Passenger Car Equivalents for Heavy Vehicles at Freeways and Multilane Highways: Some Critical Issues

THIS FEATURE DISCUSSES SOME CRITICAL ISSUES RELATED TO THE CONCEPT AND USE OF PASSENGER CAR EQUIVALENCY (PCE) FACTORS FOR HEAVY VEHICLES THAT ARE INCLUDED IN THE HIGHWAY CAPACITY MANUAL (HCM) PROCEDURES FOR FREEWAYS AND MULTILANE HIGHWAYS. PRACTICAL INSIGHTS INTO THE LIMITATIONS AND APPROPRIATE USE OF THE CURRENT HCM PCE FACTORS ARE INCLUDED.

BY AHMED AL-KAISY, PH.D.

INTRODUCTION

One of the important issues affecting the accuracy of traffic analyses is heterogeneity in the vehicular traffic mix that composes a traffic stream. Typically, the majority of vehicles in a traffic stream are passenger cars or vehicles that are similar to passenger cars in physical characteristics and performance, such as sport utility vehicles, pick-up trucks and minivans.

Heavy vehicles, which usually constitute the remaining smaller proportion of a traffic mix, are larger in dimension and often inferior to passenger cars in performance. Heavy vehicles consist mainly of trucks used in freight transportation, larger buses and recreational vehicles. Despite being the smaller proportion of vehicular traffic, heavy vehicles are known for their important impacts on the traffic stream.

Historically, the effect of heavy vehicles on traffic flow has been accounted for through the use of passenger car equivalency factors. These factors are intended to approximate the effect of heavy vehicles and are expressed as multiples (of the effect) of an average passenger car.

In the United States, the *Highway Capacity Manual* (HCM) provides passenger car equivalents (PCEs) for use in capacity and level of service (LOS) analyses. Using PCEs, a heterogeneous mix of vehicles in a traffic stream can be expressed in a standardized unit of traffic, such as passenger car. PCEs are considered essential in carrying out most traffic analyses.

BACKGROUND

The first edition of HCM treated the presence of heavy vehicles in the traffic stream in a very simplistic manner. Specifically, a single factor of 2.0 was used to represent the impact of heavy vehicles on multilane highways in level terrain. In other words, trucks had the same effect as two passenger cars.[1]

The subsequent edition of HCM provided a more sophisticated treatment of the effect of heavy vehicles on traffic flow and introduced the term "passenger car equivalent."[2] The most important feature of this treatment was the fact that PCEs were a function of LOS. Specifically, PCE factors were classified into two groups. The first group applied to LOS A through C; the second group applied to LOS D and E.

The 1985 HCM included a different treatment of the effect of heavy vehicles based on research that had been conducted since the preceding edition in 1965.[3] Although the use of the PCE concept continued in that version, PCEs included in freeways and multilane highway procedures were not sensitive to LOS (PCEs were applicable to any LOS).

In addition, three different sets of PCEs on upgrades were provided for heavy vehicles with different levels of vehicle performance as measured by weight-to-power ratio. Those sets of PCEs corresponded to heavy vehicles with 100, 200 and 300 lb/hp, respectively.

The most recent version of HCM provides a simplified (and more approximate) approach to quantifying the effect of heavy vehicles on the traffic stream compared with the 1965 and 1985 HCM editions.[4] These procedures employ PCEs that represent the full spectrum of heavy vehicles in the traffic mix regardless of performance and the full range of traffic conditions regardless of LOS. In other words, PCEs are not sensitive to the performance of heavy vehicles or traffic level.

Since the introduction of PCEs in 1965, many researchers have tried to quantify the effect of heavy vehicles on traffic flow by developing HCM-like PCE factors using different methodologies and equivalency criteria.[5–11] Although a few of those studies utilized field data, most used traffic simulation to derive PCEs for a wide range of traffic and geometric conditions.

