

EXAMINING THE EFFECT OF HEAVY VEHICLES DURING CONGESTION USING PASSENGER CAR EQUIVALENTS

Ahmed Al-Kaisy¹ and Younghan Jung²

¹Department of Civil Engineering, Montana State University
PO Box 173900, Bozeman, Montana, USA 59717.

²Department of Civil Engineering, Bradley University
1501 West Bradley Avenue, Peoria, Illinois, USA 61625.

ABSTRACT

An investigation into the effect of heavy vehicles on traffic flow during congestion is presented in this paper. Several factors that are thought of as determinants of this effect were considered in this investigation. Empirical data and microscopic traffic simulation were used in the analysis. The simulation model was calibrated and validated using field data at two study sites near Toronto, Canada. One site is located on level terrain while the other is located on a 1-km long 3% upgrade. Simulation experiments were conducted using the calibrated model at the two study sites. Passenger car equivalency factor derived from queue discharge flow was used as an indicator of heavy vehicles' effect. While study results suggest some similarities between free-flow and congested traffic regimes concerning heavy vehicles' effect, some important differences exist due to the different mechanisms that govern heavy vehicles' performance in the two regimes. Also, lane-use restriction and the location of bottleneck relative to upgrade were found to have considerable influence on heavy vehicles' effect during congestion.

Keywords: Heavy vehicles, trucks, queuing, congestion, simulation

INTRODUCTION

Heavy Vehicles (HVs) are known for their significant effect on traffic due to their larger dimensions (in general) and inferior performance compared with an average automobile. These vehicles include trucks, buses, and recreational vehicles, with each category having a wide variety of size, power, and design concepts. Historically, the Highway Capacity Manual (HCM) procedures have treated heavy vehicles' effect through the use of Passenger Car Equivalents (PCEs). Using those PCEs, a non-homogeneous mix of vehicles in a traffic stream can be expressed in a standardised unit of traffic, i.e. Passenger Car (PC). While the PCE factors provided by the HCM were derived based on free-flow conditions, they have been used (unknowingly) by transportation professionals for all traffic conditions, i.e. congested and non-congested operations. Recent empirical observations suggest that heavy vehicles' effect is significantly greater during congestion and queuing operations (compared with free-flow operations) and that the use of the HCM PCE factors for congested facilities may involve a considerable amount of error (Al-Kaisy et al. 2002). Specifically, the acceleration and deceleration cycles, a situation normally experienced during congestion or stop-and-go conditions, is expected to impose an extra limitation on the performance of heavy vehicles, and in particular on their acceleration away from the front end of the queue that had been moving slowly. The literature review found no other study that investigates the heavy vehicles' effect during congestion.

The current research involves an investigation of several important factors on the effect of heavy vehicles during congestion using empirical data and traffic simulation. These factors involve grade, grade length, percentage of heavy vehicles, lane-use restriction by vehicle type, and the location of bottleneck with respect to grade. This investigation is deemed very important due to the fact that recurrent and non-recurrent bottlenecks have become commonplace on urban highways and many traffic engineers need to deal with congested facilities on a regular basis. Further, no guidance exists in the current practice concerning the treatment of heavy vehicles' effect during congestion.

STUDY SCOPE AND OBJECTIVES

The objective of the current study is to examine the effect of heavy vehicles on traffic stream during congestion. This investigation is mainly concerned with level and upgrade highway segments where the presence of heavy vehicles typically has serious impacts on traffic operations. Several factors that are thought of as important determinants of this effect are investigated in this study.

STUDY DESIGN

In this study, field data and traffic simulation were used to investigate the influence of several factors on heavy vehicles' effect. Field data on queue discharge flow at the location of bottleneck was collected at two study sites near Toronto, Ontario, Canada. One study site is a recurrent freeway bottleneck (level terrain) while the other site is located on a 1-km long 3% upgrade with the bottleneck location at the bottom of the upgrade. Detailed information on field data and study sites can be found in Al-Kaisy et al. (2002). The traffic simulation model INTEGRATION was used to perform simulation experiments in this study. This simulation model has the ability to simulate heavy vehicles performance on grades. Queue discharge flow data at the two study sites was used to calibrate and validate the traffic simulation model. The Passenger Car Equivalency (PCE) factor derived from the queue discharge flow (counts of passenger cars and heavy vehicles) was used as an indicator of heavy vehicles' effect. Upon calibrating and validating the simulation model, experimental design was prepared for simulation experiments to test the influence of the various factors on heavy vehicles' effect. Those factors involved grade, grade length, percentage of heavy vehicles, restriction on lane use by vehicle type, and location of bottleneck with respect to upgrade. The design of experiment involved parametric analyses to test the effect of each of the above variables on heavy vehicles effect (measured in PCE value). The conditions at the study sites were selected as default values that were held constant for each variable while investigating any of the other variables. The values considered in these parametric (sensitivity) analyses are provided in Table 1. The calibrated simulation model was then used to simulate and test the different scenarios as outlined in the experimental design of the parametric analyses.

