Developing Passenger-Car Equivalents for Left-Turning Trucks at Compressed Diamond Interchanges

JAMES E. WEST AND GLEN S. THURGOOD

A study on the effects of light and heavy trucks on left-turning queues at compressed diamond interchanges is described. The headway method was used for determining passenger-car equivalents (PCEs) of various left-turning light and heavy truck classes, including some specialty vehicles. Inside turn radii were 15 to 18 m (50 to 60 ft), which is typical of many left turns for compressed diamond interchanges, where freeway on/off ramps are brought in as close to the freeway as possible. Composite PCEs for standard light and heavy trucks are reported as 1.7 and 4.4, respectively. PCEs for specialty vehicles are given as well.

Of all the elements that make up a freeway, the interchange is commonly one of the greatest capacity-limiting factors in the system. To minimize the bottleneck problem, several types of grade-separated interchanges have been used with varying degrees of success, the most common being variations of the diamond interchange. Within the last 15 years or so, a modified version of the diamond interchange has gained popularity. It is commonly referred to as the single-point urban interchange (SPUI) and has been touted by some as the universal answer to the problem of efficiently moving vehicles on and off the freeway. Others are cautious and are involved in research to determine exactly how efficient and safe the SPUI really is (*1–3*). As a result, there is considerable interest in comparing the operating characteristics of the SPUI with those of the diamond interchange.

Observing heavy trucks turning left at SPUI interchanges leaves one with the impression that the SPUI geometry handles left-turn maneuvers much more efficiently than do the short-radius turns permitted by the compressed diamond configuration. On the other hand, the lower clearance interval between phase transitions at compressed diamond interchanges appears to favor vehicles making through movements. If this assumption is correct, one interchange design may have a capacity advantage over the other, depending on the size of the interchange and the number of trucks in the traffic stream and their predominant movement. Recent research into SPUI operation supports this hypothesis by showing that SPUIs are not always more efficient at moving traffic than standard diamond interchanges (*2*). (NCHRP Project 3-47, which is ongoing, would consider the diamond interchange in this research to be a tight urban diamond rather than a compressed diamond.)

The research in this paper describes the method used in calculating left-turning passenger-car equivalents (PCEs) for trucks at diamond interchanges, with the hope that the procedure will also be used at SPUIs, whereby left-turning PCEs may be compared between the two interchanges to determine which design has the least negative impact on truck operation. The results of the research may be particularly important at locations where truck operations are high, such as interchanges near industrial and warehouse areas, since an improper evaluation of the effect of heavy vehicles on interchange operation could substantially affect the accuracy of any operational analyses.

J. E. West, Kimley-Horn and Associates, Inc., 9320 S.W. Barbur Boulevard, Suite 130, Portland, Oreg. 97219. G. S. Thurgood, Department of Civil Engineering, Brigham Young University, 368-J Clyde Building, Provo, Utah 84602.

FACTORS INFLUENCING PCEs

In understanding the capacity of signalized intersections, it is assumed that the ideal traffic stream consists of only passenger cars and such other factors as 0 percent grade, 3.7-m (12-ft) lanes, no parking, and dry pavement conditions. In most instances, the traffic stream is less than ideal and contains a mixture of cars and trucks. As trucks are introduced into the traffic flow, the ability of the roadway to carry vehicles is reduced because of the increased size of the trucks and their lower performance characteristics.

In defining the effect of trucks on traffic flow, the term "PCE" was introduced in the 1965 *Highway Capacity Manual*. PCE referred to "the number of passenger cars displaced in the traffic flow by a truck or bus, under the prevailing roadway and traffic conditions" (*4*). A review of current literature indicates that three general factors affect the size of the PCE: truck length, truck turning and acceleration characteristics, and behavior of following drivers (*5*). PCEs are also influenced by traffic conditions, weather, and other environmental factors; however, these factors were not considered specifically in this analysis.

The first factor (truck length) is relatively easy to understand. Passenger cars typically are shorter than 5.5 m (18 ft), whereas it is common for large five-axle trucks to be longer than 15 m (50 ft) (*6*). Physically, trucks take up more space than passenger cars; therefore, as the length of the truck increases, that portion of the PCE increases also.

Truck turning and acceleration characteristics are based on the performance capabilities of the truck, such as minimum turning radii and weight-to-horsepower ratio. Vehicle performance curves show that passenger cars can accelerate more than twice as fast as heavy trucks on a 0 percent grade (*6,7*). Differences in truck acceleration characteristics and their inability to negotiate small-radius turns cause them to have longer travel times through an intersection, thus increasing the PCE. If it were possible to improve truck performance so that the weight-to-horsepower ratio was essentially that of a car, this factor could be reduced; however, even with the latest engine power improvements, the difference is still significant because of turning limitations.