PASSENGER CAR EQUIVALENTS: SOME CRITICAL ISSUES

This feature aims to shed light on some important issues critical to the understanding of the effect of heavy vehicles on traffic flow and, therefore, on the use of PCEs for heavy vehicles in traffic analyses.

Mechanism of Heavy Vehicles' Effect

The effect of heavy vehicles on traffic flow is mainly attributed to two important factors: physical dimensions and performance. Compared with passenger cars, heavy vehicles are known for their larger dimensions, inferior acceleration performance and lower maximum speeds on steep and/or relatively long upgrades.

The role of these differences on the effect of heavy vehicles varies under different traffic and geometric conditions. In this regard, three important factors are closely related to the different mechanisms of the effect of heavy vehicles:

- Terrain: level, rolling and mountainous terrains
- Traffic regime: unsaturated versus saturated conditions
- Traffic level for unsaturated conditions

Terrain: On highway segments with level grade and free-flow (unsaturated) conditions, the effect of heavy vehicles is mainly related to their physical dimensions. Specifically, heavy vehicles generally are larger than passenger cars and the average gaps in front of and behind heavy vehicles are larger than those associated with passenger cars. Under these conditions, the effect of their performance on traffic flow typically is minimal because they are able to travel at speeds generally close to the average speed of passenger cars.

However, a speed differential between passenger cars and heavy vehicles may exist on level freeway segments due to different speed limits imposed by highway authorities, increasing the effect of heavy vehicles.

The mechanism of the effect of heavy vehicles on upgrades under unsaturated conditions differs significantly from that described on level highway segments. Besides their larger dimensions and larger headways, heavy vehicles usually exhibit inferior performance on upgrades. Speeds of heavy vehicles normally decline as they travel on upgrades until they eventually reach crawl speeds (if the upgrade is of sufficient length).

A crawl speed is a limiting speed mainly determined by weight-to-power ratio and grade percentage. Crawl speed could be considerably lower than the average speed of passenger cars on a specific upgrade. On steep upgrades, the impact of speed differential may far exceed the impact of physical dimensions and larger headways described earlier. It should be clear that the impact of heavy vehicles on downgrades is relatively comparable to level terrain because engine performance is not much of an issue in determining their effect.

Traffic Regime: After the onset of congestion (forced-flow conditions), the mechanism of the effect of heavy vehicles imposes a greater impact on the traffic stream compared with steady flow conditions. Acceleration-deceleration cycles, a condition normally experienced during queuing or stop-and-go operations, introduce another inconsistency between the behavior of passenger cars and heavy vehicles within the traffic mix. The acceleration performance of heavy vehicles is different from that of passenger cars. This aspect of heavy vehicles' performance applies to all types of terrain (level highway segments and upgrades).

It is important to remember that the PCE factors used in the current HCM procedures account for the effect of heavy vehicles' dimensions and performance only under steady-state conditions. The inferior acceleration performance exhibited after the onset of congestion is not incorporated. Because capacity often is realized at saturated (bottleneck) operations, the use of HCM PCEs for demand-capacity analysis during queuing operations is expected to underestimate the effect of heavy vehicles.

Traffic Level (Unsaturated Conditions): Under steady-state conditions, the effect of heavy vehicles on traffic flow is expected to vary with the prevalent traffic level. This effect primarily is a function of the interaction between heavy vehicles and other smaller vehicles in the traffic stream. At low volumes, it is reasonable to expect that larger and slow-moving vehicles would have only a small effect on traffic flow. As traffic volume increases, the effect would be expected to increase due to the greater interaction between heavy vehicles and other smaller vehicles in the traffic mix.

In support of this argument, a few studies reported that PCE factors increase steadily as traffic level increases.[12] The 1965 HCM is consistent with this argument. It provides two sets of passenger car equivalents: one for favorable operating conditions (LOS A through C) and another for less favorable conditions (LOS D and E). However, the PCEs employed by the capacity analysis procedures for freeways and multilane highways in the subsequent versions of HCM are not sensitive to traffic levels.