SELECTION OF SIMULATION MODEL

Upon careful consideration, the traffic simulation model INTEGRATION was selected to perform simulation runs as it has the ability to model the performance of heavy vehicles on grades and their effect on traffic flow. Specifically, the model accounts for the larger dimensions of heavy vehicles and their inferior performance particularly acceleration performance on grades. To model grades, a separate optional input file is required. To model vehicles other than passenger cars, INTEGRATION allows the user to select from many standard small and heavy vehicles when inputting the demand file. Alternatively, a vehicle with special performance characteristics (non-standard) can also be modeled using an optional input file that requires detailed information about vehicle's weight, power, aerodynamics, etc. More information on model features can be found in the user's guide (M. Van Aerde & Associates 2002).

Table 1. Values of main factors investigated.

Factor				
Grade (%)	Grade Length (km)	% of Heavy Vehicles	Lane Use Restriction by Vehicle Type	Location of Bottleneck Relative to Grade
0	0.2	2	No restriction on lane use	Bottleneck at bottom of upgrade
2	0.6	4		
3	1.0	5	Left lane restricted on all HVs	Bottleneck at top of upgrade
4	1.4	6		
5	2.0	8	Left and middle lanes restricted on all HVs	
6		10		
		15		
		20	Left lane restricted on all HVs & middle lane restricted on larger HVs	
		25		

ASSESSING THE EFFECT OF HEAVY VEHICLES

Consistent with the HCM analytical procedures, the effect of heavy vehicles on traffic flow was assessed through the use of passenger car equivalency factors. However, the equivalency criterion that was used in developing the PCEs in this research is the Queue Discharge Flow (QDF) which is different from that used by the HCM, i.e. average density. This is because the QDF is what governs the operation of the freeway or multi-lane highway after the onset of congestion. This “queue discharge flow” is often considered to reflect the real long-term capacity of a recurrent or non-recurrent bottleneck. The QDF is defined by the HCM as “traffic flow that has just passed through a bottleneck and is accelerating back to the free flow speed of the freeway” (TRB 2000). Studies suggest that the queue discharge flow rate from the bottleneck is slightly lower than the maximum flows observed before breakdown (TRB 2000). Upstream queuing may occur for three or more hours a day, whereas the capacity prior to flow breakdown and queuing lasts at most an hour, and often for only 15 minutes.

In using QDF to derive the PCE factors from field data, an optimization technique was used to determine a single PCE factor that would minimize the variation in QDF observations for the many successive 5-minute intervals in each data set. The mean value of the PCE factors from all data sets were then used as an estimate of heavy vehicles’ effect at that particular site. More details on this procedure can be found in Al-Kaisy et al. (2002).

To derive the PCE factors from simulation experiments, the QDF is first measured in terms of two separate counts: passenger cars and heavy vehicles. Knowing the capacity of the study site from empirical data in pcph (from the previous research described above), the PCE from each simulation run can be found using the following formula:

$$\text{PCE} = (\text{Actual Field Capacity in pcph} - \text{Number of PCs}) / \text{Number of HVs}$$

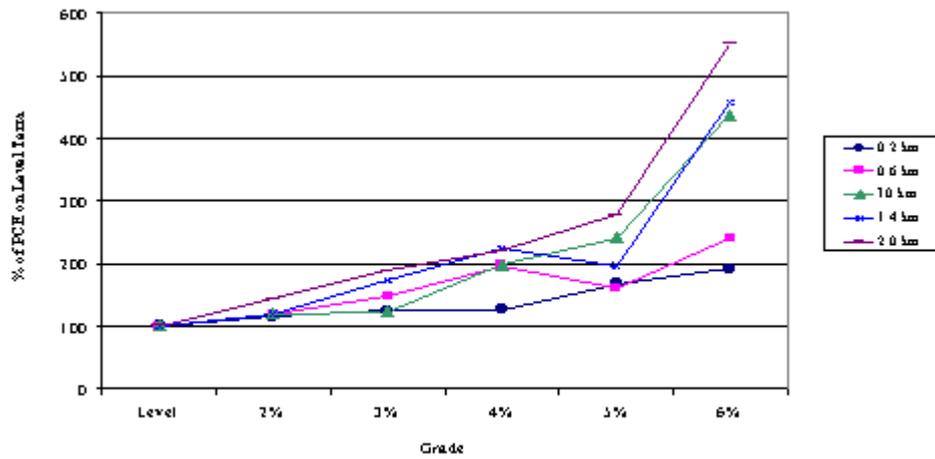
Where the number of passenger cars and heavy vehicles are hourly flow rates found from simulation output. The field capacity in pcph represents the mean value of all capacities observed at the study site using the PCE factors from optimization as described earlier.

