.5	1.5	3.5	2.5	2.0	1.5	3.5	3.0	2.5	1.5	3.0	2.5	2.0	1.5	5.5	3.5	2.0
	2.01	1.25	4.5	3.5	2.5	1.5	4.5	3.5	2.5	1.5	3.5	3.0	2.5	1.5	4.0	3.0	2.5	1.5	3.0	2.5	2.0	1.5	5.5	3.5	2.0
	2.41	1.50	4.5	3.5	3.0	1.5	4.5	3.5	2.5	1.5	3.5	3.0	2.5	1.5	4.0	3.0	2.5	1.5	3.5	3.0	2.5	1.5	5.5	3.5	2.0
6	0.40	0.25	3.0	3.0	2.5	1.5	3.0	3.0	2.5	1.5	3.0	2.5	2.0	1.5	3.0	2.5	2.0	1.5	2.5	2.5	2.0	1.5	5.5	3.5	2.0
	0.80	0.50	5.0	4.0	3.0	2.0	4.5	4.0	3.0	2.0	4.0	3.5	2.5	1.5	4.0	3.5	3.0	2.0	4.0	3.5	2.5	1.5	5.5	3.5	2.0
	1.21	0.75	6.0	4.5	3.5	2.0	5.5	4.5	3.0	2.0	5.0	4.0	3.0	2.0	5.0	4.0	3.0	2.0	4.5	4.0	3.0	2.0	5.5	3.5	2.0
	1.61	1.00	6.5	5.0	3.5	2.0	6.0	4.5	3.0	2.0	5.5	4.0	3.0	2.0	5.5	4.0	3.0	2.0	5.0	4.0	3.0	2.0	5.5	3.5	2.0
	2.01	1.25	6.5	5.0	3.5	2.0	6.0	4.5	3.5	2.0	6.0	4.5	3.0	2.0	6.0	4.5	3.0	2.0	5.5	4.0	3.0	2.0	5.5	3.5	2.0
	2.41	1.50	7.0	5.0	3.5	2.0	6.5	5.0	3.5	2.0	6.0	4.5	3.0	2.0	6.0	4.5	3.5	2.0	5.5	4.5	3.0	2.0	6.0	3.5	2.0

Table 8. Percentage difference in calculated PCE for different pavement types compared to asphalt fair pavement.

Upgrade (%)	Length (km)	Length (mi)	% Error From Asphalt Fair																						
			Asphalt Poor				Concrete Poor				Asphalt Good				Concrete Good				Concrete Excellent				Snow Covered		
			Percentage of Trucks and Buses																						
			5	10	25	100	5	10	25	100	5	10	25	100	5	10	25	100	5	10	25	100	5	10	25
2	0.40	0.25	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-33%	0%	0%	0%	0%	0%	0%	0%	-33%	267%	133%	33%
	0.80	0.50	0%	33%	0%	0%	0%	33%	0%	0%	-25%	0%	0%	-33%	-25%	0%	0%	0%	-25%	0%	0%	-33%	175%	133%	33%
	1.21	0.75	0%	33%	0%	0%	0%	33%	0%	0%	-25%	0%	0%	-33%	-25%	0%	0%	0%	-25%	0%	0%	-33%	175%	133%	33%
	1.61	1.00	0%	33%	0%	0%	0%	33%	0%	0%	-25%	0%	0%	-33%	-25%	0%	0%	0%	-25%	0%	0%	-33%	175%	133%	33%
	2.01	1.25	0%	33%	0%	0%	0%	33%	0%	0%	-25%	0%	0%	-33%	-25%	0%	0%	0%	-25%	0%	0%	-33%	175%	133%	33%
	2.41	1.50	0%	33%	0%	0%	0%	33%	0%	0%	-25%	0%	0%	-33%	-25%	0%	0%	0%	-25%	0%	0%	-33%	175%	133%	33%
4	0.40	0.25	25%	0%	0%	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-25%	0%	175%	75%	0%
	0.80	0.50	20%	20%	0%	0%	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-20%	0%	0%	120%	40%	0%
	1.21	0.75	33%	0%	25%	0%	17%	0%	25%	0%	0%	-17%	0%	0%	17%	-17%	0%	0%	0%	-17%	0%	0%	83%	17%	0%
	1.61	1.00	14%	17%	0%	0%	14%	0%	0%	0%	0%	-17%	-20%	0%	0%	0%	0%	0%	-14%	-17%	-20%	0%	57%	17%	-20%
	2.01	1.25	13%	17%	0%	0%	13%	17%	0%	0%	-13%	0%	0%	0%	0%	0%	0%	0%	-25%	-17%	-20%	0%	38%	17%	-20%
	2.41	1.50	13%	17%	20%	0%	13%	17%	0%	0%	-13%	0%	0%	0%	0%	0%	0%	0%	-13%	0%	0%	0%	38%	17%	-20%
6	0.40	0.25	0%	20%	25%	0%	0%	20%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-17%	0%	0%	0%	83%	40%	0%
	0.80	0.50	11%	14%	20%	0%	0%	14%	20%	0%	-11%	0%	0%	-25%	-11%	0%	20%	0%	-11%	0%	0%	-25%	22%	0%	-20%
	1.21	0.75	9%	13%	17%	0%	0%	13%	0%	0%	-9%	0%	0%	0%	-9%	0%	0%	0%	-18%	0%	0%	0%	0%	-13%	-33%
	1.61	1.00	8%	11%	17%	0%	0%	0%	0%	0%	-8%	-11%	0%	0%	-8%	-11%	0%	0%	-17%	-11%	0%	0%	-8%	-22%	-33%
	2.01	1.25	8%	11%	0%	0%	0%	0%	0%	0%	0%	0%	-14%	0%	0%	0%	-14%	0%	-8%	-11%	-14%	0%	-8%	-22%	-43%
	2.41	1.50	8%	0%	0%	0%	0%	0%	0%	0%	-8%	-10%	-14%	0%	-8%	-10%	0%	0%	-15%	-10%	-14%	0%	-8%	-30%	-43%
		average =	11%	17%	7%	0%	6%	14%	4%	0%	-10%	-3%	-3%	-13%	-8%	-2%	0%	0%	-15%	-6%	-5%	-13%	96%	52%	-2%

asphalt pavement across the selected grades. As the proportion of trucks increased however, the effect of poor pavement was less.

The effect of good pavement was only significant at 5% trucks. Overall, the calculated PCE for good concrete pavement was 2% lower than the PCE for the default pavement type. Similarly, the calculated PCE for good asphalt pavement was on average 5% lower than the PCE for fair asphalt. The PCE on good pavements exhibited much less variability because the value of the rolling coefficient and pavement friction coefficient for good pavement is very close to the value of the coefficients for the default, fair asphalt, pavement. Excellent concrete pavement had a much improved rolling coefficient and pavement friction coefficient compared to the default pavement. For this reason, the PCE for excellent concrete pavement was always lower than the PCE for fair asphalt. On average, the PCE for excellent concrete was 8% lower than the PCE for fair asphalt; however, the effect of excellent concrete pavement decreased as the proportion of trucks increased.

Snow covered pavement resulted in PCEs that were as much as 267% higher than the PCEs calculated for the default pavement. Snow covered pavement does not depend on the pavement type beneath, but represents 5.08 cm (2 in) of snow cover. The effect of snow covered pavement decreased as the proportion of trucks increased. The effect of snow cover was not primarily limited only to trucks; it also affected the speed of passenger cars. For this reason, the PCEs exhibited a different trend than for the other pavement types. The PCEs for snow covered pavement were constant regardless of the percent or length of grade. Snow cover dramatically increases the pavement rolling coefficient and decreases the friction coefficient. Essentially, the worst effect of the snow cover applied to all grade combinations. In the case of long 6% grades, the PCEs calculated for snow covered pavement were actually less than the PCEs calculated for the default pavement. This represents the situation that passenger cars were also slowed down due to the snow cover. Since the entire traffic stream slowed down, the PCE of trucks was not as high as it was for the other pavement types and conditions where passenger cars in the traffic stream remained at higher speeds. Roadway surface coefficients were not obtained for rainy (wet pavement) conditions, but the effect of wet pavement on the PCEs is expected to be similar with a different magnitude.

4.9 Variability of PCE by Truck Aerodynamic Treatment

Truck aerodynamic treatment was found only to have a significant effect on the calculated PCE for 10% proportion of trucks, with a percentage difference of 14%. This partially confirms a hypothesis of this research. However, it was expected that the effect of aerodynamic treatment would also be significant at 5% trucks, as it was for the pavement type and condition presented in section 4.8. The aerodynamic treatment of trucks affects the vehicle drag coefficient, which in turn affects the maximum acceleration. The default aerodynamic treatment was full aerodynamic treatment, with a drag coefficient of 0.58. Two other aerodynamic treatment options were examined, one with partial aerodynamic aids on the roof and the other with no aerodynamic aids.

Table 9 shows the percentage difference of the PCE for the different aerodynamic treatments as compared to full aerodynamic treatment. It is not expected that the calculated PCE for either of the two aerodynamic treatment options should be lower than the default PCE because the effect of these treatments decreases the maximum vehicle acceleration obtainable. The calculated PCE for partial aerodynamic aids on the roof was

Table 9. Percentage difference in calculated PCE for different aerodynamic treatments compared to full aerodynamic treatment.

Upgrade (%)	Length (km)	Length (mi)	% Error From Full Aerodynamic Treatment							
			Partial Aerodynamic Aids				No Aerodynamic Aids			
			Percentage of Trucks and Buses							
			5	10	25	100	5	10	25	100
2	0.40	0.25	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	-25%	0%	0%	0%	0%	33%	0%	0%
	1.21	0.75	-25%	0%	0%	0%	0%	33%	0%	0%
	1.61	1.00	0%	33%	0%	0%	0%	33%	0%	0%
	2.01	1.25	0%	33%	0%	0%	0%	33%	0%	0%
	2.41	1.50	0%	33%	0%	0%	0%	33%	0%	0%
4	0.40	0.25	0%	0%	0%	0%	25%	0%	0%	0%
	0.80	0.50	20%	0%	0%	0%	20%	0%	0%	0%
	1.21	0.75	17%	0%	0%	0%	17%	0%	25%	0%
	1.61	1.00	0%	0%	0%	0%	14%	0%	0%	0%
	2.01	1.25	0%	0%	0%	0%	0%	17%	0%	0%
	2.41	1.50	0%	0%	0%	0%	0%	17%	0%	0%
6	0.40	0.25	0%	20%	0%	0%	0%	20%	0%	0%
	0.80	0.50	0%	0%	20%	0%	0%	14%	20%	0%
	1.21	0.75	0%	0%	0%	0%	0%	13%	0%	0%
	1.61	1.00	0%	0%	0%	0%	0%	0%	0%	0%
	2.01	1.25	8%	0%	-14%	0%	0%	0%	0%	0%
	2.41	1.50	-8%	0%	0%	0%	-8%	0%	0%	0%
		average =	-1%	7%	0%	0%	4%	14%	3%	0%

on average 4% higher than the default PCE. The greatest effect of the aerodynamic treatment was at 10% trucks, and the effect decreased as the proportion of trucks increased. Similarly, the calculated PCE for no aerodynamic aids was on average 6% higher than the default PCE. Again, the effect of aerodynamic treatment was only significant for 10% proportion of trucks. A realistic truck population may contain a variety of aerodynamic treatments; these simulation results cover a worst case scenario, a single truck population with no aerodynamic treatments.

4.10 Variability of PCE for Three Lane Segments

The calculated PCE for three lane freeway segments was found only to be significantly different from two lane freeway segments at 5% proportion of trucks. This partially confirms a hypothesis of this research. Two different situations were examined, one in which trucks were allowed to use any of the three lanes and one in which trucks were restricted from using the leftmost lane. Truck restrictions are common for many three lane freeway segments. Table 10 shows the percentage difference of the PCE for three lane segments as compared to two lane segments. The PCEs for three lane freeway segments are generally lower because the third lane allows the opportunity for cars to pass while trucks in the middle lane are passing other trucks. The calculated PCE for three lane segments averages -9% for 5% proportion of trucks. This average is not significant, but a preponderance of the observations for 5% proportion of trucks are significantly different (having absolute differences greater than 10%). At higher proportion of trucks, the PCE for three lane segments is hardly different than for two lane segments. The truck lane restriction had no effect on the calculated PCE as compared with three lane segments without truck lane restriction. This suggests that a truck lane

Table 10. Percentage difference in calculated PCE for three lane freeway segments compared to two lane freeway segments.

Upgrade (%)	Length (km)	Length (mi)	% Error From Two Lane Fwy Segments							
			Three Lanes w/o Restrictions				Three Lanes w/ Restrictions			
			Percentage of Trucks and Buses							
			5	10	25	100	5	10	25	100
2	0.40	0.25	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	-25%	0%	0%	0%	-25%	0%	0%	0%
	1.21	0.75	-25%	0%	0%	0%	-25%	0%	0%	0%
	1.61	1.00	-25%	0%	0%	0%	-25%	0%	0%	0%
	2.01	1.25	-25%	0%	0%	0%	-25%	0%	0%	0%
	2.41	1.50	0%	0%	0%	0%	0%	0%	0%	0%
4	0.40	0.25	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	20%	0%	0%	0%	0%	0%	0%	0%
	1.21	0.75	0%	-17%	0%	0%	0%	-17%	0%	0%
	1.61	1.00	0%	0%	-20%	0%	0%	0%	-20%	0%
	2.01	1.25	-13%	0%	0%	0%	-13%	0%	0%	0%
	2.41	1.50	-13%	0%	0%	0%	-13%	0%	0%	0%
6	0.40	0.25	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	-11%	0%	0%	0%	0%	0%	0%	0%
	1.21	0.75	-9%	0%	0%	0%	-9%	0%	0%	0%
	1.61	1.00	-8%	-11%	0%	0%	-8%	-11%	0%	0%
	2.01	1.25	-17%	-11%	-14%	0%	-8%	-11%	-14%	0%
	2.41	1.50	-15%	-10%	-14%	0%	-15%	-10%	-14%	0%
		average =	-9%	-3%	-3%	0%	-9%	-3%	-3%	0%

restriction provides no significant capacity increase as compared with no truck lane restriction. However, this must be considered in light of the fact that trucks in the simulation and realistically tend only to use the two rightmost lanes on grades anyway.

4.11 Variability of PCE for Truck Speed Limit

The institution of a truck speed limit was found to significantly affect the calculated PCE; percentage differences exceeded 10%. This confirms a hypothesis of this research. The default situation was an equal speed limit for all vehicles at 112.6 km/h (70 mi/h). The simulated truck speed limit restricted trucks to 88.5 km/h (55 mi/h). Table 11 shows the percentage difference of the PCE for the truck speed limit as compared with the PCE without a separate truck speed limit. The calculated PCE for the truck speed limit was on average 32% higher than the calculated PCE without a truck speed limit. The greatest effect of the truck speed limit occurs at 5% proportion of trucks. As the proportion of trucks increases, the effect of the truck speed limit decreases. However, the truck speed limit still produces a significant increase in the calculated PCE for 25% proportion of trucks. At times, the calculated PCE for the truck speed limit was double the PCE without a separate truck speed limit. For 100% proportion of trucks, the truck speed limit actually had no substantial effect.

4.12 Variability by Level of Congestion

The level of congestion was found to significantly affect the calculated PCE; percentage differences exceeded 10%. Average density was used in this research as a determinant of the level of congestion. It was found that an average density value of 12.4 pc/km/ln (20 pc/ml/ln) resulted in PCEs that most closely matched those provided in the HCM 2000. This average density value corresponds to LOS C. However, it is also

Table 11. Percentage difference in calculated PCE for a truck speed limit at 88.5 km/hr (55 mi/h) compared to no separate truck speed limit 112.6 km/hr (70 mi/h).