Equivalency Criteria

Although they are essential in carrying out capacity analyses, PCE factors have been the subject of an old and long argument about the definition of equivalency and the basis for deriving their numerical values. This is partly due to the loose definition of PCEs in subsequent versions of HCM and the simplistic approach often used in developing PCEs.

The definition of equivalency in the 1965 HCM is "the number of passenger cars displaced in the traffic flow by a truck or a bus, under the prevailing roadway and traffic conditions."[13]

This definition is so general that it virtually could encompass any criterion as a basis for equivalency. The 1965 HCM utilized average speed as the criterion to derive PCE factors for freeways and multilane highways.

In the 1985 HCM, equivalency is defined as "the number of passenger cars that would consume the same percentage of the *freeway's capacity* as one truck, bus, or recreational vehicle under prevailing roadway and traffic conditions."[14]

This definition is more specific than that of the 1965 HCM because it restricts the equivalency to a single criterion: capacity (traffic flow rate).

However, an investigation of the available literature shows that PCE factors provided in the 1985 HCM were derived using average speed as an equivalency criterion.[15] This raises serious questions about the consistency between the PCE concept as defined in HCM and the numerical values provided in the analytical procedures of that same document.

The most recent edition of HCM 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."[16]

Average density in the traffic stream was used as the equivalency criterion in developing the PCE factors. It was deemed that this traffic parameter, which is an indicator of proximity to other vehicles in the traffic stream, directly relates to drivers' perception of the quality of service.

Traditionally, most previous research on PCEs utilized the same parameters as those used to measure LOS as a basis for equivalency. This was stated explicitly by Krammes and Crowley: "The basis for equivalence should be the parameters used to define LOS for the roadway type in question."[17]

Apparently, this statement is based on an implicit assumption that those PCEs are intended for use in LOS analyses. This approach is shared by the recent version of HCM as well as most previous studies, which addressed heavy vehicles' effect on different types of highway facilities.

Although using the above approach in assessing heavy vehicles' effect may be appropriate for LOS analyses, its use for other traffic analyses may involve a significant amount of approximation and error.

Application Type

The effect of heavy vehicles on the capacity of a bottleneck may be different from their effect on average density at relatively low traffic levels (unsaturated conditions). This is mainly related to the different mechanisms of heavy vehicles' effect during the two different traffic regimes that were described earlier in this feature.

Under queuing operations, the acceleration/deceleration performance of heavy vehicles may become a major determinant of their effect on the traffic stream. Under steady-state operations, physical dimensions and larger headways may contribute more to the effect of heavy vehicles.

This may indicate an important limitation in the HCM procedures that normally provide a single set of PCE factors for use in capacity and LOS analyses. The above example suggests that, although those PCEs may provide a reasonable approximation of heavy vehicles' effect for LOS analysis, it may not be appropriate for use in determining capacity. Because capacity is a very important input to many traffic analyses, capacity-based PCE factors need to be developed for heavy vehicles using an appropriate equivalency criterion that reflects at-capacity (saturated) operations.

A study by Al-Kaisy, Hall and Reisman utilized the queue discharge flow from a bottleneck as an equivalency criterion in developing PCE factors for forced-flow (saturated) conditions.[18] Another study by Fan utilized volume-to-capacity ratio instead of average density as a criterion to develop capacity-based PCE factors for capacity applications.[19] Although it should be clear that the HCM procedures for freeways and multilane highways are applicable only to free-flow conditions (LOS A to LOS E), the PCEs provided in those procedures are used in estimating highway capacity as well.

The previous argument suggests that the equivalency criterion for PCEs needs to reflect the application at hand or, in other words, needs to be application-sensitive. This understanding of the basis for selecting the equivalency criteria was expressed by Van Aerde and Yagar:[20]

"Passenger car equivalents have generally been assumed to be similar for capacity, speed, platooning, and other types of analysis. This notion appears to be incorrect and is perhaps one of the main sources of discrepancies among the various PCE studies."