In this study, an average weight-to-power ratio of 85 kg/kW (roughly 140 lb/hp) was deemed appropriate to represent a typical heavy vehicles mix on freeways. This average is consistent with the empirical observations found in the literature (Ahanotu 1999, Rakha et al. 2002, TRB 1998). In coding INTEGRATION simulation, 60% of heavy vehicles were assumed to have 100 lb/hp and the remaining 40% of heavy vehicles 200 lb/hp. These are among the standard vehicle types that can readily be modeled in INTEGRATION.

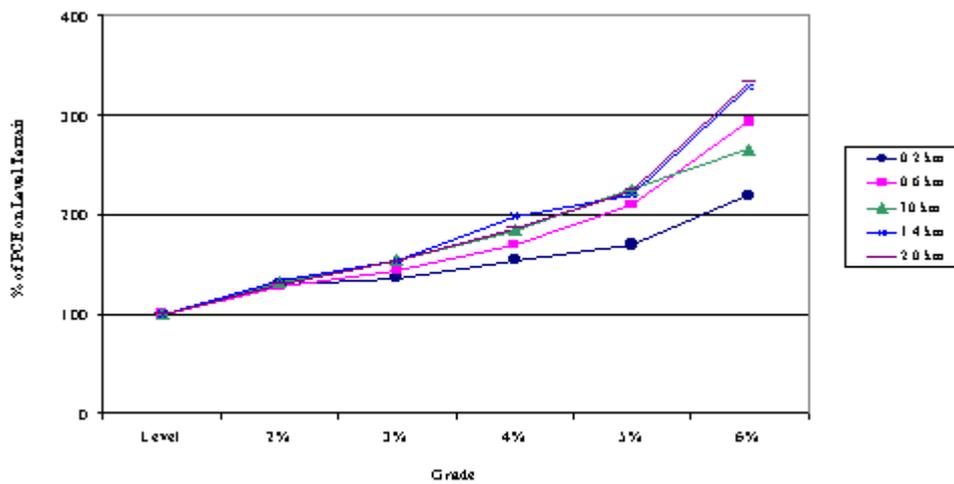
STUDY RESULTS

The effect of grade

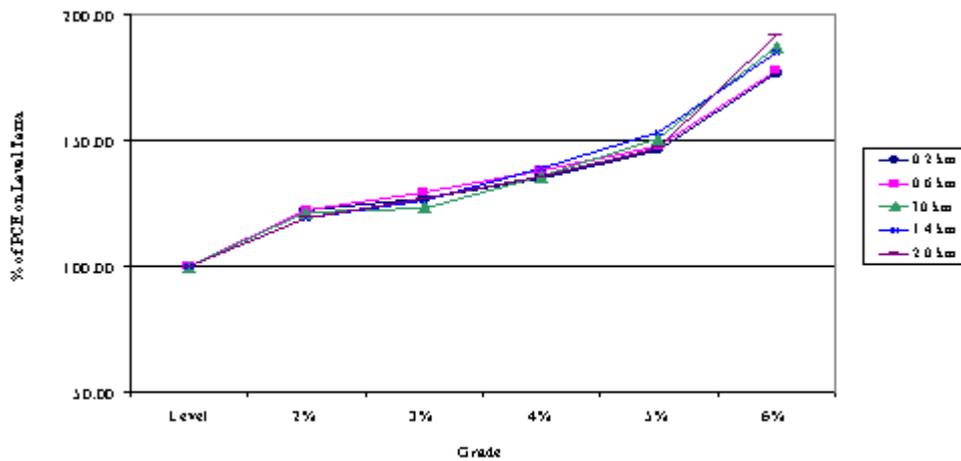
In general, heavy vehicles exhibit inferior performance on highway upgrades and particularly on steeper upgrades. This is true when traffic operates at the free-flow (non-congested) regime as well as at the forced-flow (congested) regime. At the free-flow regime on level terrain, the effect of heavy vehicles is mainly attributed to the larger space taken up by those vehicles due to its larger dimensions (in general) and the larger gaps in front of and behind these vehicles. At the free-flow regime on upgrades, the effect of heavy vehicles may also be attributed to traveling at crawling speed which could be considerably lower than the speed of passenger cars. After the onset of congestion, another important factor contributes to the effect of heavy vehicles both on level terrain and on upgrades. This factor is the inferior acceleration performance of trucks during stop-and-go conditions, or upon leaving the front end of the queue.