Upgrade (%)	Length (km)	Length (mi)	% Error From No Truck Speed Limit			
			Truck Speed Limit			
			Percentage of Trucks and Buses			
			5	10	25	100
2	0.40	0.25	67%	33%	33%	0%
	0.80	0.50	50%	67%	33%	0%
	1.21	0.75	75%	100%	33%	0%
	1.61	1.00	75%	100%	33%	0%
	2.01	1.25	100%	100%	33%	0%
	2.41	1.50	100%	100%	33%	0%
4	0.40	0.25	50%	25%	0%	0%
	0.80	0.50	80%	40%	25%	0%
	1.21	0.75	83%	33%	25%	0%
	1.61	1.00	71%	33%	0%	0%
	2.01	1.25	63%	50%	0%	0%
	2.41	1.50	63%	33%	0%	0%
6	0.40	0.25	33%	40%	25%	0%
	0.80	0.50	22%	29%	20%	0%
	1.21	0.75	27%	25%	17%	0%
	1.61	1.00	17%	11%	17%	0%
	2.01	1.25	25%	11%	0%	0%
	2.41	1.50	15%	10%	0%	0%
		average =	56%	47%	18%	0%

desirable to quantify the effect of the level of congestion on the PCE because many freeway segments do not operate at LOS C. Figure 9 shows the variability of the calculated PCE for different average density values, ranging from 9.3 to 24.9 veh/km/ln (15 to 40 veh/mi/ln). This range of average density values represents a LOS that ranges from B to E.

It can be observed from figure 9 that for grades of 2 or 4%, the calculated PCE does not vary by much. However, for steeper grades such as 6 or 8%, the calculated PCE varies significantly by the average density value. Table 12 shows the percentage difference of the PCE calculated for the different average density values compared to the PCE calculated for an average density value of 12.4 pc/km/ln (20 pc/ml/ln). The greatest difference occurs for average density values within the LOS D regime. This means that PCE is most critical at LOS D congestion. The PCEs calculated for LOS B congestion are mostly lower, and the PCEs calculated for LOS D or E congestion are mostly higher than the PCEs calculated at LOS C congestion. The effect of level of congestion may be accounted for by multiplying the PCEs calculated at LOS C congestion by a scale factor.

4.13 Combined Effect of Variables on PCEs

The individual effect of each of the variables presented in the previous sections was examined with respect to the default scenario. This default scenario consisted of a single truck population with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp), operating on fair asphalt pavement, with full aerodynamic features, with no separate truck speed limit, and a level of congestion corresponding to LOS C. The variability of the PCE was considered independent of any interaction that may occur when these variables are combined. Demarchi and Setti (19) discussed the limitations of

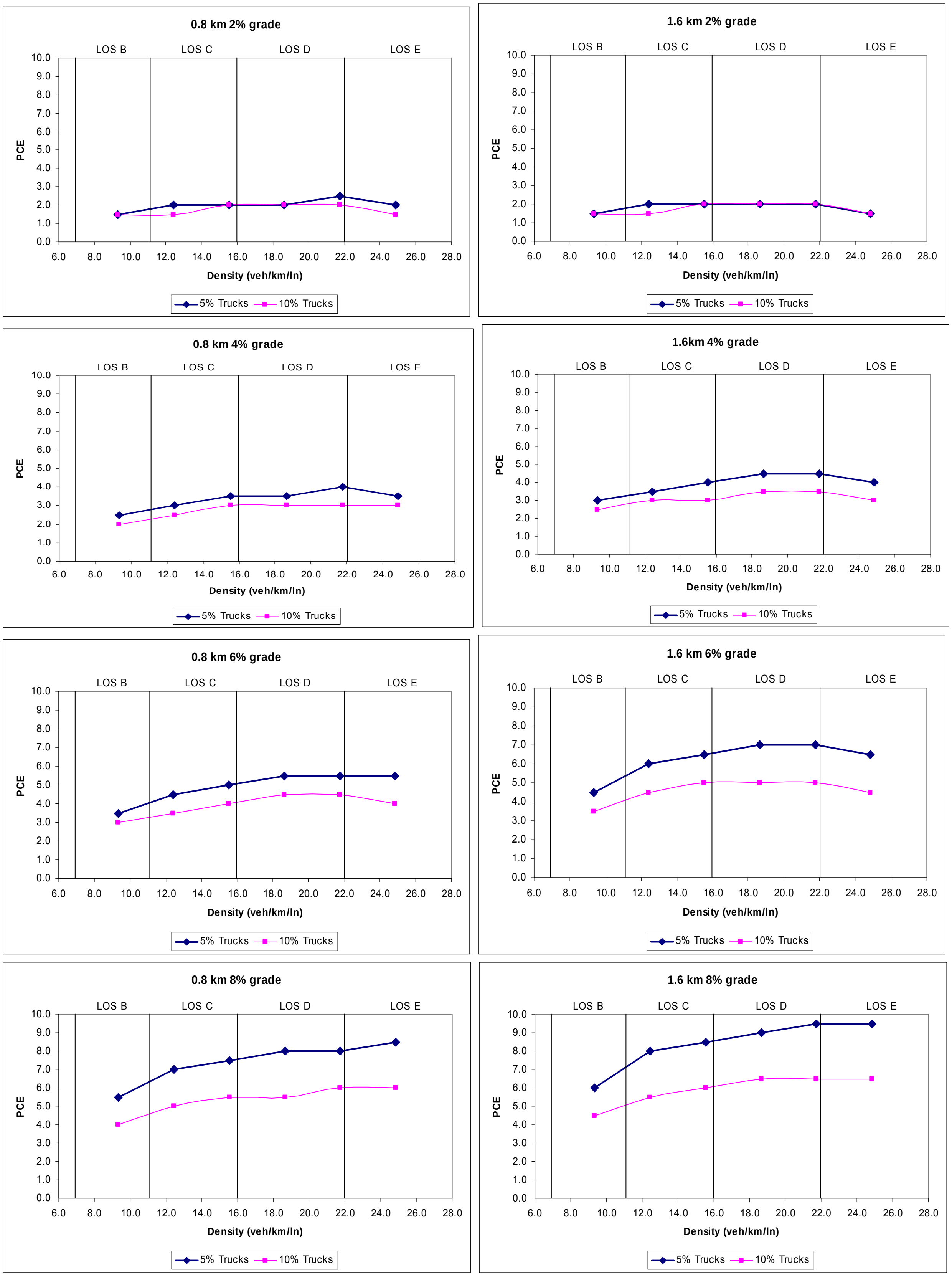

Figure 9. PCE variability by level of congestion for average single truck population 83.7 kg/kW (137.5 lb/hp).

Table 12. Percentage difference in calculated PCE for different levels of congestion, average single truck population 83.7 kg/kW (137.5 lb/hp).

Upgrade (%)	Density		% Error From LOS C Congestion, 12.4 veh/km/lm (20 veh/mi/ln)											
	(veh/mi/ln)		15		20		25		30		35		40	
	(veh/km/ln)		9.3		12.4		15.5		18.6		21.8		24.9	
	% Trucks		5	10	5	10	5	10	5	10	5	10	5	10
	Length (km)	Length (mi)												
2	0.40	0.25												
	0.80	0.50	-25%	0%	0%	0%	0%	33%	0%	33%	25%	33%	0%	0%
	1.21	0.75												
	1.61	1.00	-25%	0%	0%	0%	0%	33%	0%	33%	25%	33%	0%	0%
	2.01	1.25												
	2.41	1.50												
4	0.40	0.25												
	0.80	0.50	-17%	-20%	0%	0%	17%	20%	17%	20%	33%	20%	17%	20%
	1.21	0.75												
	1.61	1.00	-14%	-17%	0%	0%	14%	0%	29%	17%	29%	17%	14%	0%
	2.01	1.25												
	2.41	1.50												
6	0.40	0.25												
	0.80	0.50	-22%	-14%	0%	0%	11%	14%	22%	29%	22%	29%	22%	14%
	1.21	0.75												
	1.61	1.00	-25%	-22%	0%	0%	8%	11%	17%	11%	17%	11%	8%	0%
	2.01	1.25												
	2.41	1.50												
8	0.40	0.25												
	0.80	0.50	-21%	-20%	0%	0%	7%	10%	14%	10%	14%	20%	21%	20%
	1.21	0.75												
	1.61	1.00	-25%	-18%	0%	0%	6%	9%	13%	18%	19%	18%	19%	18%
	2.01	1.25												
	2.41	1.50												
		average=	-22%	-14%	0%	0%	8%	16%	14%	21%	23%	23%	13%	9%

calculating the PCE of a specific truck type out of a population that contained multiple truck types. They found that the combined impact of multiple truck types was not accounted for by simply taking the algebraic sum of the impact of each truck type separately. Their recommendation to workaround this problem was to consider only an aggregate PCE which would represent all truck types present. This recommendation was adopted in this research with respect to multiple truck populations, as presented in chapter 5.

A similar consideration may be made for the interaction among the different roadway and traffic characteristics considered in this research. However, it is unreasonable to calculate an aggregate PCE for each combination of the roadway and traffic characteristics examined in this research, or further, for all the roadway and traffic characteristics that exist. Therefore an aggregate PCE that accounts for the roadway and traffic characteristics was not calculated. Instead it was decided to determine what error might be expected if the individual effects of the variables are combined algebraically. A set of simulations was conducted for two case studies that involved variability of the weight to power ratio, pavement type and condition, and level of congestion simultaneously. Both case studies were examined at 10% proportion of trucks. The first case study considered a single truck population with a weight to power ratio of 106.6 kg/kW (175 lb/hp), operating on poor concrete pavement, and a level of congestion corresponding to LOS D. Each of these variables tends to increase the PCE when considered individually. The second case study considered a single truck population with a weight to power ratio of 68.5 kg/kW (112.5 lb/hp), operating on excellent concrete pavement, and a level of congestion corresponding to LOS B. Each of these variables tends to decrease the PCE when considered individually.

For each case study, flow and density data were obtained as output from traffic simulations. The equivalent passenger car throughput (base flow) was calculated as

$$q_B = (1 - P_T) \cdot q_M + P_T \cdot E_T \cdot SF \cdot q_M \qquad [4.1]$$

where q_B is the base flow rate (passenger cars only), P_T is the proportion of all trucks, q_M is the mixed vehicle flow rate, E_T is the aggregate PCE of trucks, and SF are any number of scale factors which are recommended to account for the effect of roadway and traffic characteristics. A set of scale factors are recommended in chapter 6, which were determined based upon the results presented in this chapter. The scale factors are based on a ratio of the PCE; they are multiplicative such that they will either increase or decrease the PCE calculated for the default situation depending on whether the variable in question has an increasing or decreasing effect on the PCE. It was assumed for the case study that the effects of different variables on the PCE could be combined without considering any interactive effects. A consequence of this assumption is that the scale factor for a variable that tends to increase the PCE may counteract the scale factor for a variable that tends to decrease the PCE. However, this consequence was not examined in the two case studies presented here because in either case study, all of the variables tend to have the same effect on the PCE.

The base flow was calculated using the default flow data at a level of congestion corresponding to LOS B and LOS D. The only scale factor applied to the default flow data was a scale factor that accounts for the effect of the level of congestion. Table 13 shows the flow data and calculated base flow for the default scenario as well as the two

Table 13. Case study 1 and 2 for combined effect of variables.

Upgrade (%)	Length (km)	Length (mi)	Default Flows 10% single trucks 83.3 kg/kW (137.5 lb/hp), fair asphalt pavement			Base Flow at density = 9.3 veh/km/ln	Base Flow at density = 19.6 veh/km/ln	Case Study 1 10% single truck 106.6 kg/kW (175 lb/hp), poor concrete pavement		Base Flow at density = 19.6 veh/km/ln	Error from default base flow	Case Study 2 10% single truck 68.5 kg/kW (112.5 lb/hp), excellent concrete pavement		Base Flow at density = 9.3 veh/km/ln	Error from default base flow
			LOS B	LOS C	LOS D	(pc/h/ln)	(pc/h/ln)	LOS C	LOS D	(pc/h/ln)		LOS B	LOS C	(pc/h/ln)	
2	0.40	0.25													
	Flow (veh/h/ln)		814	1352	1846	1065	2044	1350	1835	1976	-3%	817	1349.0	963	-10%
	Density (veh/km/ln)		7.0	12.6	19.0			15.0	24.0			8.0	13.8		
	0.80	0.50													
	Flow (veh/h/ln)		819	1344	1840	1049	2042	1353	1842	1868	-9%	823	1351.0	960	-8%
	Density (veh/km/ln)		7.2	12.6	19.0			16.5	26.2			8.0	14.0		
	1.21	0.75													
	Flow (veh/h/ln)		817	1346	1833	1040	2051	1347	1822	1894	-8%	820	1351.8	952	-8%
	Density (veh/km/ln)		7.2	12.8	18.8			16.1	25.2			8.1	14.0		
	1.61	1.00													
	Flow (veh/h/ln)		820	1349	1829	1035	2052	1358	1856	1924	-6%	817	1356.1	954	-8%
	Density (veh/km/ln)		7.3	12.8	18.7			16.8	23.9			8.1	14.0		
	2.01	1.25													
	Flow (veh/h/ln)		820	1356	1826	1035	2056	1361	1847	1929	-6%	816	1355.0	950	-8%
	Density (veh/km/ln)		7.3	13.0	18.7			17.2	23.2			8.1	14.0		
	2.41	1.50													
	Flow (veh/h/ln)		827	1352	1830	1032	2057	1349	1818	1982	-4%	828	1347.3	948	-8%
	Density (veh/km/ln)		7.4	13.0	18.7			16.5	22.3			8.2	14.3		
4	0.40	0.25													
	Flow (veh/h/ln)		818	1348	1828	1069	2033	1348	1825	2049	1%	821	1348.0	964	-10%
	Density (veh/km/ln)		7.2	13.2	20.3			14.6	23.6			8.0	13.8		
	0.80	0.50													
	Flow (veh/h/ln)		821	1345	1828	1063	2057	1350	1843	2079	1%	822	1350.4	990	-7%
	Density (veh/km/ln)		7.6	14.1	21.3			16.1	25.8			8.0	13.9		
	1.21	0.75													
	Flow (veh/h/ln)		824	1348	1833	1078	2107	1356	1829	2251	7%	823	1351.6	1008	-7%
	Density (veh/km/ln)		7.9	14.6	22.1			16.5	24.0			8.1	14.1		
	1.61	1.00													
	Flow (veh/h/ln)		819	1352	1831	1063	2079	1350	1829	2278	10%	820	1341.8	1002	-6%
	Density (veh/km/ln)		8.0	14.8	22.5			16.7	23.1			8.1	14.1		
	2.01	1.25													
	Flow (veh/h/ln)		822	1346	1820	1063	2068	1348	1832	2277	10%	819	1342.0	998	-6%
	Density (veh/km/ln)		8.0	14.9	22.4			17.1	22.6			8.2	13.9		
	2.41	1.50													
	Flow (veh/h/ln)		823	1342	1834	1041	2042	1350	1831	2354	15%	817	1347.9	998	-4%
	Density (veh/km/ln)		8.2	15.1	23.0			15.9	22.5			8.2	14.0		
6	0.40	0.25													
	Flow (veh/h/ln)		825	1349	1824	1063	2003	1347	1826	2180	9%	824	1346.2	992	-7%
	Density (veh/km/ln)		7.6	14.2	22.2			14.5	24.0			8.1	13.9		
	0.80	0.50													
	Flow (veh/h/ln)		817	1356	1835	1054	2031	1353	1823	2394	18%	821	1352.9	1054	0%
	Density (veh/km/ln)		8.3	16.1	25.2			15.8	24.9			8.1	14.0		
	1.21	0.75													
	Flow (veh/h/ln)		821	1350	1823	1055	2051	1345	1833	2479	21%	826	1352.7	1079	2%
	Density (veh/km/ln)		8.8	17.0	25.9			16.5	25.4			8.2	14.1		
	1.61	1.00													
	Flow (veh/h/ln)		822	1342	1815	1072	2102	1349	1832	2699	28%	820	1350.7	1109	3%
	Density (veh/km/ln)		9.0	17.4	26.2			16.8	23.2			8.1	13.9		
	2.01	1.25													
	Flow (veh/h/ln)		812	1341	1821	1049	2078	1345	1854	2702	30%	816	1354.0	1105	5%
	Density (veh/km/ln)		9.2	17.7	26.5			16.5	23.7			8.1	14.2		
	2.41	1.50													
	Flow (veh/h/ln)		822	1356	1833	1082	2153	1351	1802	2964	38%	815	1352.2	1132	5%
	Density (veh/km/ln)		9.3	18.1	26.8			16.3	21.7			8.1	14.1		

case studies. The base flow for the first and second case studies was calculated using scale factors to account for the effect of weight to power ratio, pavement type and condition, and level of congestion. The percent error was calculated between the case study base flow and the default base flow. For the first case study, the error in the calculated base flow was as much as 38% on a 2.41 km (6 mi), 6% grade. However, if an up to 15% error in the calculated base flow is acceptable, the combined effect of the variables (use of multiple scale factors) may be applied for up to a 2.41 km (1.5 mi), 4% grade or a 0.4 km (0.25 mi) 6% grade. The shaded area in table 13 represents the range of grades where the combined effect of the variables results in too great of errors. For the second case study, the error in the calculated base flow was as much as 10% on a 0.40 (0.25 mi), 2% grade. The combined effect of the variables may be applied for all of the grade length and percent combinations examined for the second case study.