The third factor—the behavior of a following driver—is the most difficult element to quantify. Large trucks often are difficult to see around and create an uncomfortable feeling for a driver following behind closely. As a result, it is common for drivers to increase the separation between the two vehicles until a comfortable gap is achieved. Increasing the distance between vehicles further increases the PCE (*5*). The ability of following cars to accelerate is also limited by the acceleration and speed of the leading truck.

CURRENT VALUES FOR PCEs

Since the introduction of the term PCE almost 30 years ago, much research has been performed to quantify acceptable values; however, almost all of the studies have examined trucks moving in a straight path.

The basis for much of the research was pioneered in studies by Greenshields, et al. that dealt with saturation flow theory and vehicle start-up time (*8*). Their results, although slightly refined since their introduction, have proved to be remarkably accurate and consistent with later studies (*7*). Their findings and the later research by others give a clear understanding of the dynamics of starting a standing queue of vehicles.

When a stopped queue of vehicles prepares to move, the driver of the first vehicle must see the green signal indication and react to the change by removing his or her foot from the brake and then accelerating across the stop line. The process requires a relatively long period for the first vehicle. The second vehicle makes the same perception and reaction response but is able to initiate it at almost the identical time as the first vehicle. This allows the second vehicle to reduce its headway (the time to cross the stop line after the first car crosses). A similar procedure occurs for the remaining vehicles in the queue, with succeeding vehicles further reducing their headways. At about the sixth vehicle, the effects of starting up the queue are dissipated and the remaining vehicles travel at a constant headway and speed (*7*). As trucks are introduced into the traffic stream, they increase the time that it takes for the queue of stopped vehicles to achieve saturation flow.

Since the introduction of PCEs, researchers have developed their own suggested values, each taking into account some of the factors that affect PCEs. Miller found that compared with a car, it took an additional 1.79 sec for a commercial truck to cross the stop line. He divided the average headway of the truck by the average headway of a passenger car and obtained a PCE value of 1.85. Miller's work was one of the first to define quantitatively a PCE value (*9*).

Carstens essentially repeated Miller's procedure by measuring headways, where measurements were made as the front bumpers passed a stop line (known as leading headway). His research resulted in a PCE of 1.63, a value that supports Miller's findings (*10*).

Later, Branston and van Zuylen measured headways as the rear bumpers crossed the stop line (lagging headway). They attempted to separate trucks into two classes. Their results showed PCEs for medium and heavy trucks to be 1.35 and 1.68, respectively. It should be noted that their classification of heavy trucks did not include any trucks with five or more axles (*11*).

The 1985 *Highway Capacity Manual* (HCM) uses a PCE of 1.5 to 1.6 for signalized intersections to determine its heavy vehicle factor; this method is used by many engineers. The HCM factor makes no attempt to separate heavy vehicles in any way, but instead groups trucks, buses, and recreational vehicles into one category. Therefore, the PCE is an average value for all the types of vehicles (*7*).

Not all PCE research has focused on trucks traveling in a straight path. Although it is unclear what parameters were involved in obtaining the results, an Australian PCE methodology recommends using a combined value of 2.5 for a nonconflict turning truck and 3.9 for a conflict turning truck (*12*).

Although each researcher attempted to define a PCE value, it was not until later that a methodology was developed that included essentially all the factors that make up a PCE.

STUDY METHODOLOGY

General

In May 1987 a report by Molina et al. suggested that PCEs for light and heavy trucks traveling along a straight path should be 1.7 and 3.7, respectively (*5*). Their research gives strong reason to believe that current PCEs are low, but unfortunately their work did not evaluate the effect of trucks turning left at an intersection. Their methodology was the model for conducting this research into PCEs for left-turning trucks.

Study Model

The headway method is the most common method used for calculating PCEs. Equation 1 describes the difference between truck and passenger-car headways:

$$\text{PCE} = h_t/h_c \qquad (1)$$

where h_t is the headway of the truck, and h_c is the saturation flow headway of a passenger car.

Equation 1 describes the effect of the increased size of the truck and its lower acceleration characteristics. Although Equation 1 is the most common method used to calculate PCEs, it does not consider the generally slower discharge rate of trucks, which affects start-up lost time and saturation flow headways.

To account for the effect of the slower truck acceleration that propagates down the queue of vehicles, causing increased delay, a factor must be added to Equation 1. This additional factor, which includes start-up lost time, is perhaps one of the major differences from early PCE studies. The inclusion in the model of start-up lost time is intentional and was expected to yield higher PCEs than those found by other researchers.

The additional factor is the incremental increase in the headways caused by the truck. Not all of the incremental increase is caused by slower truck acceleration: some of the increase is a result of passenger cars shying away from the large truck rather than the physical impedance. The increase is measured to the point at which the vehicles following the truck are no longer impeded and are able to travel at a speed as if the truck were not present in the traffic stream.