(a) 2% Heavy Vehicles



(b) 8% Heavy Vehicles



(c) 20% Heavy Vehicles

Figure 1. The effect of grade on PCE factors at various percentages of HVs.

Figures 1-a, 1-b, and 1-c show the influence of grade on the PCE factors of heavy vehicles at three different percentages of heavy vehicles. What is shown in these figures is the PCE factor expressed as a percentage of that for the same scenario but on level terrain. These figures clearly show that, in general, the effect of heavy

vehicles on traffic flow increases with the increase in grade. This trend is quite expected as the performance of heavy vehicles generally typically declines with the increase in grade percentage. The figures also show that the influence of grade on the PCE factors is generally higher at longer grade lengths and smaller percentages of heavy vehicles. Specifically, in Figure 1-a, the PCE factor for a 2-km 6% upgrade is around 550% of the PCE factor on level terrain when the percentage of heavy vehicles is around 2%. The effect of heavy vehicles on the same upgrade would decrease significantly when the percentage of heavy vehicles increases to 20%. In the latter scenario, the PCE factor is only about 190% of the PCE factor on level terrain (versus 550% in the former scenario). Further, the patterns exhibited in these figures show that grade length will not have a major effect on the PCE factors at higher percentages of heavy vehicles.

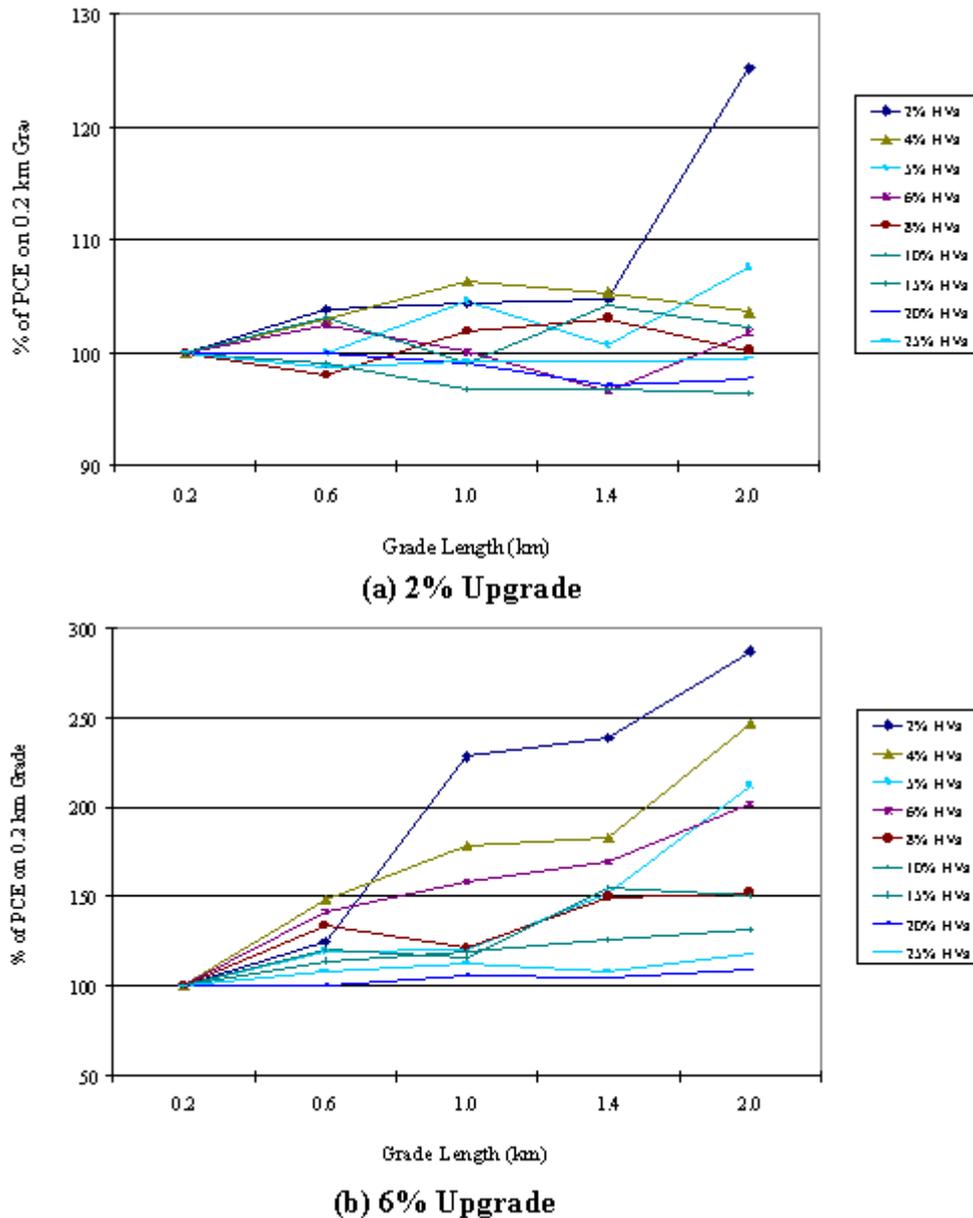


Figure 2. The effect of grade length on PCE factors at various percentages of HVs: (a) 2% upgrade (b) 6% upgrade.