The two case studies do not constitute a comprehensive review of the combined effect of roadway and traffic characteristics. However, the case studies do illustrate that there is an applicable range where the use of multiple scale factors may be used if a certain error in the calculated base flow is acceptable. It may be prudent that further research should focus on the applicable range of the combined effect of the roadway and traffic characteristics on the PCE.

4.14 Conclusions

Based on the results presented for single truck populations, the following conclusions have been made. First, truck weight to power ratio has a significant effect on the calculated PCE. A scale factor may be applied to the PCEs calculated for the average weight to power ratio to account for the effect of weight to power ratio. Second, the PCE of trucks remains relatively constant for grades longer than 3.22 km (2 mi), thus the range of grade lengths provided in the HCM 2000 should be extended to include a 3.22 km (2 mi) grade. Third, since the PCE of trucks continues to increase as the percentage grade increases to 8%, PCEs should be provided for steeper grades and assumed to continue to increase as the grade increases. Fourth, engine power only significantly affects the PCE at a low engine power and a low proportion of trucks. It is sufficient to determine PCEs for different weight to power ratios, but to ignore the variability of engine power within a weight to power ratio. Fifth, since the PCE of trucks remains relatively constant for a proportion of trucks greater than 60%, PCEs should be provided for up to 60% proportion of trucks. Sixth, pavement type and condition significantly affects the calculated PCE. Adjustments for pavement type and condition should be made, especially for a low proportion of trucks. Seventh, aerodynamic treatment significantly affects the calculated PCE for a low proportion of trucks only; it is sufficient not to make an adjustment for aerodynamic treatment. Eighth, the PCE for three lane segments is significantly lower than the PCE for two lane segments only for a low proportion of trucks, thus an adjustment for the number of lanes is not necessary. In addition, lane restrictions have no impact on the calculated PCE. Ninth, a separate truck speed limit below the speed limit of other vehicles causes a significant increase in the calculated PCE. A scale factor may be applied to the PCEs calculated for trucks without a separate speed limit in order to account for the effect of a truck speed limit. Tenth, the PCEs provided in the HCM 2000 were calculated for LOS C congestion. A scale factor may be applied to the PCEs to account for the effect of level of congestion. Eleventh, the combined affect of roadway and traffic characteristics results in errors in the calculated base flow that are not entirely accounted for by the combination of individual scale factors. However, with the exception of very steep grades, the error due to the combined effects is acceptable. Further study should focus on the applicability of multiple scale factors to account for the combined effects of roadway and traffic characteristics.

Chapter 5. Results for Multiple Truck Populations

5.1 Background

In the previous chapter, the calculation of the PCE of trucks was simplified by assuming that all trucks had the same characteristics. However, a realistic truck population may contain any number of trucks with different operating characteristics. Multiple truck populations were investigated as part of this research in order to examine the validity of the single truck population simplification. Multiple truck populations were defined to contain trucks with different weight to power ratios. This not only represents the variability in engine power, but also the difference between loaded and unloaded trucks. Pursuant the finding from the single truck population tests, that a truck population with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp) most closely matched the PCEs from the HCM 2000, multiple truck populations were created to have the same average weight to power ratio. Six different multiple truck populations were created.

Two of the multiple truck populations, referred to as J and K, were created to model the distribution observed in the I-81 truck survey in Virginia (23). The J population was created to match the exact bin frequencies from the I-81 truck survey. However, due to aggregating the data into bins of 5.2 kg/kW (25 lb/hp), the average weight to power ratio of this population was 93.5 kg/kW (153.5 lb/hp). The K population was modified to closely match the distribution observed in the I-81 truck survey, while maintaining an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp). Figure 10 shows the distribution of trucks in the J and K populations. It can be observed from figure 10 that the population distributions are similar to a normal distribution with skew to the right.

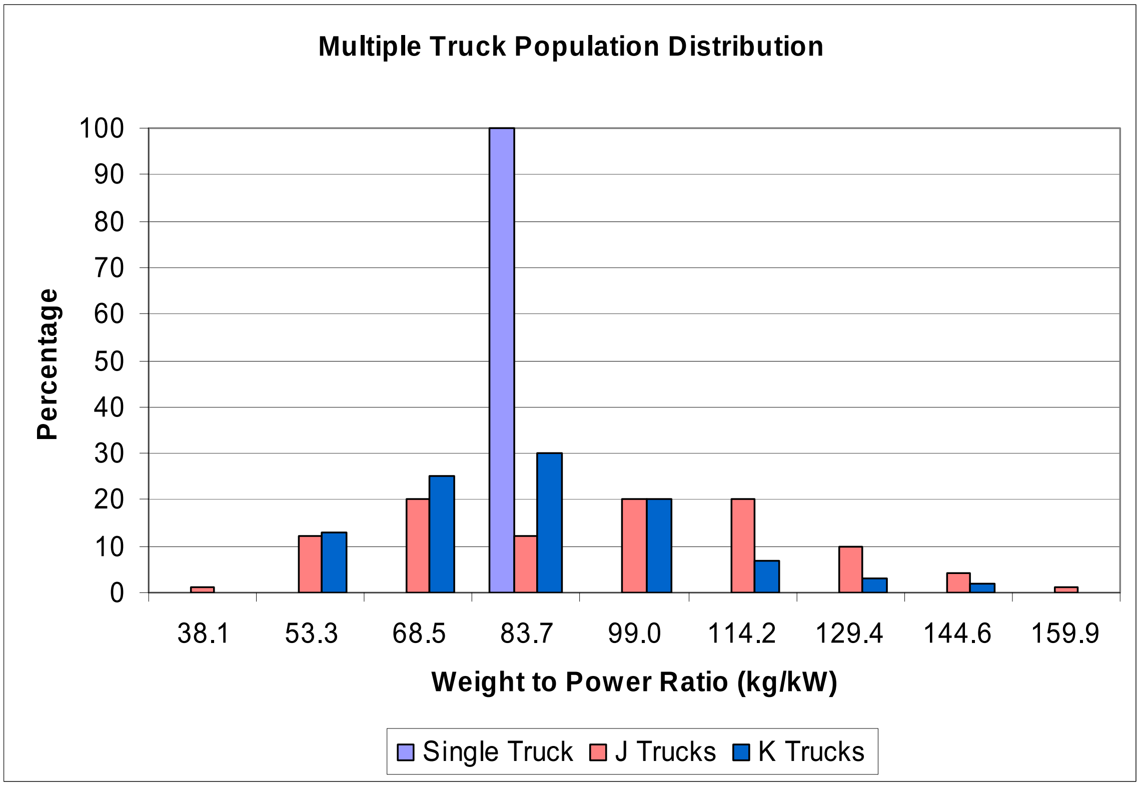

Figure 10. Truck distribution for J and K multiple truck populations.

Four of the multiple truck populations, referred to as L, M, N, and O, were created to model a normal distribution with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp). These normal distributions were created by varying the standard deviation of the weight to power ratio in increments of 10% of the average weight to power ratio. Thus the standard deviation of the L population was 10% of the average weight to power ratio or 8.37 kg/kW (13.75 lb/hp) and so on up to 40% of the average weight to power ratio for the O population. Figure 11 shows the obtained multiple truck population distributions. These distributions also contain a skew to the right, which was created to account for the criteria that the lowest weight to power truck simulated was 38.1 kg/kW (62.5 lb/hp). Of the normal multiple truck population distributions, the N population most closely matched the results of the I-81 truck survey, having a standard deviation of 25.12 kg/kW (41.25 lb/hp).

In a similar way as the single truck population investigations, the multiple truck populations were examined to see that they closely matched the PCEs provided in the HCM 2000. The variability of the multiple truck population by length and percent grade was used to validate the chosen population. High proportion of trucks, pavement type and condition, aerodynamic treatment, three lane segments, truck speed limit, and level of congestion were then examined for the multiple truck population.

The variables mentioned above were used to verify the hypotheses of this research. The primary hypothesis in testing multiple truck populations was that the calculated PCEs would be the same as those calculated for a single truck population with the same weight to power ratio. Section 5.3 presents the results of the comparison between single and multiple truck populations. The other hypotheses that were

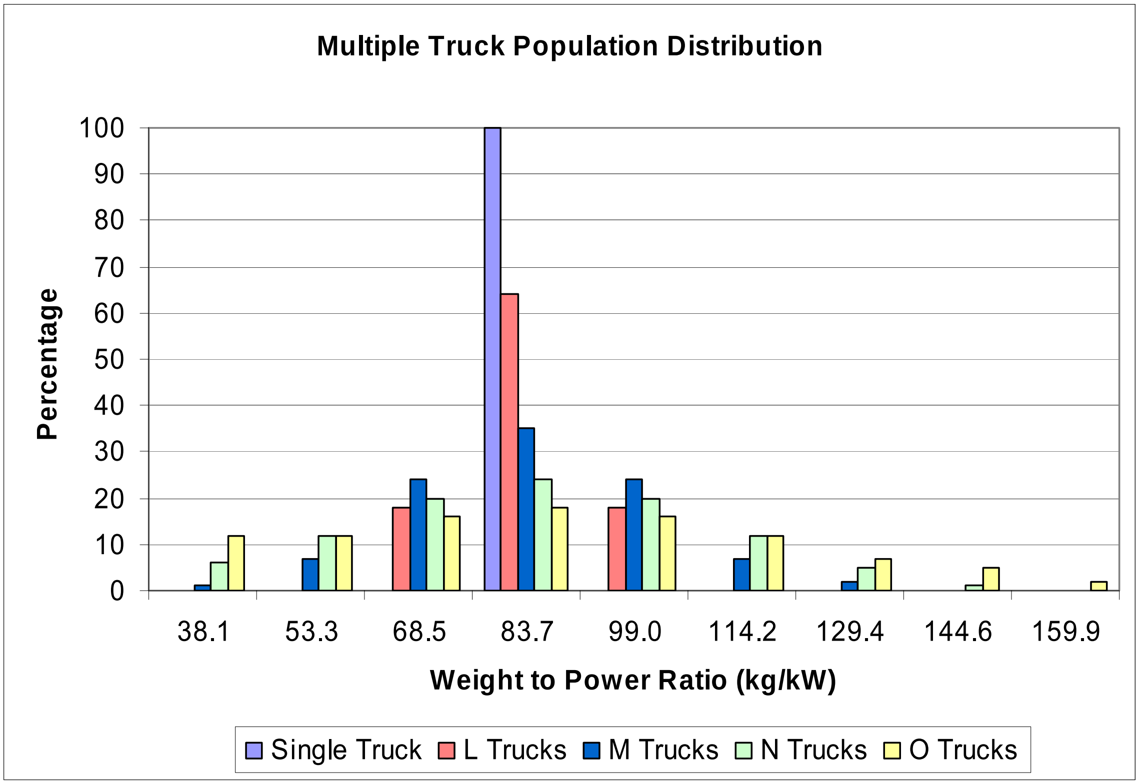

Figure 11. Truck distribution for L, M, N, and O multiple truck populations.

tested for single truck populations were also tested for multiple truck populations. It was hypothesized that the PCE for a multiple truck population decreases with increasing proportion of trucks. Section 5.6 presents the results of the variability of PCE by proportion of trucks. Another hypothesis of this research was that pavement type and condition significantly influence the PCE, with poor pavement types having higher PCEs in comparison to the default pavement type. The results of the variability of PCE by pavement type and condition are presented in section 5.7. It was hypothesized that truck aerodynamic treatment would significantly affect the PCE. Section 5.8 presents the results of the variability of PCE by truck aerodynamic treatment. Another hypothesis of this research was that PCEs for three lane freeway segments would be much lower than PCEs for two lane freeway segments. The results of the variability of PCE for three lane segments are presented in section 5.9. It was hypothesized that the institution of a truck speed limit below the speed limit of other vehicles would result in significantly higher PCEs. The results of the variability of PCE for a truck speed limit are presented in section 5.10. A final hypothesis of this research was that the level of congestion will significantly effect the calculated PCE. Section 5.11 presents the variability of PCE by level of congestion.