Heavy Vehicle Mix

The effect of individual heavy vehicles on traffic flow is expected to vary due to variations in physical dimensions, vehicle weight, engine performance, aerodynamic features and loading status (unloaded, partially loaded, or fully loaded). This heterogeneity is expected to vary by location and time. From a practical point of view, the extensive heterogeneity is very difficult to model at best.

Therefore, it is reasonable to expect that the current system of PCE factors, which is insensitive to heavy vehicle mix, would involve a fair amount of approximation in modeling the effect of heavy vehicles.

Historically, performance measured in weight-to-power ratio has been perceived as the most important determinant of heavy vehicles' effect, particularly on upgrades, and is used as the basis to account for heavy vehicle mix in practice. This ratio is a function of engine power, vehicle weight and cargo weight.

Traditionally, two approaches were followed in quantifying heavy vehicles' performance for the purpose of PCE use: a discrete approach and an aggregate approach. The discrete approach divides heavy vehicles into categories of performance and provides PCE factors for each of those categories. This approach has the advantage of being more detailed and more accurate in the following situations:

- Microscopic analyses in which the effect of a specific heavy vehicle (or type of vehicle) with a known weight-to-power ratio is investigated.
- Macroscopic analyses in which the average weight-to-power ratio of the mix can be estimated.

This approach was followed in the 1985 HCM, in which three sets of PCE factors on upgrades were provided for three different performance categories of 100, 200 and 300 lb/hp, respectively.

The aggregate approach provides one set of PCE factors based on the average weight-to-power ratio of a "typical" heavy vehicle mix. The advantage is that it does not require information about heavy vehicles' weight and performance on the facility under investigation. The main drawback is that it does not allow the analyst to accurately estimate the effect of heavy vehicles should information on weight and performance be available.

Furthermore, it is illogical to expect that a single value for average weight-to-power ratio could represent the heavy vehicle mix on all freeways and multilane highways nationwide with reasonable accuracy. The current edition of HCM follows this aggregate approach and provides a single set of PCE factors that is applicable to any mix of heavy vehicles.

SOME PRACTICAL CONSIDERATIONS

In light of the critical issues presented in this feature, it is important to provide a few practical considerations regarding the use of PCE factors in performing various analyses.

- One of the important issues that traffic engineers deal with on a regular basis is the analysis of queues and congestion. The HCM PCE factors were shown to be inappropriate for those applications. A set of PCE factors for congested conditions published in a recent study could be a useful resource until more formal PCE factors become available in HCM.[21]
- With regard to heavy vehicle mix, traffic engineers and practitioners should be aware that the current HCM PCE factors for free-flow conditions were derived for an average weight-to-power ratio of 100 kg/kW (equivalent to 164 lb/hp). This average weight-to-power ratio is considered somewhat conservative when compared to empirical observations that were reported in two recent studies on interstate highways.[22,23] Therefore, the use of HCM PCE factors should provide for conservative analysis and design with respect to the general mix of heavy vehicles on interstate and multilane highways.
- It is important to use the queue discharge flow rate (bottleneck capacity) as an equivalency criterion in developing PCE factors for use in determining capacity and the analysis of queues and congestion. On the other hand, the equivalency criterion for performance under free-flow conditions should be the same as the performance measure used to assess the quality of service.

CONCLUDING REMARKS

PCE factors for heavy vehicles are an effective means to account for the presence of heavy vehicles in the traffic stream in performing traffic analyses. Traditionally, those factors are included in the HCM procedures for various highway facilities. This feature discusses some critical issues concerning the concept and use of HCM PCE factors at freeways and multilane highways and provides a few practical considerations. Understanding these issues is important to appreciate the limitations and appropriate use of HCM PCE factors. ■

References

1. Highway Research Board. *Highway Capacity Manual: Practical Applications for Research*. Washington, DC, USA: Department of Traffic and Operations, Committee on Highway Capacity, 1950.

2. Highway Research Board. *Highway Capacity Manual: Special Report 87*. Washington, DC: National Research Council (NRC), Department of Traffic and Operations, Committee on Highway Capacity, 1965.