The effect of grade length

Grade length is another important factor that is believed to have an important influence in determining the effect of HVs on traffic flow. Figures 2-a and 2-b show the effect of grade length on PCE factors at various percentages of heavy vehicles for two different grades 2% and 6% respectively. What is shown in this figure is the PCE factor expressed as a percentage of that for the same scenario but on 0.2 km grade length. It is clearly exhibited by these figures that the effect of grade length on PCE factors varies widely as it is a function of the steepness of grade and heavy vehicle's percentage. In Figure 2-a, the effect of grade length on

PCE factor is almost negligible for all the percentages of heavy vehicles investigated by this study. Specifically, except for 2-km upgrade with 2% HVs, the change in PCE factors for all the scenarios investigated was in the range of -5% to +8%. Given the stochastic nature of the simulation model, much of these small variations may not be attributed to the change in grade length. A completely different pattern is exhibited in Figure 2-b. In this figure, it is clear that the PCE factors generally increase with the increase in grade length. However, while this increase is very significant for low percentages of heavy vehicles, it becomes hardly noticeable when heavy vehicles constitute a significant proportion of the traffic mix.

The effect of heavy vehicles' percentage

To test the influence of the proportion of heavy vehicles on the PCE factor, a 1-km two-lane facility (study site 2) was used in simulation while changing the percentage of heavy vehicles from 2% to 25% and the grade from 0% to +6%. The results of this investigation are shown in Figure 3. This figure shows the PCE factor expressed as a percentage of that for the same scenario when the percentage of heavy vehicles is only 2%. Two distinct patterns are exhibited in this figure. The first pattern is concerned with level terrain and small grades (up to 3%) and it generally shows a small increase in the PCE factor as the percentage of heavy vehicles increases. Most of this increase is achieved when the percentage of heavy vehicles reaches 5% and remains relatively constant or fluctuates thereafter. The second pattern, which is concerned with steeper grades, generally shows a decrease in the PCE factors as the percentage of heavy vehicles increases. Two phenomena could be behind these two patterns.

The first phenomenon is that as the number of heavy vehicles increases, the likelihood of occupying the two lanes at the location of bottleneck by heavy vehicles would increase thus increasing the impedance to traffic and consequently the PCE factor. The other phenomenon is that higher percentage of heavy vehicles would increase the likelihood of successive arrivals of heavy vehicles at the bottleneck location (platooning). The effect of these successive arrivals (platoons) of heavy vehicles on smaller vehicles in the traffic stream would be noticeably lower than the sum of their individual effects on traffic if arrived separately. Heavy vehicles accelerating on the upgrade at the location of bottleneck would cause less impedance on other heavy vehicles than on passenger cars and other smaller vehicles. Apparently, the impact of the first phenomenon is dominant at level terrain and low grades while the impact of the second phenomenon is more evident at steeper grades where the acceleration performance of heavy vehicles climbing the upgrade becomes an issue.