5.2 Speed-Flow-Density Relationships

The speed-flow-density relationships for the uncongested flow regime were created using flow and density output data obtained from the traffic simulations. The base vehicle speed-flow-density relationships were already presented in figure 3 and remained unchanged for the multiple truck population research. Figure 12 shows the speed-flow-density relationships for the multiple truck population N, with an average

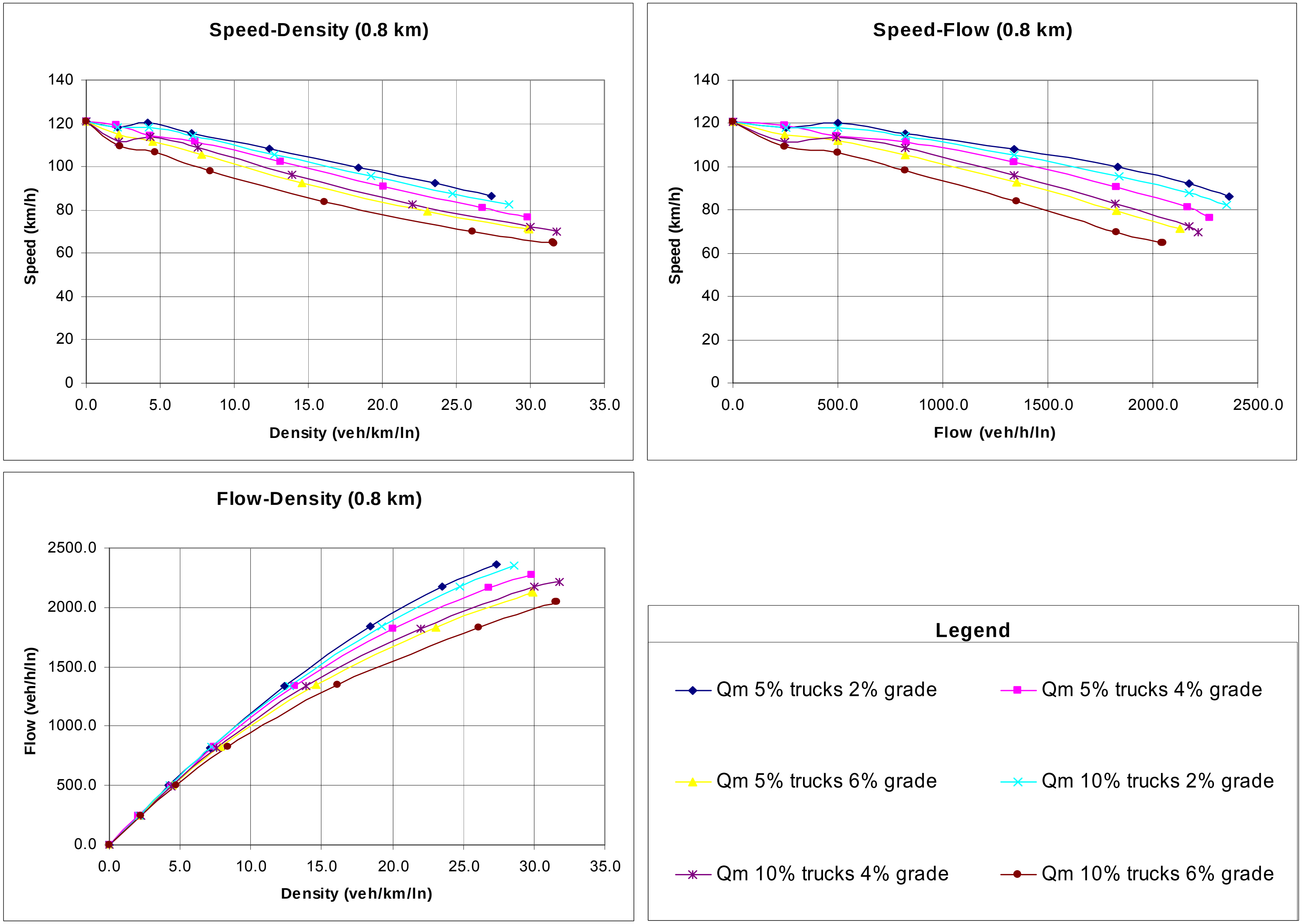

Figure 12. Speed-flow-density relationships, mixed vehicle flow multiple truck population of 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp).

weight to power ratio of 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp). It can be observed from the flow-density relationship that for an equal density value, flow decreases with increasing proportion of trucks and even more so for increasing percentage grade. This trend is also observed in the speed-density and speed-flow relationships at equal values of density and flow respectively. The general trends observed in the mixed vehicle speed-flow-density relationships are as would be expected for freeway segments in the uncongested flow regime.

5.3 PCE for Single vs Multiple Truck Populations

The PCEs calculated for a multiple truck population were not significantly different from the PCEs calculated for a single truck population; percentage differences rarely exceeded 10%. This disproves a hypothesis of this research, that a multiple truck population would perform differently than a single truck population. Figure 13 shows the calculated PCE for multiple truck populations plotted relative to the PCE from the HCM 2000 for specific grades. The M multiple truck population most closely matches the HCM 2000 PCEs for the range of values presented in figure 13. However, as mentioned in section 5.1, the N multiple truck population most closely matched the I-81 truck survey results. For this reason, the N multiple truck population was chosen for further investigative study. Overall, the calculated PCEs for the multiple truck populations were rarely more than 0.5 in absolute difference from the HCM 2000 PCEs.

The calculated PCEs for the N multiple truck population are provided in table 14. The difference between the single and multiple truck population is characterized in table 15, which shows the percentage difference between the PCEs calculated for the average single truck population and the PCEs calculated for the N multiple truck population. The

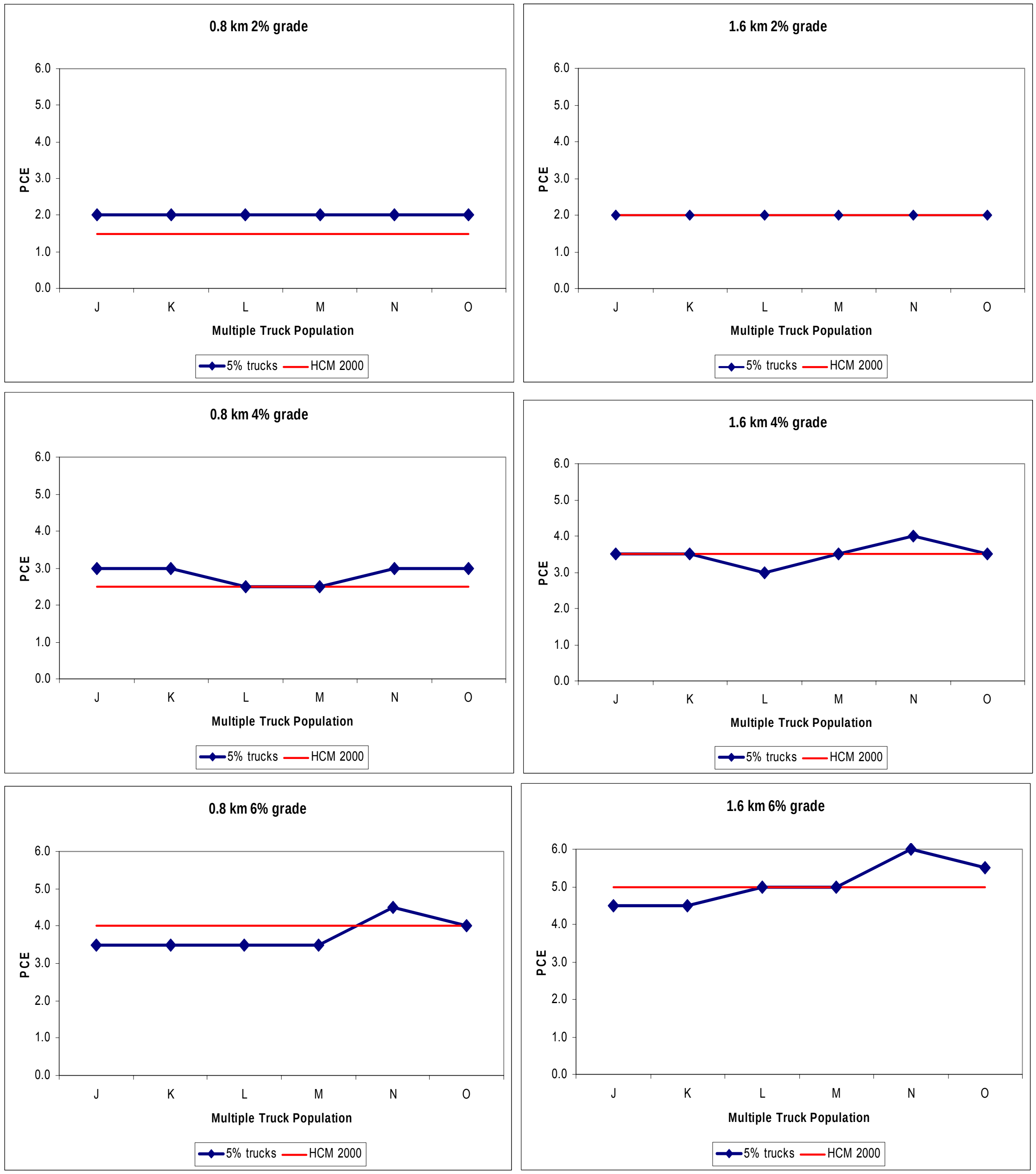

Figure 13. PCE variability by multiple truck populations at LOS C congestion.

Table 14. PCEs for trucks and buses on upgrades, N multiple truck population, 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp) at LOS C congestion.

Upgrade (%)	Length (km)	Length (mi)	E_T																
			Percentage of Trucks and Buses																
			2	4	5	6	8	10	15	20	25	30	40	50	60	70	80	90	100
1	0.40	0.25																	
	0.80	0.50																	
	1.21	0.75																	
	1.61	1.00																	
	2.01	1.25																	
	2.41	1.50																	
2	0.40	0.25			1.5			1.5		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	0.80	0.50			2.0			1.5		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	1.21	0.75			2.0			2.0		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	1.61	1.00			2.0			2.0		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	2.01	1.25			2.0			2.0		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	2.41	1.50			2.0			2.0		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
3	0.40	0.25																	
	0.80	0.50																	
	1.21	0.75																	
	1.61	1.00																	
	2.01	1.25																	
	2.41	1.50																	
4	0.40	0.25			2.0			2.0		2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	0.80	0.50			3.0			2.5		2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5
	1.21	0.75			3.5			3.0		2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	1.61	1.00			4.0			3.0		2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	2.01	1.25			4.0			3.0		2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0
	2.41	1.50			4.0			3.0		2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
5	0.40	0.25																	
	0.80	0.50																	
	1.21	0.75																	
	1.61	1.00																	
	2.01	1.25																	
	2.41	1.50																	
6	0.40	0.25			3.0			2.5		2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5
	0.80	0.50			4.5			3.5		3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0
	1.21	0.75			5.5			4.5		3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	1.61	1.00			6.0			4.5		3.5	3.0	3.0	2.5	2.5	2.5	2.5	2.5	2.5	2.0
	2.01	1.25			6.0			4.0		3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5	2.5
	2.41	1.50			6.0			4.0		3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5

Table 15. Percentage difference in calculated PCE for N multiple truck population compared to the average single truck population.

Upgrade (%)	Length (km)	Length (mi)	% Error From Single Truck Population																
			Percentage of Trucks and Buses																
			2	4	5	6	8	10	15	20	25	30	40	50	60	70	80	90	100
1	0.40	0.25																	
	0.80	0.50																	
	1.21	0.75																	
	1.61	1.00																	
	2.01	1.25																	
	2.41	1.50																	
2	0.40	0.25			0%			0%		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50			-33%			0%		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	1.21	0.75			-33%			-33%		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	1.61	1.00			0%			-33%		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	2.01	1.25			0%			-33%		0%	0%	0%	0%	0%	0%	0%	0%	0%	-50%
	2.41	1.50			0%			-33%		0%	0%	0%	0%	0%	0%	0%	0%	0%	-50%
3	0.40	0.25																	
	0.80	0.50																	
	1.21	0.75																	
	1.61	1.00																	
	2.01	1.25																	
	2.41	1.50																	
4	0.40	0.25			0%			0%		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50			-20%			0%		0%	0%	0%	0%	-33%	-33%	0%	0%	0%	0%
	1.21	0.75			0%			0%		0%	-25%	0%	0%	0%	0%	-33%	-33%	-33%	-33%
	1.61	1.00			-14%			0%		0%	0%	-25%	0%	0%	0%	-33%	-33%	-33%	-33%
	2.01	1.25			0%			0%		0%	0%	-25%	-25%	0%	0%	-33%	-33%	-33%	-33%
	2.41	1.50			0%			0%		0%	0%	0%	0%	0%	0%	-33%	-33%	-33%	-33%
5	0.40	0.25																	
	0.80	0.50																	
	1.21	0.75																	
	1.61	1.00																	
	2.01	1.25																	
	2.41	1.50																	
6	0.40	0.25			0%			0%		0%	-25%	0%	0%	0%	0%	-33%	-33%	0%	0%
	0.80	0.50			0%			0%		0%	-20%	0%	0%	0%	-25%	0%	0%	0%	0%
	1.21	0.75			0%			-13%		14%	0%	0%	0%	0%	0%	-25%	0%	0%	0%
	1.61	1.00			0%			0%		0%	0%	0%	17%	0%	0%	-25%	-25%	-25%	0%
	2.01	1.25			0%			11%		14%	14%	0%	0%	0%	0%	-25%	-25%	-25%	-25%
	2.41	1.50			8%			20%		14%	14%	0%	17%	0%	0%	-25%	-25%	-25%	-25%
		average=			-5%			-6%		2%	-2%	-3%	0%	-2%	-3%	-15%	-13%	-12%	-16%
		average=	-6%																
		average=	-2%																

average difference is -6% considering all observations, and as little as -2% if observations for the very high proportion of trucks (70 to 100% trucks) are ignored. A proportion of trucks beyond 70% is not very likely, but was used in this research for investigative purposes. The closest match between the single and multiple truck populations occurs for PCEs calculated for between 30 to 60% trucks. This is a very meaningful result because freeways operating with between 30 to 60% trucks may typify current freeways with heavy truck use. It was expected that the effect of multiple truck populations would be most dramatic for freeways with heavy truck use; however this observation supports the contrary. These data present no significant evidence that the multiple truck population performs differently than the single truck population.

5.4 Variability of PCE by Length of Grade

The PCE was observed to increase as the length of grade increased. This trend exists in the PCEs provided in the HCM 2000, and it was observed for the average single truck population results presented in section 4.4. Figure 14 shows the variability of the PCE over lengths of grade ranging from 0.40 to 2.41 km (0.25 to 1.5 mi). In all but one of the plots, the PCE is constant for grades 1.6 km (1 mi) and longer. This suggests that grades longer than 1.6 km (1 mi) have no additional effect on truck performance. The HCM 2000 similarly shows this trend by providing PCEs for length of grade criteria 1.6 km (1 mi) and longer for grades 4, 5, or 6%. However, for grades 2 and 3%, the length of grade criteria includes grades 2.4 km (1.5 mi) and longer. There is slightly more variability in the PCE by length of grade for the N multiple truck population as compared to the average single truck population. This variability is evidence of the interaction of different truck types among other trucks and passenger cars in the traffic stream.

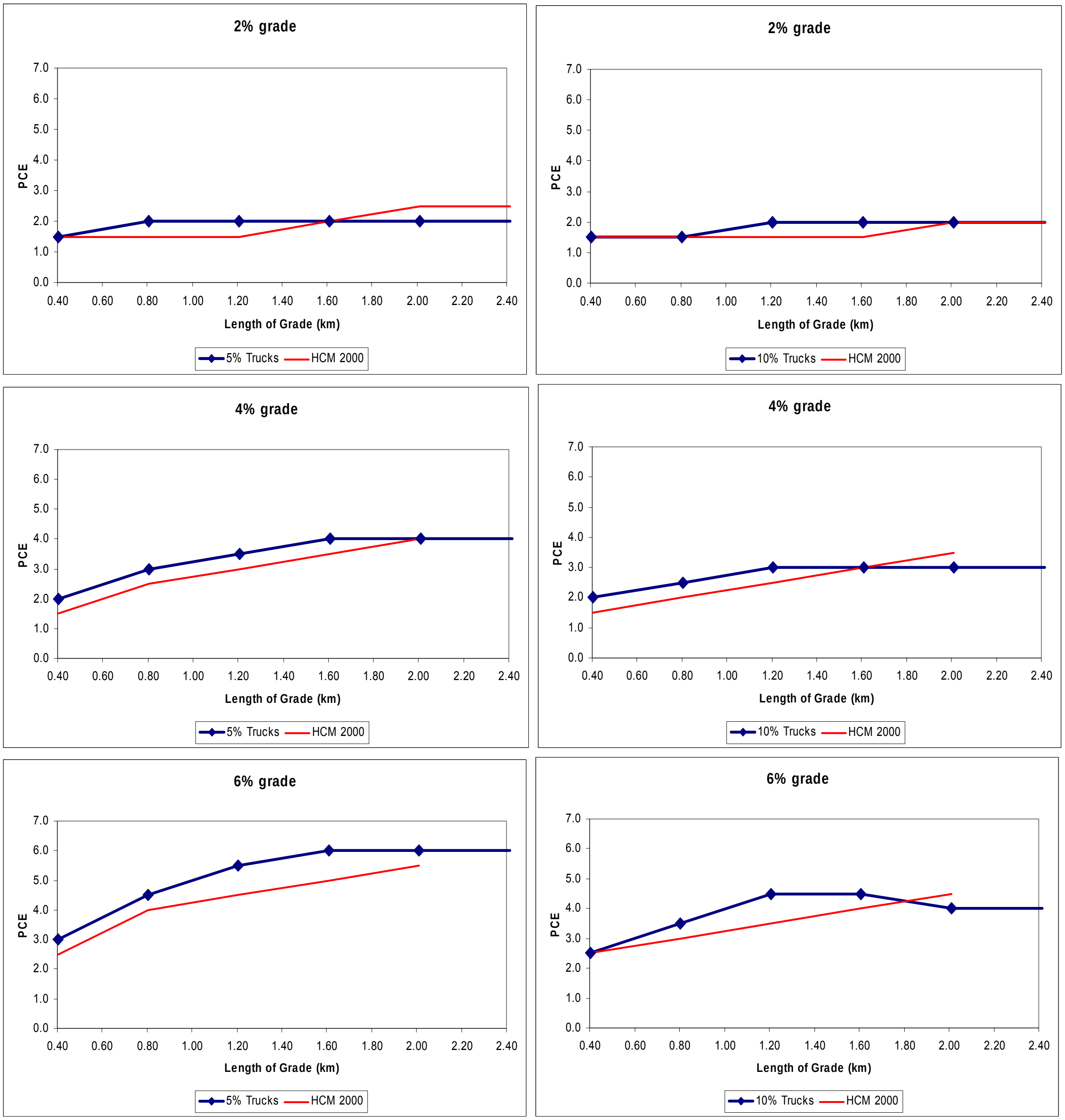

Figure 14. PCE variability by length of grade for N multiple truck population, 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp) at LOS C congestion.