3. Transportation Research Board (TRB). *Highway Capacity Manual: Special Report 209. Third Edition*. Washington, DC: NRC, 1985.

4. TRB. *Highway Capacity Manual. Fourth Edition*. Washington, DC: NRC, 2000.

5. Krammes, R. and K. Crowley. "Passenger Car Equivalents for Trucks on Level Freeway Segments." *Transportation Research Record*, No. 1091 (1986).

6. St. John, A.D. "Nonlinear Truck Factor for Two-Lane Highways." *Transportation Research Record*, No. 615 (1976).

7. Sumner, R., D. Hill and S. Shapiro. "Segment Passenger Car Equivalent Values for Cost Allocation on Urban Arterial Roads." *Journal of Transportation Research—Part A*, Vol. 18, No. 5 (1984): 399–406.

8. Huber, M. "Estimation of Passenger Car Equivalents of Trucks in Traffic Stream." *Transportation Research Record*, No. 869 (1982).

9. Van Aerde, M. and S. Yagar. "Capacity, Speed and Platooning Vehicle Equivalents for Two-Lane Rural Highways." *Transportation Research Record*, No. 971 (1984).

10. Webster, N., and L. Elefteriadou. "A Simulation Study of Truck Passenger Car Equivalents on Basic Freeway Sections." *Journal of Transportation Research—Part B*, Vol. 33, No. 5 (1999): 323–336.

11. Werner, W. "Passenger Car Equivalencies of Trucks, Buses and Recreational Vehicles for Two-Lane Rural Highways." *Transportation Research Record,* No. 615 (1976).

12. Webster and Elefteriadou, note 10 above; and Keller, E. and J. Saklas. "Passenger Car Equivalents from Network Simulation." *Journal of Transportation Engineering,* Vol. 110, No. 1 (1984): 397–411.

13. Highway Research Board, note 2 above.

14. TRB, note 3 above.

15. Webster and Elefteriadou, note 10 above.

16. TRB, note 4 above.

17. Krammes and Crowley, note 5 above.

18. Al-Kaisy, A.F., F.L. Hall and E. Reisman. "Developing Passenger Car Equivalents for Heavy Vehicles During Queue Discharge Flow." *Journal of Transportation Research—Part A*, Vol. 36, No. 8 (2002): 61–78.

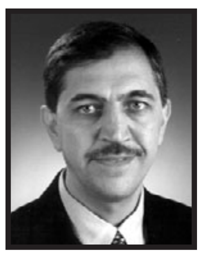
19. Fan, H.S. "Passenger Car Equivalents for Vehicles on Singapore Expressways." *Journal of Transportation Research—Part A*, Vol. 24, No. 5 (1990): 391–396.

20. Van Aerde and Yagar, note 9 above.

21. Al-Kaisy, A.F., Y. Jung and H. Rakha. "Developing Passenger Car Equivalency Factors for Heavy Vehicles during Congestion." *Journal of Transportation Engineering*, Vol. 131, No. 7 (2005).

22. Ahanotu, D.N. "Heavy-Duty Vehicle Weight and Horsepower Distributions: Measurement of Class-Specific Temporal and Spatial Variability." Ph.D. thesis, Georgia Tech, 1999.

23. Rakha H. and I. Lucic. "Variable Power Vehicle Dynamics Model for Estimating Maximum Truck Acceleration Levels." *Journal of Transportation Engineering,* Vol. 128, No. 5 (2002): 412–419.



AHMED AL-KAISY, *Ph.D., is an assistant professor in the Civil Engineering Department at Montana State University in Bozeman, MT, USA. Formerly, he served as an assistant professor at Bradley University in Peoria, IL, USA and has held positions as research associate, project engineer and highway design engineer in the public and private sectors. He holds a Ph.D. in civil engineering from Queen's University in Ontario, Canada and has extensive teaching and research experience in transportation engineering. He is an associate member of ITE.*