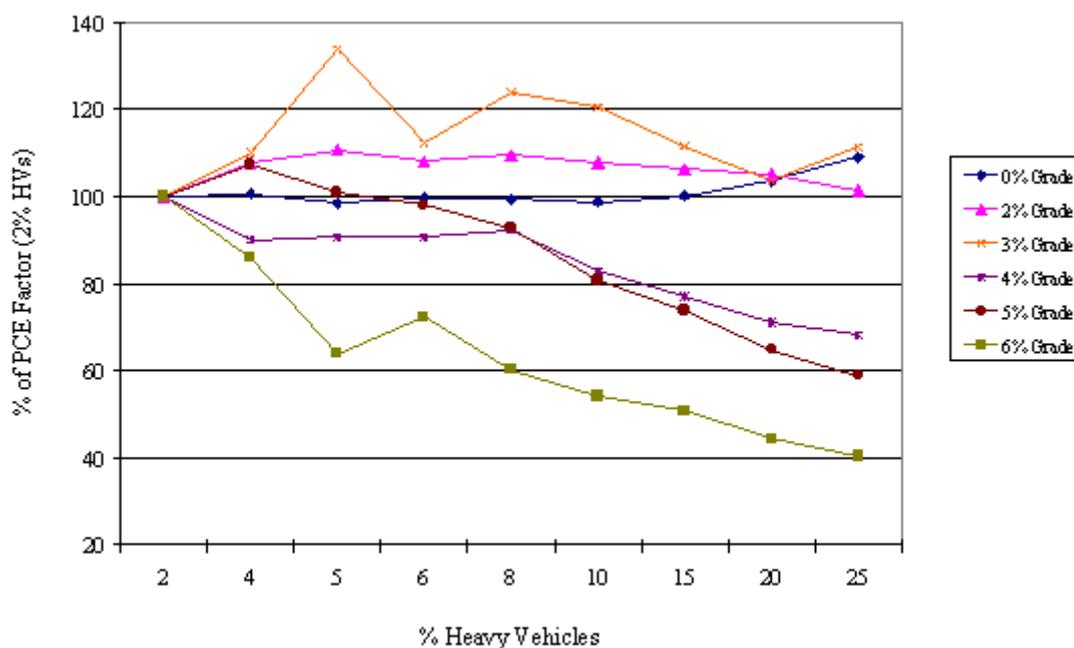


Figure 3. The effect of heavy vehicles' percentage on PCE factors at various grades on a 1-km two-lane highway facility.

The effect of lane-use restriction

Restrictions on the use of the traveled lanes by all or some heavy vehicles may have an important influence on their effect on traffic flow. This is expected as lane-use restriction rules will result in some kind of partial segregation between the smaller vehicles (mainly automobiles) and heavy vehicles. As mentioned in section 4, two types of heavy vehicles were used in simulation experiments: the larger heavy vehicles with weight-to-power ratio of 200 lb/hp and smaller heavy vehicles with weight-to-power ratio of 100 lb/hp.

To test the influence of lane-use restriction rules, a three-lane highway facility on 3% 1-km upgrade was chosen to do this investigation (same grade and grade length as study site 2).

The scenarios considered in this investigation are:

- No restriction on lane use
- All heavy vehicles are restricted from use of left-lane
- All heavy vehicles are restricted from use of left and middle lanes
- All heavy vehicles are restricted from use of left-lane and only larger heavy vehicles are restricted from use of middle-lane

Figure 4 shows the PCE factors for the above scenarios of lane-use restriction at different percentages of heavy vehicles. LL and ML in this figure refer to left lane and middle lane respectively. The patterns shown in this figure are very important as they have implications that may help in minimizing the effect of heavy vehicles (mainly trucks) through the use of traffic control measures.

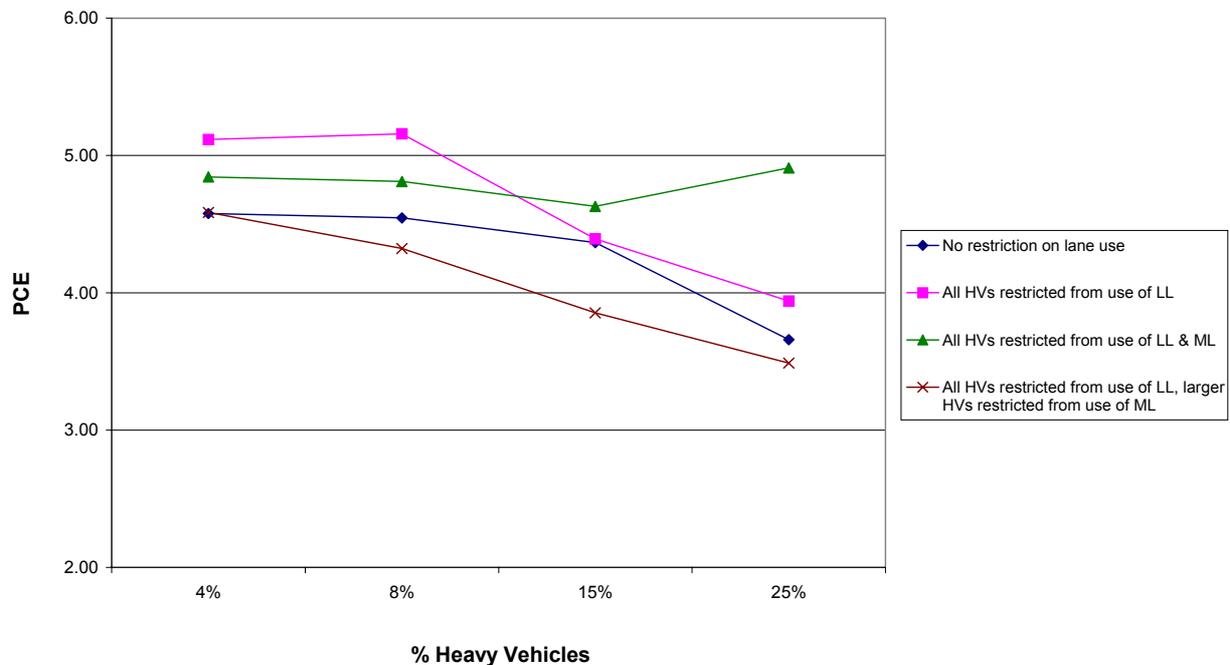


Figure 4. Influence of lane-use restriction on PCE factors at different percentages of heavy vehicles.