However, the trends observed in figure 14 are not significantly different than the trends observed in the single truck population results to suggest that the multiple truck population performs differently.

5.5 Variability of PCE by Percent Grade

The PCE was observed to increase as the percent grade increased. This trend was also used to validate the selected multiple truck population because it is a determining factor used in the PCEs provided in the HCM 2000. Figure 15 shows the variability of the PCE over percent grades ranging from 1 to 6%. It is clear that the N multiple truck population with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp) very closely matches the trend in PCEs from the HCM 2000. Regardless of the length of grade, the PCE for 1% grades is always 1.5. In addition, the relationship between PCE and percent grade is almost the same for all grades 1.6 km (1 mi) and longer. This supports the observation made in section 5.5 that the PCE is the same for grades 1.6 km (1 mi) and longer. The average difference in PCE from one percent grade to the next is 0.4. A uniform incremental increase of 0.5 is most clearly observed for higher proportion of trucks, like 20 or 25% trucks. For the 5% proportion of trucks, the incremental increase is more likely to be either 0.5 or 1.0 from one percent grade to the next.

5.6 Variability of PCE by Proportion of Trucks

The proportion of trucks in the traffic stream was found to have a significant effect on the calculated PCE only at low proportion of trucks. As the proportion of trucks increases, the PCE decreases. This confirms a hypothesis of this research. The decreasing trend in PCEs with proportion of trucks is especially evident for longer and steeper

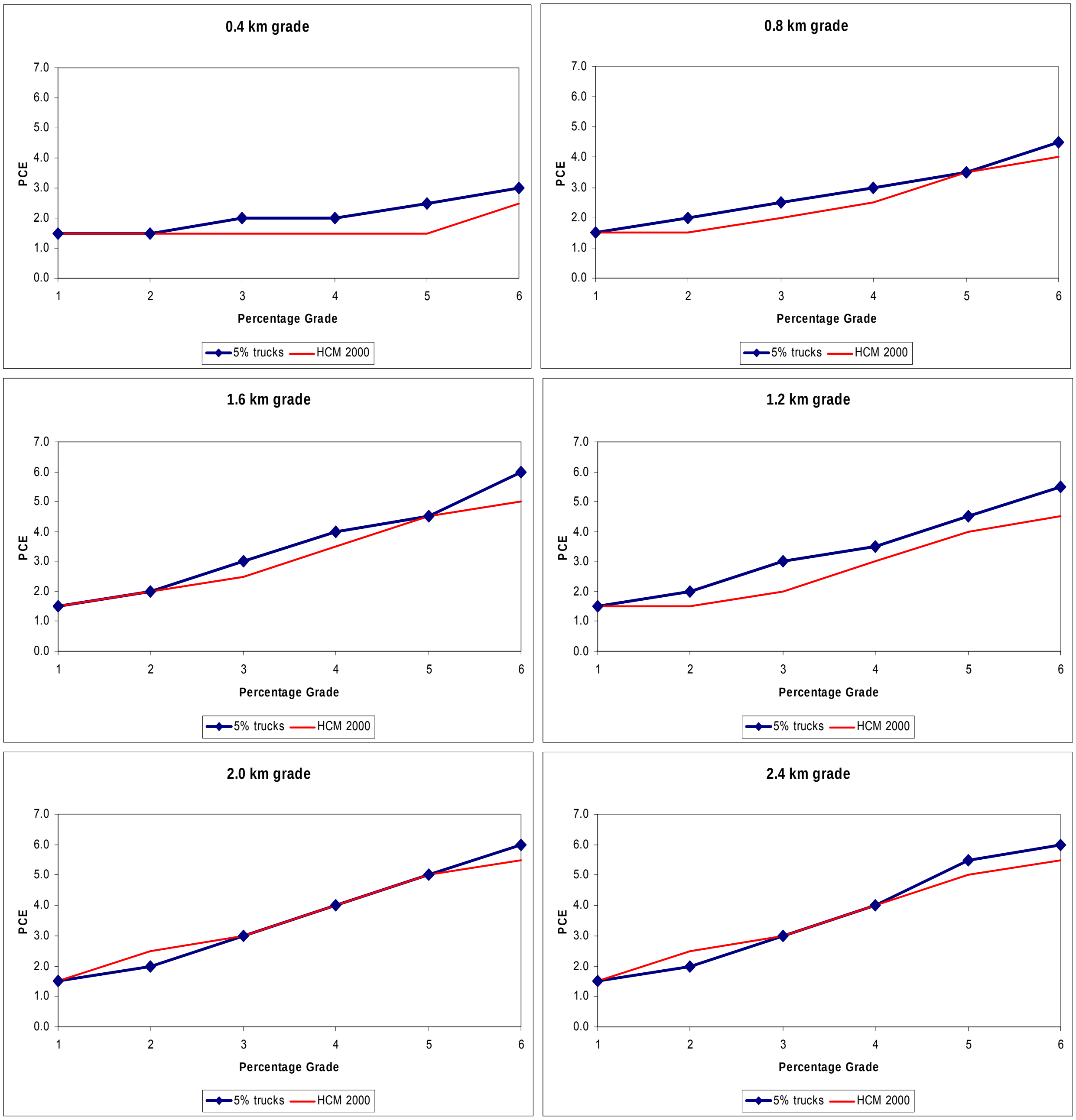

Figure 15. PCE variability by percentage grade for N multiple truck population, 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp) at LOS C congestion.

grades. Figure 16 shows the variability of the PCE over proportion of trucks ranging from 5% to 100%. It can be observed that the PCE is highest for low proportion trucks, and that the PCE decreases and levels off as the proportion trucks increases. The PCE past 60% trucks shows very little variability. In fact, the calculated PCE has no variability between 40 and 60% trucks. Since this range may represent an upper limit on the reasonable proportion of trucks, PCEs provided up to 40% trucks would sufficiently describe the variability of PCE by proportion of trucks. In comparison to the single truck population, variability of PCE by proportion of trucks is less for the multiple truck population. This is contrary to what was expected in this research. It seems that the multiple truck population has a smoothing effect, which results in less variability as compared to the single truck population.

5.7 Variability of PCE by Pavement Type and Condition

Pavement type and condition was found to have a significant effect on the calculated PCE; percentage differences exceeded 10%. This confirms a hypothesis of this research. The default pavement type for simulations in this research was fair asphalt pavement. Table 16 shows the calculated PCEs for the different pavement types and conditions for the N multiple truck population. Table 17 shows the variability of the PCE for different pavement types and conditions calculated as the percent difference from the default pavement type. Poor asphalt and poor concrete pavement always had higher or equal PCEs as compared with fair asphalt. The PCEs for the poor asphalt pavement was on average 11% higher than the PCEs for the fair asphalt pavement, and the PCEs for the poor concrete pavement was on average 6% higher. For either of these pavement types, there was much less variability for 100% trucks as compared to a lower proportion of

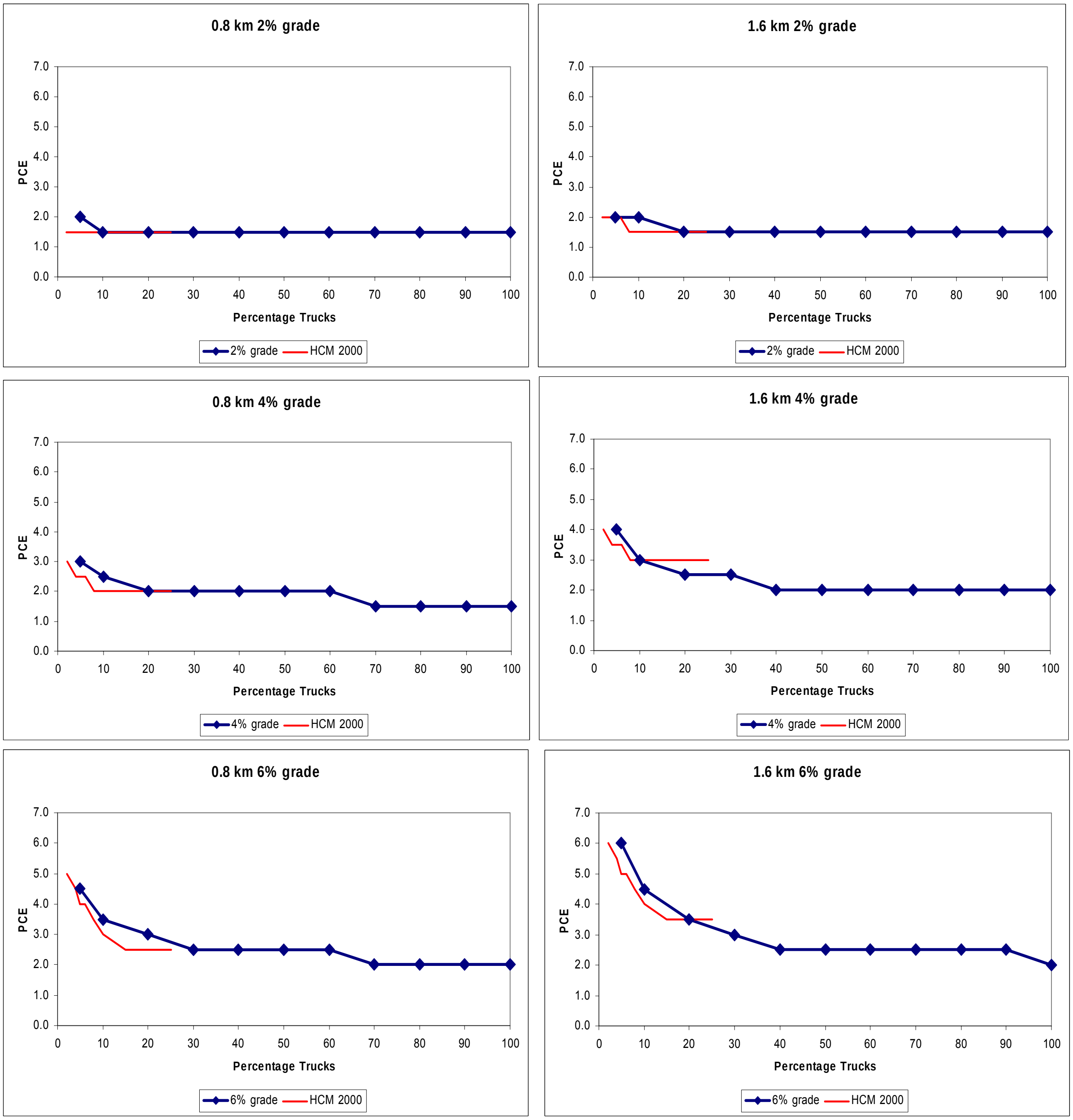

Figure 16. PCE variability by proportion of trucks for N multiple truck population, 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp) at LOS C congestion.

Table 16. PCEs for trucks and buses on upgrades with different pavement types, N multiple truck population, 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp) at LOS C congestion.

Upgrade (%)	Length (km)	Length (mi)	E_T																			
			Asphalt Poor				Concrete Poor				Asphalt Good				Concrete Good				Concrete Excellent			
			Percentage of Trucks and Buses																			
			5	10	25	100	5	10	25	100	5	10	25	100	5	10	25	100	5	10	25	100
2	0.40	0.25	2.0	1.5	1.5	1.5	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	0.80	0.50	2.0	2.0	1.5	1.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	1.21	0.75	2.0	2.0	2.0	1.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	1.61	1.00	2.5	2.0	2.0	1.5	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	2.01	1.25	2.5	2.0	2.0	1.5	2.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5
	2.41	1.50	2.5	2.0	2.0	1.5	2.5	2.0	2.0	1.5	2.0	2.0	1.5	1.5	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5
4	0.40	0.25	2.5	2.0	2.0	1.5	2.0	2.0	2.0	1.5	2.0	2.0	2.0	1.5	2.0	2.0	2.0	1.5	2.0	2.0	2.0	1.5
	0.80	0.50	3.5	3.0	2.5	1.5	3.0	2.5	2.0	1.5	2.5	2.5	2.0	1.5	2.5	2.5	2.0	1.5	2.5	2.5	2.0	1.5
	1.21	0.75	4.0	3.5	2.5	2.0	3.5	3.0	2.5	2.0	3.0	2.5	2.0	1.5	3.5	3.0	2.5	2.0	3.0	2.5	2.0	1.5
	1.61	1.00	4.5	3.5	2.5	2.0	4.0	3.5	2.5	2.0	3.5	3.0	2.5	2.0	4.0	3.0	2.5	2.0	3.0	3.0	2.0	2.0
	2.01	1.25	4.5	3.5	2.5	2.0	4.5	3.5	2.5	2.0	4.0	3.0	2.5	2.0	4.0	3.0	2.5	2.0	3.5	3.0	2.5	2.0
	2.41	1.50	4.5	3.5	2.5	2.0	4.5	3.5	2.5	2.0	4.0	3.0	2.5	2.0	4.0	3.0	2.5	2.0	3.5	3.0	2.5	2.0
6	0.40	0.25	3.0	3.0	2.5	2.0	3.0	3.0	2.5	1.5	3.0	2.5	2.0	1.5	3.0	2.5	2.0	1.5	2.5	2.5	2.0	1.5
	0.80	0.50	5.5	4.0	3.0	2.0	5.0	4.0	3.0	2.0	4.5	3.5	2.5	2.0	4.5	3.5	3.0	2.0	4.0	3.5	2.5	2.0
	1.21	0.75	6.5	4.5	3.5	2.5	6.0	4.5	3.0	2.5	5.5	4.0	3.0	2.0	5.5	4.0	3.0	2.0	5.0	4.0	3.0	2.0
	1.61	1.00	6.5	5.0	3.5	2.5	6.0	4.5	3.0	2.0	5.5	4.0	3.0	2.0	5.5	4.5	3.0	2.0	5.5	4.0	3.0	2.0
	2.01	1.25	6.5	4.5	3.0	2.5	6.0	4.0	3.0	2.5	5.5	4.0	3.0	2.0	5.5	4.0	3.0	2.0	5.5	4.0	3.0	2.0
	2.41	1.50	6.5	4.5	3.5	2.5	6.0	4.0	3.0	2.5	5.5	4.0	3.0	2.0	5.5	4.0	3.0	2.0	5.5	4.0	3.0	2.0

Table 17. Percentage difference in calculated PCE for different pavement types compared to asphalt fair pavement.