The first scenario is not common in real-life applications as heavy vehicles are almost always prohibited from using the leftmost lane(s) on multi-lane highways. However, it is considered by this investigation in an attempt to understand the effect of trucks as it relates to their distribution on the traveled lanes. Figure 4 shows that the effect of heavy vehicles under this scenario is relatively small compared with the second and third scenarios of lane-use restriction. Under this scenario, it seems that passenger cars can easily find one or two lanes with appropriate average speed(s) and change lanes once they're stuck behind heavy vehicles. Also, under this scenario, smaller heavy vehicles are not much affected by the inferior performance of larger heavy vehicles as they can change lanes with relative easiness.

When lane-use restriction on left lane is imposed on all heavy vehicles, the situation for passenger cars will not improve much especially at lower percentages of heavy vehicles. This is mainly because it is very unlikely that all the traveled lanes are simultaneously occupied by heavy vehicles at the same location in the

absence of any lane-use restriction. However, the situation for smaller heavy vehicles (60% of all heavy vehicles) would be worse as they would become more affected by larger heavy vehicles, i.e. they would have less freedom in shifting to other lanes to avoid the impedance of larger heavy vehicles. At higher percentages of heavy vehicles, the effect of lane-use restriction would be less evident and the PCE curve would become very close to the original scenario (no restriction). This is partly due to platooning of heavy vehicles on the right and middle lanes that minimizes their effect on traffic flow.

In the third scenario, all heavy vehicles are restricted from the use of the left and middle lanes. Under this scenario, the situation for passenger cars improves as most of them occupy these two lanes and therefore don't have to mix with heavy vehicles. However, the situation for heavy vehicles (especially smaller HVs) is negatively affected particularly when a large number of HVs have to use the right lane (at high % of HVs). In this scenario, there are two factors that come into play when the percentage of heavy vehicles increases. The first is the platooning of heavy vehicles which induces a decrease in the PCE factor, while the second is the lack of freedom in shifting lanes for smaller HVs which tends to increase the PCE factor.

This explains why the PCE factor does not decrease with the increase in heavy vehicles' percentage as the two factors tend to cancel out each other's effect. In the last scenario, all HVs are restricted from the use of left lane and only larger HVs are restricted from the use of middle lane. Compared with the previous lane-restriction scenario, the situation for passenger cars is expected to slightly deteriorate due to the fact that passenger cars now share the middle lane with the smaller HVs. However, the situation for smaller HVs (which constitute the majority of heavy vehicles) will largely improve as they will be allowed to share the middle lane with passenger cars and thus be less affected by the impedance of larger HVs. The net result of the previous effects would be an improved traffic operations and less effect of heavy vehicles on traffic flow. Therefore, this scenario exhibited the lowest effect of heavy vehicles on traffic flow when compared with the other three scenarios discussed earlier.

The effect of location of bottleneck relative to upgrade

The location of bottleneck relative to upgrade is expected to have an effect on the PCE factor for heavy vehicles. This expectation is based on the fact that the impedance imposed by heavy vehicles on passenger cars during stop-and-go conditions is different when the queue occupies a level highway segment or an upgrade segment. To test this logical assumption, simulation experiments are conducted at study site 2 (same grade and grade length) with the location of bottleneck at the bottom and at the top of upgrade respectively. Also, two-lane and three-lane facilities are considered in this investigation. In practice, the bottleneck is typically located where capacity reaches its lowest level (due to lane blockage or change in geometric properties). The change in the PCE factor that would result from the change in bottleneck location (from bottom to top of upgrade) for the two facilities is then examined and the results are presented in Figure 5. This figure shows the increase or decrease in the PCE factor (as a result of change in bottleneck location) expressed as a percentage of the PCE factor when the bottleneck location is at the bottom of upgrade. When the bottleneck location is at the bottom of upgrade, queuing and stop-and-go operations take place on the facility upstream (level terrain). On the other hand, when the bottleneck location is at the top of the upgrade (or at any other point on the upgrade), the queuing takes place on the upgrade and may extend on the facility upstream. As acceleration performance of trucks and other heavy vehicles is greatly affected on grades, it is logical to expect that the PCE factor when the bottleneck is at the top of upgrade would be higher than the PCE factor when the bottleneck is at the bottom of upgrade.