Upgrade (%)	Length (km)	Length (mi)	% Error From Asphalt Fair																			
			Asphalt Poor				Concrete Poor				Asphalt Good				Concrete Good				Concrete Excellent			
			Percentage of Trucks and Buses																			
			5	10	25	100	5	10	25	100	5	10	25	100	5	10	25	100	5	10	25	100
2	0.40	0.25	33%	0%	0%	0%	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	0%	33%	0%	0%	0%	33%	0%	0%	-25%	0%	0%	0%	-25%	0%	0%	0%	-25%	0%	0%	0%
	1.21	0.75	0%	33%	33%	0%	0%	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-25%	0%	0%	0%
	1.61	1.00	25%	0%	33%	0%	0%	0%	33%	0%	-25%	-25%	0%	0%	0%	-25%	0%	0%	-25%	-25%	0%	0%
	2.01	1.25	25%	0%	33%	0%	25%	0%	33%	0%	-25%	-25%	0%	0%	0%	0%	0%	0%	-25%	-25%	0%	0%
	2.41	1.50	25%	0%	33%	0%	25%	0%	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-25%	-25%	0%	0%
4	0.40	0.25	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	17%	20%	25%	0%	0%	0%	0%	0%	-17%	0%	0%	0%	-17%	0%	0%	0%	-17%	0%	0%	0%
	1.21	0.75	14%	17%	0%	0%	0%	0%	0%	0%	-14%	-17%	-20%	-25%	0%	0%	0%	0%	-14%	-17%	-20%	-25%
	1.61	1.00	13%	17%	0%	0%	0%	17%	0%	0%	-13%	0%	0%	0%	0%	0%	0%	0%	-25%	0%	-20%	0%
	2.01	1.25	13%	17%	0%	0%	13%	17%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-13%	0%	0%	0%
	2.41	1.50	13%	17%	0%	0%	13%	17%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-13%	0%	0%	0%
6	0.40	0.25	0%	20%	0%	33%	0%	20%	0%	0%	0%	0%	-20%	0%	0%	0%	-20%	0%	-17%	0%	-20%	0%
	0.80	0.50	22%	14%	0%	0%	11%	14%	0%	0%	0%	0%	-17%	0%	0%	0%	0%	0%	-11%	0%	-17%	0%
	1.21	0.75	18%	0%	17%	25%	9%	0%	0%	25%	0%	-11%	0%	0%	0%	-11%	0%	0%	-9%	-11%	0%	0%
	1.61	1.00	8%	11%	17%	25%	0%	0%	0%	0%	-8%	-11%	0%	0%	-8%	0%	0%	0%	-8%	-11%	0%	0%
	2.01	1.25	8%	13%	0%	0%	0%	0%	0%	0%	-8%	0%	0%	-20%	-8%	0%	0%	-20%	-8%	0%	0%	-20%
	2.41	1.50	8%	13%	17%	0%	0%	0%	0%	0%	-8%	0%	0%	-20%	-8%	0%	0%	-20%	-8%	0%	0%	-20%
		average =	15%	12%	12%	5%	7%	8%	6%	1%	-8%	-5%	-3%	-4%	-4%	-2%	-1%	-2%	-15%	-6%	-4%	-4%

trucks. The variability in PCE was significant for the poor asphalt pavement at 5, 10, and 25% proportion of trucks. The calculated PCE for good concrete pavement was not significantly different than the PCE calculated for the default pavement at any proportion of trucks. Similarly, the calculated PCE for good asphalt pavement was on average only 5% lower than the PCEs for fair asphalt pavement, and the difference was only significant at 5% proportion of trucks. The PCE for excellent concrete pavement was on average 7% lower than the PCE for fair asphalt. This represents a significant decrease in the PCE due to the increased pavement condition. Again, the greatest variability in the PCE calculated for excellent concrete pavement was for 5 or 10% proportion of trucks.

5.8 Variability of PCE by Truck Aerodynamic Treatment

Truck aerodynamic treatment was found only to have a significant effect on the calculated PCE for 10% proportion of trucks. This partially confirms a hypothesis of this research. However, it was expected that the effect of aerodynamic treatment would also be significant at 5% trucks, as it was for the pavement type and condition presented in section 5.7. This same result was observed for the average single truck population presented in section 4.8. It is not expected that the calculated PCE for either of the two aerodynamic treatment options should be lower than the default PCE because the effect of these treatments decreases the maximum vehicle acceleration obtainable. Table 18 shows the percentage difference of the PCE for the different aerodynamic treatments as compared to the full aerodynamic treatment. The calculated PCE for partial aerodynamic aids on the roof was on average 1% higher than the default PCE. A significant difference (10%) between the PCEs calculated for partial aerodynamic treatment and the default, full, aerodynamic treatment was only observed at 10% proportion of trucks. The

Table 18. Percentage difference in calculated PCE for different aerodynamic treatments compared to full aerodynamic treatment.

Upgrade (%)	Length (km)	Length (mi)	% Error From Full Aerodynamic Treatment							
			Partial Aerodynamic Aids				No Aerodynamic Aids			
			Percentage of Trucks and Buses							
			5	10	25	100	5	10	25	100
2	0.40	0.25	0%	0%	0%	0%	33%	0%	0%	0%
	0.80	0.50	0%	33%	0%	0%	0%	33%	0%	0%
	1.21	0.75	0%	33%	0%	0%	0%	33%	0%	0%
	1.61	1.00	0%	0%	0%	0%	0%	0%	0%	0%
	2.01	1.25	0%	0%	0%	0%	0%	0%	0%	0%
	2.41	1.50	0%	0%	0%	0%	25%	0%	33%	0%
4	0.40	0.25	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	0%	0%	0%	0%	0%	0%	0%	0%
	1.21	0.75	0%	0%	0%	0%	0%	0%	0%	0%
	1.61	1.00	0%	0%	0%	0%	0%	0%	0%	0%
	2.01	1.25	0%	17%	0%	0%	13%	17%	0%	0%
	2.41	1.50	0%	0%	0%	0%	13%	17%	0%	0%
6	0.40	0.25	0%	20%	-20%	0%	0%	20%	0%	0%
	0.80	0.50	11%	14%	0%	0%	11%	14%	0%	0%
	1.21	0.75	9%	0%	0%	0%	9%	0%	0%	0%
	1.61	1.00	0%	0%	0%	0%	0%	0%	0%	0%
	2.01	1.25	0%	0%	0%	-20%	0%	13%	0%	0%
	2.41	1.50	-8%	0%	0%	-20%	0%	0%	0%	0%
		average =	1%	7%	-1%	-2%	6%	8%	2%	0%

calculated PCE for no aerodynamic aids was on average 4% higher than the default PCE, but the difference in the PCEs was significant for 10% proportion of trucks. Although realistic truck populations contain a variety of aerodynamic treatments, the simulation results suggest that even the worst case, a multiple truck population with no aerodynamic treatments, does not have significantly higher PCEs across the full range of proportion of trucks.

5.9 Variability of PCE for Three Lane Segments

The calculated PCE was found only to be significantly different (10%) for three lane freeway segments as compared to two lane freeway segments for 5% proportion of trucks. This partially confirms a hypothesis of this research. Two different situations were examined, one in which trucks were allowed to use any of the three lanes and one in which trucks were restricted from using the leftmost lane. Table 19 shows the percentage difference of the PCE for three lane segments as compared to two lane segments. The effect of three lane segments is only significant at 5% proportion of trucks. For 5% proportion of trucks, the calculated PCE for three lane segments without lane restrictions averages 8% less than the PCE for two lane segments. However, at a higher proportion of trucks, the PCE for three lane segments is hardly different than for two lane segments. The truck lane restriction had no effect on the calculated PCE as compared with three lane segments without truck lane restriction. This suggests that a truck lane restriction provides no significant capacity increase as compared with no truck lane restriction. However, this must be considered in light of the fact that trucks in the simulation and realistically tend only to use the two rightmost lanes on grades anyway.

Table 19. Percentage difference in calculated PCE for three lane freeway segments compared to two lane freeway segments.

Upgrade (%)	Length (km)	Length (mi)	% Error From Two Lane Fwy Segments							
			Three Lanes w/o Restrictions				Three Lanes w/ Restrictions			
			Percentage of Trucks and Buses							
			5	10	25	100	5	10	25	100
2	0.40	0.25	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	-25%	0%	0%	0%	-25%	0%	0%	0%
	1.21	0.75	0%	33%	0%	0%	-25%	33%	0%	0%
	1.61	1.00	0%	0%	0%	0%	0%	0%	0%	0%
	2.01	1.25	0%	-25%	0%	0%	0%	0%	0%	0%
	2.41	1.50	0%	0%	0%	0%	0%	0%	0%	0%
4	0.40	0.25	0%	0%	0%	0%	0%	0%	0%	0%
	0.80	0.50	-17%	0%	0%	0%	0%	0%	0%	0%
	1.21	0.75	-14%	-17%	-20%	0%	-14%	0%	-20%	0%
	1.61	1.00	-13%	0%	0%	0%	-13%	0%	0%	0%
	2.01	1.25	-13%	0%	0%	0%	-13%	0%	0%	0%
	2.41	1.50	-13%	0%	0%	0%	-13%	0%	0%	0%
6	0.40	0.25	0%	0%	0%	33%	0%	0%	0%	33%
	0.80	0.50	0%	0%	0%	0%	0%	0%	0%	0%
	1.21	0.75	-9%	-11%	0%	0%	0%	-11%	0%	0%
	1.61	1.00	-17%	-11%	0%	0%	-8%	-11%	0%	0%
	2.01	1.25	-17%	-13%	0%	-20%	-17%	-13%	0%	-20%
	2.41	1.50	-17%	-13%	0%	-20%	-17%	-13%	0%	-20%
		average =	-8%	-3%	-1%	0%	-8%	-1%	-1%	0%

5.10 Variability of PCE for Truck Speed Limit

The institution of a truck speed limit was found to significantly affect the calculated PCE; percentage differences exceeded 10%. This confirms a hypothesis of this research. The default situation was an equal speed limit for all vehicles at 112.6 km/h (70 mi/h). The simulated truck speed limit restricted trucks to 88.5 km/h (55 mi/h). Table 20 shows the percentage difference of the PCE for the truck speed limit as compared to without a truck speed limit. The calculated PCE for the truck speed limit was on average 32% higher than the calculated PCE without a truck speed limit. It is interesting to note that for 100% trucks, the truck speed limit actually had no affect. The maximum difference was a calculated PCE that was 150% higher than the PCE without a truck speed limit. The institution of a truck speed limit below the passenger car speed limit results in a significant capacity reduction. However, the effect of the truck speed limit decreases as the proportion of trucks increases.

5.11 Variability by Level of Congestion

The level of congestion was found to significantly affect the calculated PCE; percentage differences exceeded 10%. Average density was used in this research as a determinant of the level of congestion. It was found that an average density value of 12.4 pc/km/ln (20 pc/ml/ln) resulted in PCEs that most closely matched those provided in the HCM 2000. This average density value corresponds to LOS C. However, it is also desirable to quantify the effect of the level of congestion on the PCE because many freeway segments do not operate at LOS C. Figure 17 shows the variability of the calculated PCE for different average density values ranging from 9.3 to 25.9 veh/km/ln (15 to 40 veh/mi/ln). This range of average density values represents a LOS that ranges

Table 20. Percentage difference in calculated PCE for a truck speed limit at 88.5 km/hr (55 mi/h) compared to no separate truck speed limit 112.6 km/hr (70 mi/h).

Upgrade (%)	Length (km)	Length (mi)	% Error From No Truck Speed Limit			
			Truck Speed Limit			
			Percentage of Trucks and Buses			
			5	10	25	100
2	0.40	0.25	67%	33%	33%	0%
	0.80	0.50	75%	67%	33%	0%
	1.21	0.75	100%	100%	33%	0%
	1.61	1.00	125%	75%	33%	0%
	2.01	1.25	125%	75%	33%	0%
	2.41	1.50	150%	75%	67%	0%
4	0.40	0.25	50%	25%	0%	0%
	0.80	0.50	50%	40%	25%	0%
	1.21	0.75	57%	33%	0%	0%
	1.61	1.00	50%	33%	20%	0%
	2.01	1.25	50%	50%	20%	0%
	2.41	1.50	63%	50%	20%	0%
6	0.40	0.25	33%	40%	0%	0%
	0.80	0.50	33%	29%	0%	0%
	1.21	0.75	27%	11%	17%	0%
	1.61	1.00	17%	11%	17%	0%
	2.01	1.25	25%	25%	17%	-20%
	2.41	1.50	25%	25%	17%	0%
		average =	62%	44%	21%	-1%

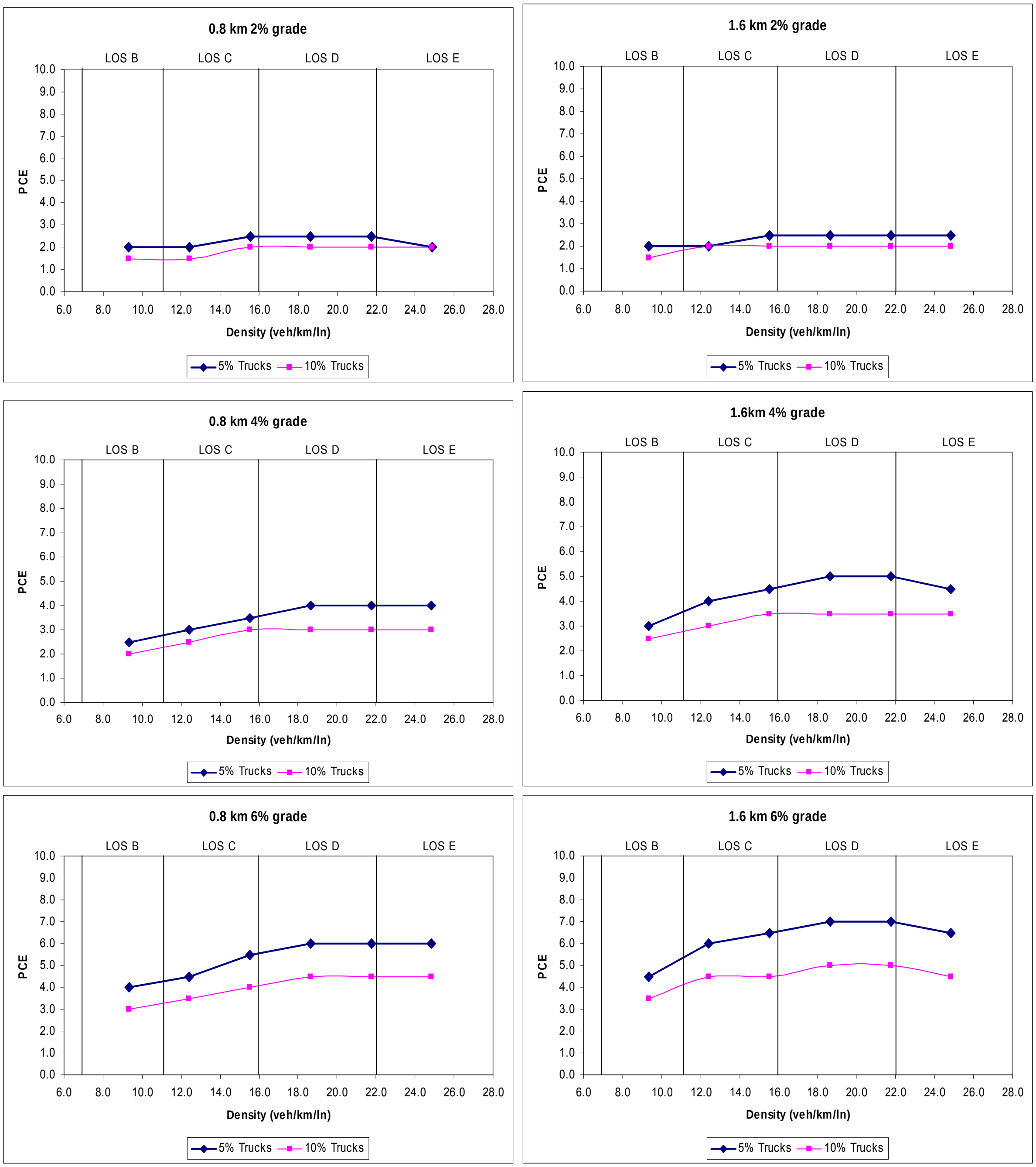

Figure 17. PCE variability by level of congestion for N multiple truck population, 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp) at LOS C congestion.

from B to E. It can be observed from figure 17 that for 2% grades, the calculated PCE does not vary by much. However, for steeper grades such as 4 or 6%, the calculated PCE varies significantly by the average density value. Table 21 shows the percentage difference of the PCE calculated for the different average density values compared to the PCE calculated for an average density value of 12.4 pc/km/ln (20 pc/ml/ln). The greatest difference occurs for an average density values within the LOS D regime. This means that PCE is most critical at LOS D congestion.