This is clearly shown in the patterns exhibited in Figure 5. Specifically, three distinct patterns are shown in this figure:

- In almost all the conditions investigated, the PCE factor when the bottleneck is at the top of upgrade is higher than that when the bottleneck is at the bottom of upgrade.
- The increase in the PCE factor is very significant at low percentage of heavy vehicles and continues to decline as this percentage increases. This is quite expected as the likelihood of having successive heavy vehicle arrivals is increased which leads to lower impact on other smaller vehicles as discussed in section 6.3.
- The increase in the PCE factor due to change in bottleneck location is much more significant on the two-lane highway facility compared with the three-lane facility. This is also expected as the likelihood of the two lanes being affected by low-performance climbing trucks simultaneously at the same location is

higher than the same likelihood for the three lanes. In other words, it is easier for passenger cars to avoid the impedance of trucks on the three-lane facility compared with the two-lane facility.

The first pattern has important implications in situations when traffic engineers have some control on the location of bottleneck such as in planning lane closures at work zones.

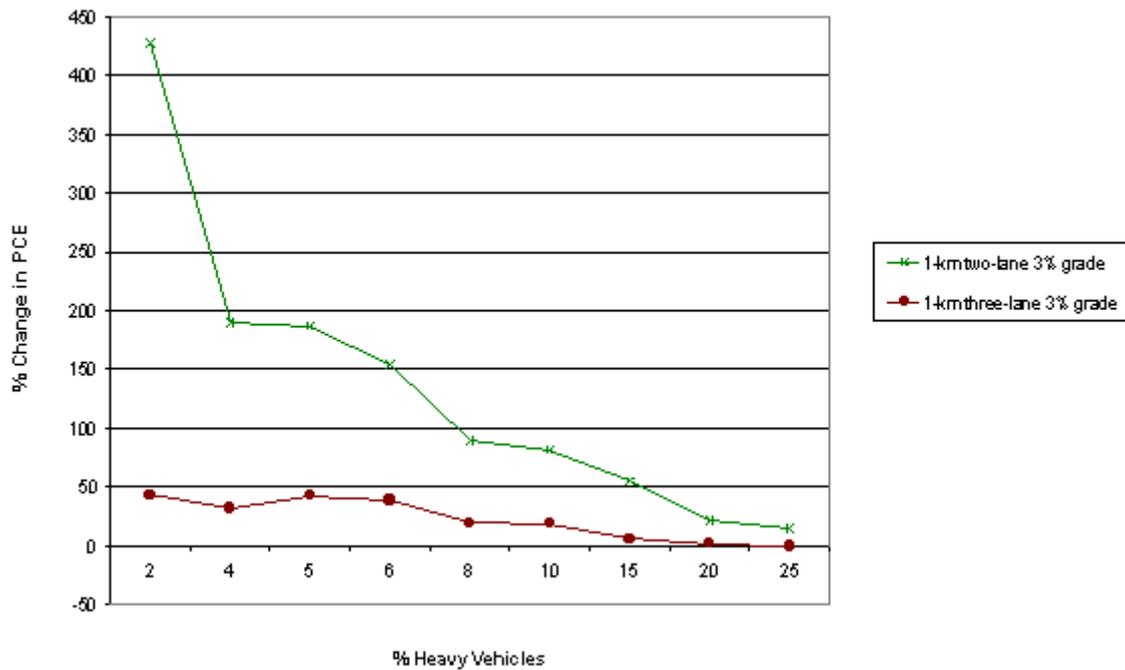


Figure 5. Effect of bottleneck location relative to upgrade on PCE factor.

SUMMARY OF FINDINGS

An investigation into the effect of heavy vehicles on traffic stream during congestion is presented in this paper.

The most important findings of this investigation are:

- Similar to traffic operations at free-flow conditions, the effect of heavy vehicles increases with the increase in grade percentage.
- Grade length has only small effect on the PCE factor of heavy vehicles at more gentle upgrades while it has a significant effect on this factor at steeper upgrades.
- Unlike free-flow conditions, the effect of heavy vehicles' percentage on PCE factor is dependent on the subject grade. The PCE factor increases with the increase in the percentage of heavy vehicles at more gentle upgrades while it decreases at steeper upgrades.
- Concerning lane-use restriction by vehicle type, the least effect of heavy vehicles on traffic at multi-lane highway facilities is expected to occur when all heavy vehicles are restricted from the use of the leftmost lane(s) and only larger heavy vehicles are restricted from the use of the middle lane(s).
- Results suggest that the effect of heavy vehicles when the location of bottleneck is at the top of the upgrade (or at any other point on the upgrade) is higher than the effect when the bottleneck is at the bottom of the upgrade.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Hesham Rakha from Virginia Tech for his valuable support and help in using the traffic simulation model INTEGRATION.

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