5.12 Conclusions

Based on the results presented for multiple truck populations, the following conclusions have been made. First, multiple truck populations do not perform significantly different from single truck populations to produce different PCEs. The assumption of a single truck population is therefore a valid simplification. Second, the PCE of trucks remains relatively constant for grades longer than 1.6 km (1 mi), thus the range of grade lengths provided in the HCM 2000 are adequate. Third, since the PCE of trucks remains constant for a proportion of trucks greater than 60%, PCEs should be provided for up to 60% proportion of trucks. Fourth, pavement type and condition significantly effects the calculated PCE for a low proportion of trucks only; adjustments for pavement type and condition should only be made for a low proportion of trucks. Fifth, aerodynamic treatment significantly affects the calculated PCE for a low proportion of trucks only; adjustments for aerodynamic treatment should only be made for a low proportion of trucks. Sixth, the PCE for three lane segments is significantly lower than the PCE for two lane segments only for a low proportion of trucks, thus an adjustment for the number of lanes should be made only for a low proportion of trucks. In addition, lane

Table 21. Percentage difference in calculated PCE for different levels of congestion, N multiple truck population, 83.7 kg/kW (137.5 lb/hp) and standard deviation of 25.12 kg/kW (41.25 lb/hp).

Upgrade (%)	Density		% Error From LOS C Congestion, 12.4 veh/km/lm (20 veh/mi/ln)											
	(veh/mi/ln)		15		20		25		30		35		40	
	(veh/km/ln)		9.3		12.4		15.5		18.6		21.8		24.9	
	% Trucks		5	10	5	10	5	10	5	10	5	10	5	10
	Length (km)	Length (mi)												
2	0.40	0.25												
	0.80	0.50	0%	0%	0%	0%	25%	33%	25%	33%	25%	33%	0%	33%
	1.21	0.75												
	1.61	1.00	0%	-25%	0%	0%	25%	0%	25%	0%	25%	0%	25%	0%
	2.01	1.25												
	2.41	1.50												
4	0.40	0.25												
	0.80	0.50	-17%	-20%	0%	0%	17%	20%	33%	20%	33%	20%	33%	20%
	1.21	0.75												
	1.61	1.00	-25%	-17%	0%	0%	13%	17%	25%	17%	25%	17%	13%	17%
	2.01	1.25												
	2.41	1.50												
6	0.40	0.25												
	0.80	0.50	-11%	-14%	0%	0%	22%	14%	33%	29%	33%	29%	33%	29%
	1.21	0.75												
	1.61	1.00	-25%	-22%	0%	0%	8%	0%	17%	11%	17%	11%	8%	0%
	2.01	1.25												
	2.41	1.50												
		average=	-13%	-16%	0%	0%	18%	14%	26%	18%	26%	18%	19%	16%

restrictions have no impact on the calculated PCE. Seventh, a separate truck speed limit below the speed limit of other vehicles causes a significant increase in the calculated PCE. A scale factor may be applied to the PCEs calculated for trucks without a separate speed limit in order to account for the effect of a truck speed limit. Eighth, the PCEs provided in the HCM 2000 were calculated for LOS C congestion. A scale factor may be applied to the PCEs to account for the effect of level of congestion.

Chapter 6. Conclusions and Recommendations

6.1 Recommended PCE Table

Based on the results and conclusions presented in this research, a recommended PCE table has been created as shown in table 22. This PCE table has incorporated the recommendations presented in sections 6.2 and 6.3 with regard to the variables investigated in this research. The PCEs in table 22 have been calculated for a single truck population with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp), with full aerodynamic aids, fair asphalt pavement, and LOS C congestion. The PCEs listed in table 22 are very similar to the PCEs provided in the HCM 2000 and are in a compatible format with the HCM 2000. It can be observed that grades up to 3.22 km (2 mi) in length and grades up to 8% have been added to the PCE table. In addition, the proportion of trucks has been expanded to include up to 60% proportion of trucks. The incorporation of these criteria fulfills the recommendations presented in this research. The recommended scale factor tables presented in section 6.3 may be applied to this table to account for the effect of the variables found to significantly affect the PCE.

To illustrate the significance of this research in calibrating PCEs for an expanded set of roadway and traffic characteristics, a set of example problems has been worked out. The example problems are included in the appendix. Example problem 1 is a realistic case study of I-81 in Virginia. It examines a 3.22 km (2 mi) grade of 4% on northbound I-81 between milepost 126 and 128. The per lane traffic volume is assumed to be 1300 veh/h/ln, with a known 32% proportion of trucks. The traffic density at this traffic volume corresponds to a LOS C congestion. This example makes use of the PCEs provided in table 22. The PCE recommended in this research is more accurate than that

Table 22. PCEs for basic freeway segments for trucks and buses on upgrades.

Upgrade (%)	Length (km)	Length (mi)	E_T												
			Percentage of Trucks and Buses												
			2	4	5	6	8	10	15	20	25	30	40	50	60
	0.40	0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	0.80	0.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	1.21	0.75	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
1	1.61	1.00	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	2.01	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	2.41	1.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	3.22	2.00	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0
	0.40	0.25	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	0.80	0.50	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	1.21	0.75	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2	1.61	1.00	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	2.01	1.25	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	2.41	1.50	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	3.22	2.00	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	0.40	0.25	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	0.80	0.50	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	1.21	0.75	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
3	1.61	1.00	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	2.01	1.25	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	2.41	1.50	3.5	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5
	3.22	2.00	4.0	3.0	3.5	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5
	0.40	0.25	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	0.80	0.50	3.0	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5
	1.21	0.75	3.5	2.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
4	1.61	1.00	4.0	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0
	2.01	1.25	4.5	3.5	4.0	3.5	3.5	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0
	2.41	1.50	4.5	4.0	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0
	3.22	2.00	5.0	4.0	4.5	4.0	3.5	3.5	3.0	2.5	2.5	2.5	2.0	2.0	2.0
	0.40	0.25	3.5	2.5	2.5	2.5	2.0	2.5	2.0	2.0	2.0	2.0	2.0	2.0	1.5
	0.80	0.50	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.5	2.0	2.0	2.0
	1.21	0.75	5.5	4.0	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0
5	1.61	1.00	5.5	4.5	4.0	4.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0
	2.01	1.25	6.5	5.0	4.0	4.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.0
	2.41	1.50	6.5	5.0	5.0	4.5	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0
	3.22	2.00	7.5	5.0	5.5	5.0	4.5	4.0	3.5	3.0	3.0	3.0	2.5	2.5	2.0
	0.40	0.25	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	0.80	0.50	4.5	4.5	4.5	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.5	2.5	2.0
	1.21	0.75	7.5	5.5	5.5	5.0	4.5	4.0	3.5	3.5	3.0	3.0	2.5	2.5	2.5
6	1.61	1.00	7.0	6.0	6.0	6.0	5.0	4.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5
	2.01	1.25	8.5	6.5	6.0	6.0	5.0	4.5	4.0	3.5	3.5	3.0	3.0	2.5	2.5
	2.41	1.50	8.5	7.0	6.5	5.5	5.5	5.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5
	3.22	2.00	9.0	6.5	6.5	6.0	5.5	5.0	4.5	3.5	3.5	3.5	3.0	2.5	2.5
	0.40	0.25	5.0	5.0	4.5	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5	2.5	2.0
	0.80	0.50	8.0	7.5	7.0	6.5	5.5	5.0	4.5	4.0	3.5	3.5	3.0	3.0	2.5
	1.21	0.75	8.0	7.5	7.5	7.0	6.0	5.5	4.5	4.0	4.0	3.5	3.5	3.0	3.0
8	1.61	1.00	9.0	8.0	8.0	7.0	6.0	5.5	5.0	4.5	4.0	4.0	3.5	3.0	3.0
	2.01	1.25	9.5	8.0	8.0	7.0	6.0	6.0	5.0	4.5	4.0	4.0	3.5	3.0	3.0
	2.41	1.50	10.0	8.0	8.0	7.5	6.5	6.0	5.0	4.5	4.0	4.0	3.5	3.0	3.0
	3.22	2.00	10.5	9.5	8.5	7.5	6.5	6.0	5.0	4.5	4.5	4.0	3.5	3.0	3.0

provided in the HCM 2000 because it is closer to the known proportion of trucks and it has been calibrated for the correct length of grade. The best PCE provided in the HCM 2000 was for any grade greater than 1.6 km (1 mi) grade with 25% proportion of trucks. The calculated base flow (passenger cars only) using the PCE provided in the HCM 2000 is 2132 pc/h/ln. Using the PCE recommended in this research results in a calculated base flow that is 10% lower, at 1924 pc/h/ln.

6.2 Variables Not Found to Significantly Affect PCEs

A primary hypothesis of this research was that multiple truck populations would not perform differently than a single truck population with the same average weight to power ratio. This hypothesis was confirmed. The variables listed in the research methodology were tested for both single and multiple truck populations. The relationships for these variables were found to be the same for single truck populations as compared to multiple truck populations. Based on these results, it is recommended that the simplification of simulating a single truck population with an average weight to power ratio can confidently be used.

The PCE was not found to be significantly affected by variability of engine power within a single weight to power ratio truck population; percentage differences were less than 10%. The PCEs for 10% proportion of trucks for the two lowest engine powers simulated, the 10^{th} and 22^{nd} percentile engine powers, were significantly higher (13%) than the PCEs for the average truck with the 75^{th} percentile engine power. However, this trend did not apply over the whole range of applicable proportion of trucks. In addition, the PCE was not found to be significantly different for the 45^{th} or 95^{th} percentile engine power, with percentage differences less than 10%. Based on this result, it has been concluded that variability of engine power within a single weight to power ratio is not an important consideration for determining the PCE of trucks. No recommendations were made to account for the effect of engine power.

Truck aerodynamic treatment on the whole did not significantly affect PCEs. The PCEs for 10% proportion of trucks with partial and no aerodynamic aids were significantly higher (14%) than the PCEs calculated for full aerodynamic aids. However, this trend did not apply over the whole range of applicable proportion of trucks. There were not significant differences in the calculated PCEs for either 5 or 25% proportion of trucks. Since the trend is not wholly applicable, a recommendation to account for the effect of truck aerodynamic treatment has not been made.

Similarly, the effect of three lane segments on the whole was not significant. The PCEs for 5% proportion of trucks were considerably lower (9%) for three lane segments in comparison to two lane segments. However, for a slightly higher proportion of trucks, the differences were not considered significant. Since this trend is not wholly applicable to a realistic range of proportion of trucks, a recommendation to account for the effect of three lane segments has not been made. It was also found in the investigations that a truck lane restriction, limiting trucks to using the two rightmost out of three lanes, did not change the PCEs for three lane segments in any way.

6.3 Variables Found to Significantly Affect PCEs

Several of the variables hypothesized to significantly affect the PCE were found to have a significant effect on the PCE; percentage differences exceeded 10%. Of the variables tested in this research, weight to power ratio, length of grade, percent grade, proportion of trucks, pavement type and condition, truck speed limit, and level of congestion were found to have a significant effect on the calculated PCE. The effect of the length of grade and percent grade was well known at the onset of the research; however, these trends were used to validate the calculated PCEs. Based on the results of the research into the variability of PCE for each of these variables, a set of recommendations has been established for each variable.

6.3.1 Recommendation to Account for the Effect of Weight to Power Ratio

Truck weight to power ratio was found to have a significant effect on the calculated PCE, with percentage differences that exceeded 10%. A single or multiple truck population with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp) was found to most closely match the PCEs provided in the HCM 2000. Table 23 presents scale factors that may be applied to the PCE table 22 for the average weight to power ratio truck population. These scale factors account for the effect of weight to power ratio for a lighter or heavier than average weight to power ratio truck population. The light weight to power ratio is 68.5 kg/kW (112.5 lb/hp) and results in PCEs that are as much as 22% lower than the PCEs for the average weight to power ratio truck population. The heavy weight to power is 106.6 kg/kW (175 lb/hp) and results in PCEs that are as much as 30% higher than the PCEs for the average weight to power ratio truck population. The light weight to power ratio represents the 40th percentile and the heavy weight to power ratio represents the 85th percentile from a survey of trucks along I-81 in Virginia.

Example problem 2 in the appendix illustrates the significance of the weight to power ratio scale factor applied to a case study of I-81 in Virginia. The example problem is the same as example 1 except the truck population is assumed to be heavier than average, with a weight to power ratio approximately 106.6 kg/kW (175 lb/hp). The

Table 23. PCE scale factors to account for the effect of weight to power ratio.

Upgrade (%)	Weight to Power Ratio Scale Factors							
	Light Truck 68.5 kg/kW (112.5 lb/hp)				Heavy Truck 106.6 kg/kW (175 lb/hp)			
	Percentage of Trucks and Buses							
	5	10	25	100	5	10	25	100
≤ 2	0.8	1.0	1.0	0.7	1.4	1.4	1.3	1.1
> 2-4	0.8	0.8	0.9	0.8	1.4	1.4	1.3	1.1
> 4-6	0.8	0.8	0.9	0.8	1.4	1.4	1.5	1.1

calculated base flow using the PCE provided in the HCM 2000 is 2132 pc/h/ln. Using the PCE recommended in this research and the scale factor from table 23 to account for the heavier than average truck population results in a calculated base flow of 2444 pc/h/ln, 15% higher than the estimate from the HCM 2000.

6.3.2 Recommendation to Account for the Effect of Length of Grade

The relationship between the length of grade and the PCE was used to validate the PCEs calculated in this research. In addition, it was observed that the PCE for a single truck population continues to increases for lengths of grade up to 3.22 km (2 mi). Based on this observation, it is recommended that PCEs be provided for grades up to 3.22 km (2 mi) in length. The PCE table 22 has incorporated this recommendation..

6.3.3 Recommendation to Account for the Effect of Percent Grade

The relationship between the percent grade and the PCE was also used to validate the PCEs calculated in this research. It was observed that the PCE for a single truck population continues to increases for grades of 8%. Based on this observation, it is recommended that PCEs be provided for grades up to 8%. The PCE table 22 has incorporated this recommendation.

6.3.4 Recommendation to Account for the Effect of Proportion of Trucks

The proportion of trucks was found to dramatically affect the calculated PCE. The most variability of PCE by proportion of trucks occurs for a very low proportion of trucks. The PCE decreases as the proportion of trucks increases. Beyond 60% proportion of trucks, the PCE was found to be mostly constant across all lengths and percentage grades. Based on these observations, it is recommended that PCEs be provided for up to 60% proportion of trucks. This is an extension of the proportion of trucks currently provided in the HCM 2000; however, expanding the proportion of trucks will make the PCE table more applicable for freeways with a large amount of truck traffic. Many freeways in the nation have a proportion of trucks that exceeds 25%. This recommendation has been incorporated into the PCE table 22.

6.3.5 Recommendation to Account for the Effect of Pavement Type and Condition

The pavement type and condition was found to significantly affect the calculated PCE. The PCEs for poor pavement types are as much as 14% higher than the PCEs for the default (fair asphalt) pavement. Similarly, the PCEs for good or excellent pavement types are as much as 15% lower than the PCEs for the default pavement. This constitutes a capacity justification for maintenance, reconstruction, or rehabilitation projects that will improve or maintain the condition of pavements. Poor pavements had PCEs that were on average 9% higher than the default PCEs, and good pavements had PCEs that were on average 2 to 5% lower than the default PCEs. Snow covered pavement had PCEs that were constant regardless of the length or percent grade. An explanation for this observation is that snow covered pavement resulted in reduced speeds for all vehicles types, not primarily trucks as the other pavement types did. The PCEs for snow covered pavement were as much as 267% higher than the default PCEs. However, in the case of steep grades, the PCEs for snow covered pavement were lower than the default PCEs. This was a result of the speed reduction that applied to all vehicles types. Table 24 presents scale factors that may be applied to the PCE table 22 for the average truck population to account for the effect of pavement type and condition.

Example problem 3 in the appendix illustrates the significance of the pavement type and condition scale factor applied to a case study of I-81 in Virginia. The example

Table 24. PCE scale factors to account for the effect of pavement type and condition.

Upgrade (%)	Pavement Type and Condition Scale Factors																	
	Asphalt Poor			Concrete Poor			Asphalt Good			Concrete Good			Concrete Excellent			Snow Covered		
	Percentage of Trucks and Buses																	
	5	10	25	5	10	25	5	10	25	5	10	25	5	10	25	5	10	25
≤ 2	1.0	1.3	1.0	1.0	1.3	1.0	0.8	1.0	1.0	0.8	1.0	1.0	0.8	1.0	1.0	2.8	2.3	1.3
> 2-4	1.2	1.1	1.0	1.2	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	1.9	1.3	0.9
> 4-6	1.1	1.1	1.1	1.0	1.1	1.0	0.9	1.0	1.0	0.9	1.0	1.0	0.9	0.9	1.0	1.1	0.9	0.7

problem is the same as example 1 except the pavement condition is assumed to be poor asphalt rather than fair asphalt which is the default type. The calculated base flow using the PCE provided in the HCM 2000 is 2132 pc/h/ln. Using the PCE recommended in this research and the scale factor from table 24 results in a calculated base flow that is 5% lower, at 2028 pc/h/ln. Although the PCE scale factor to account for the detrimental effect of poor pavement is greater than 1, the resulting base flow remains lower than that estimated using the HCM 2000 method. This occurs because the basic PCE recommended for this case is lower than the PCE provided in the HCM 2000. The impact of pavement type and condition scale factors is more influential at a lower proportion of trucks.

6.3.6 Recommendation to Account for the Effect of Truck Speed Limit

The institution of a truck speed limit was found to significantly affect the calculated PCE. The PCEs for a truck speed limit of 88.5 km/h (55 mi/h) are as much as 100% higher than the PCEs for a speed limit of 112.6 km/h (70 mi/h) that applies to all vehicles. Although the regulation of truck speeds has not been examined from a safety perspective, this is evidence of a major capacity reduction due to truck speed regulation. Table 25 presents scale factors that may be applied to the PCE table 22 for the average truck population to account for the effect of a truck speed limit.

Example problem 4 in the appendix illustrates the significance of the speed limit scale factors. The example problem is the same as example problem 1 except the truck speed limit is assumed to be limited to 88.5km/h (55 mi/h). The calculated base flow using the PCE provided in the HCM 2000 is 2132 pc/h/ln. Using the PCE recommended in this research and the scale factor from table 25 results in a calculated base flow that is

Table 25. PCE scale factors to account for the effect of a truck speed limit.

Upgrade (%)	Truck Speed Limit Scale Factors 88.5 km/h (55 mi/h) Truck Speed Limit Percentage of Trucks and Buses		
	5	10	25
≤ 2	1.8	1.8	1.3
> 2-4	1.7	1.4	1.1
> 4-6	1.2	1.2	1.1

5% lower, at 2028 pc/h/ln. The same explanation from section 6.3.5 applies here; the PCE recommended for the basic case is lower than the PCE provided in the HCM 2000. The impact of speed limit scale factors is much more influential at a lower proportion of trucks.

6.3.7 Recommendation to Account for the Effect of Level of Congestion

The level of congestion was found to significantly affect the calculated PCE; percentage differences exceeded 10%. The PCEs calculated for an average density value of 12.4 pc/km/ln (20 pc/ml/ln), corresponding to LOS C, most closely matched the PCEs provided in the HCM 2000. However, the most critical level of congestion for calculating the PCE is in the LOS D regime. Table 26 presents scale factors that may be applied to the PCE table 22 for the average truck population to account for the effect of level of congestion.

Example problem 5 in the appendix illustrates the significance of the level of congestion scale factors. The example is the same as example problem 1 except the traffic volume is assumed to be 1500 veh/h/ln, such that the level of congestion corresponds to LOS D. The calculated base flow using the PCE provided in the HCM 2000 is 2460 pc/h/ln. Using the PCE recommended in this research and the scale factor from table 26 results in a calculated base flow that is equal to that found using the HCM 2000 method. The level of congestion scale factor does increase the PCE; however, since the basic recommended PCE is lower than the HCM 2000 PCE, the scale factor only increases the recommended PCE to a value equal to the PCE provided in the HCM 2000. Therefore, the resulting flows are equal.

Table 26. PCE scale factors to account for the effect of level of congestion.

Level of Congestion			PCE Scale Factor
LOS	Density		
	(veh/km/ln)	(veh/mi/ln)	
B	9.3	15	0.8
C	12.4	20	1.0
C	15.5	25	1.1
D	18.6	30	1.2
D	21.8	35	1.2
E	24.9	40	1.1

6.3.8 Recommendation to Account for the Combined Effect of Variables

Scale factors presented in the previous sections can confidently be used to individually account for the effect of different roadway and traffic characteristics. In addition, when considering the combined effect of different roadway and traffic characteristics, multiple scale factors may be used for low to moderately steep grades and a low proportion of trucks. When applying multiple scale factors, an error in the calculated base flow must be expected because the scale factors themselves do not account for combined effects. For heavier than average truck populations with 10% proportion of trucks operating on poor pavement and a level of congestion corresponding to LOS D, the use of multiple scale factors should be limited to grades less than or equal to 3.22 km (2 mi) and 4% or 0.40 km (0.25 mi) and 6%. For lighter than average truck populations with 10% proportion of trucks operating on good or excellent pavement and a level of congestion corresponding to LOS B, the use of multiple scale factors can be applied to all grades. It is recommended that further research focus on defining the applicable range where multiple scale factors can be used or other methods to quantify the combined effect of roadway and traffic characteristics such as those investigated in this research.

Example problem 6 in the appendix illustrates the significance of using multiple scale factors to account for the combined effect of variables. The example problem is the basic case from example problem 1, but it includes each of the modifications used in example problems 2 through 5. The calculated base flow using the PCE provided in the HCM 2000 is 2460 pc/h/ln. Using the PCE and multiple scale factors recommended in results in a calculated base flow of 3634 pc/h/ln, which is 48% than the HCM 2000 estimate. In this example problem, the combined effect of variables is overestimated by using multiple scale factors. It is recommended that no more than a couple scale factors be used in combination because the multiplicative effect of each may exaggerate the result. The use of multiple scale factors to account for the combined effects of variables should be approached with caution.

6.4 Summary of Conclusions and Recommendations

This research resulted in the calculation of PCEs for trucks for basic freeway segments. The equal density method was successfully used to calculate PCEs that replicated those found in the HCM 2000. The PCEs for a single or multiple truck population with an average weight to power ratio of 83.7 kg/kW (137.5 lb/hp) most closely matched the PCEs in the HCM 2000. It was found that PCEs calculated for a multiple truck population were not much different from PCEs calculated for a single truck population with the same average weight to power ratio. The PCEs provided in the HCM 2000 were calculated for LOS C congestion, however a set of scale factors has been recommend to account for different levels of congestion. Weight to power ratio was found to significantly affect the calculated PCE; a set of scale factors has been recommend to account for different weight to power ratios. Variability of engine power within the weight to power ratio was not found to significantly affect the calculated PCEs. It was recommended that the PCE table be expanded to include lengths of grade up to 3.22 km (2 mi) and percent grades up to 8%. In addition, it was recommended to expand the proportion of trucks to 60% proportion of trucks to make the PCE table more applicable to freeways with large amounts of truck traffic. Pavement type and condition were found to significantly affect the calculated PCE, and a set of scale factors has been recommended to account for different pavement types and conditions. Truck aerodynamic treatment was not found to significantly affect the calculated PCE over the whole range of applicable values. In a similar fashion, three lane segments were not found to significantly affect the calculated PCEs in comparison to two lane segments. It was found that truck lane restrictions for three lane segments had no effect on the calculated PCEs. The institution of a truck speed limit at 88.5 km/h (55 mi/h) was found to greatly increase the calculated PCEs; a set of scale factors has been recommended to account for this effect. The application of scale factors to account for the combined effects of the variables examined in this research should be applied carefully. An error should be expected due to the combined effect of variables, especially for steep grades with a heavier than average truck population.

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Appendix

<u>Example Problem 1</u>

Northbound I-81 in Virginia between milepost 126 and 128 is a 3.22 km (2.0 mi) grade of 4%. The per lane traffic volume is assumed to be 1300 veh/h/ln, with a known 32% proportion of trucks. The traffic density at this traffic volume corresponds to a LOS C congestion. The truck population is assumed to be equal to the average weight to power ratio. The pavement type and condition is assumed to be fair asphalt. The speed limit for both cars and trucks is 104.6 km/.h (65 mi/h).

The base flow is calculated as

$$q_B = q_M * (1 - P_T) + q_M * P_T * E_T * SF \qquad [A1.1]$$

where q_B is the base flow rate (passenger cars only), P_T = 32% is the proportion of trucks, q_M = 1300 veh/h/ln is the mixed vehicle flow rate, E_T is the PCE, and *SF* are any number of scale factors recommended in chapter 6 (applied to the proposed method only).

a) HCM 2000 method

E_T = 3.0 (for 25% trucks on a 1.6 km (1.0 mi), 4% grade)

$$q_B = 1300 * (1 - 0.32) + 1300 * 0.32 * 3.0 = 2132 \text{ pc/h/ln} \qquad [A1.2]$$

b) Proposed method

E_T = 2.5 (for 30% trucks on a 3.22 km (2.0 mi), 4% grade)

$$q_B = 1300 * (1 - 0.32) + 1300 * 0.32 * 2.5 = 1924 \text{ pc/h/ln} \qquad [A1.3]$$

Using the PCE and scale factors proposed from this research results in a base flow that is 208 pc/h/ln or 10% lower than the estimate from the HCM 2000.

Example Problem 2

Same situation as example problem 1 except the truck population is assumed to be heavier than average, a weight to power ratio approximately 106.6 kg/kW (175 lb/hp).

a) HCM 2000 method

$q_B = 2132$ pc/h/ln

b) Proposed method

E_T = 2.5 (for 30% trucks on a 3.22 km (2.0 mi), 4% grade)

SF_2 = 1.5 (adjustment for heavy truck)

$$q_B = 1300 * (1 - 0.32) + 1300 * 0.32 * 2.5 * 1.5 = 2444 \text{ pc/h/ln} \qquad [A2.1]$$

Using the PCE and scale factor proposed from this research results in a base flow that is 312 pc/h/ln or 15% higher than the estimate from the HCM 2000.

Example Problem 3

Same situation as example problem 1 except the pavement type and condition is assumed to be poor asphalt.

a) HCM 2000 method

$q_B = 2132$ pc/h/ln

b) Proposed method

E_T = 2.5 (for 30% trucks on a 3.22 km (2.0 mi), 4% grade)

SF_3 = 1.1 (for poor asphalt pavement)

$$q_B = 1300 * (1 - 0.32) + 1300 * 0.32 * 2.5 * 1.1 = 2028 \text{ pc/h/ln} \qquad [A3.1]$$

Using the PCE and scale factor proposed from this research results in a base flow that is 104 pc/h/ln or 5% lower than the estimate from the HCM 2000.

Example Problem 4

Same situation as example problem 1 except the truck speed limit is assumed to be 88.5km/h (55 mi/h).

a) HCM 2000 method

$q_B = 2132$ pc/h/ln

b) Proposed method

E_T = 2.5 (for 30% trucks on a 3.22 km (2.0 mi), 4% grade)

SF_4 = 1.1 (for truck speed limit at 88.5 km/h (55 mi/h))

$$q_B = 1300 * (1 - 0.32) + 1300 * 0.32 * 2.5 * 1.1 = 2028 \text{ pc/h/ln} \qquad \text{[A4.1]}$$

Using the PCE and scale factor proposed from this research results in a base flow that is 104 pc/h/ln or 5% lower than the estimate from the HCM 2000.

Example Problem 5

Same situation as example problem 1 except the traffic volume is assumed to be 1500 veh/h/ln. The corresponding density is approximately 20 veh/km/ln (32 veh/mi/ln), corresponding to LOS D.

a) HCM 2000 method

$$q_B = 1500 * (1 - 0.32) + 1500 * 0.32 * 3.0 = 2460 \text{ pc/h/ln} \qquad \text{[A5.1]}$$

b) Proposed method

E_T = 2.5 (for 30% trucks on a 3.22 km (2.0 mi), 4% grade)

SF_5 = 1.2 (for level of congestion corresponding to 20 veh/km/ln (32 veh/mi/ln))

$$q_B = 1500 * (1 - 0.32) + 1500 * 0.32 * 2.5 * 1.2 = 2460 \text{ pc/h/ln} \qquad \text{[A5.2]}$$

Using the PCE and scale factor proposed from this research results in a base flow that is equal to the estimate from the HCM 2000.

Example Problem 6

A combination of example problems 1 through 5. The basic grade criterion is used from example problem 1, a 3.22 km (2.0 mi) grade of 4%. The truck population is assumed to be heavier than average, although the proportion of trucks remains 32%. The pavement type and condition is assumed to be poor asphalt. A truck speed limit is assumed to be in effect at 88.5km/h (55 mi/h). The traffic volume is assumed to be 1500 veh/h/ln, with a traffic density corresponding to LOS D.

a) HCM 2000 method

$$q_B = 1500 * (1 - 0.32) + 1500 * 0.32 * 3.0 = 2460 \text{ pc/h/ln} \qquad \text{[A6.1]}$$

b) Proposed method

E_T = 2.5 (for 30% trucks on a 3.22 km (2.0 mi), 4% grade)

SF_2 = 1.5 (adjustment for heavy truck)

SF_3 = 1.1 (for poor asphalt pavement)

SF_4 = 1.1 (for truck speed limit at 88.5 km/h (55 mi/h))

SF_5 = 1.2 (for level of congestion corresponding to 20 veh/km/ln (32 veh/mi/ln))

$$q_B = 1500 * (1 - 0.32) + 1500 * 0.32 * 2.5 * 1.5 * 1.1 * 1.1 * 1.2 = 3634 \text{ pc/h/ln} \qquad \text{[A6.2]}$$

Using the PCE and multiple scale factors proposed from this research results in a base flow that is 1174 pc/h/ln or 48% higher than the estimate from the HCM 2000.

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