Unfortunately, there is no simple method for directly measuring that incremental increase. However, as a substitute, the problem may be solved by measuring the discharge time of a queue of passenger cars with a truck in the queue and then comparing it with the discharge time of a queue of the same size, which consists only of passenger cars.

The differences between the light and dark bars in Figure 1 represent the incremental increased headway accruing to each vehicle

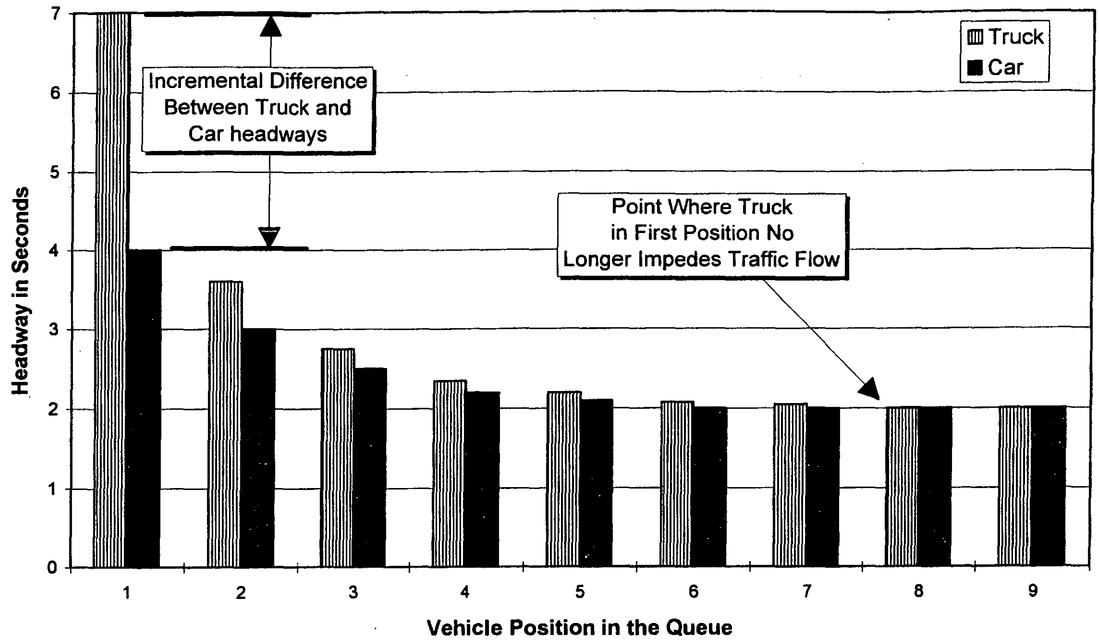

FIGURE 1 Theoretical difference between truck and passenger-car headways.

in the queue as a result of a truck being in the first position. In this example, the truck no longer impedes following vehicles at the eighth position. At that point, the headways between the two queues are essentially the same as if no truck were present. The sum of the incremental differences in discharge times between the two queues quantifies the total impact of the truck on the other vehicles in the queue (i.e., a passenger car queue with a truck in the first position versus a passenger car queue only).

By considering the incremental increase in headways, one can account for all the factors that affect the size of the PCE (truck size, acceleration, and driver behavior). In other words, the method accounts for the fact that the truck in the queue occupies more space than a passenger car and that the effects of the lower performance characteristics, coupled with driver behavior, propagate down the queue and cause a number of following vehicles to be delayed. Eventually the truck reaches the normal travel speed and the delay effects caused by the truck dissipate (*5*). At this point, the headways in the queue are essentially the same as the headways of a queue containing all passenger cars, except for the longer headway of the truck due to its longer length.

The entire theory is based in the assumption that only one truck is present in the queue at a time. Often this is not the case, but again, a direct method to account for additional trucks is not available. However, it is possible to quantify the impact of additional trucks by applying the same methodology. Even though the effect of additional trucks cannot be measured directly, it is unlikely that a second truck would double the PCE value. Judgment suggests that the truck that has the lower performance capabilities will control the PCE value. The other trucks following the control vehicle will at least be able to approach the speed of saturation headway as they cross the stop line. However, the effect of an additional truck on the moving queue due to its increased size and following driver behavior still remains.

Since it is not a simple matter to add the incremental increase in delay to Equation 1, a new equation was written that describes the desired effect. It is assumed that the PCE for a truck in a queue is a number greater than 1. Thus, the final equation that describes the effect of a truck in the traffic stream is shown in a simplified form (*5*):

$$\text{PCE} = [(\text{TT}_t - \text{TT}_c)/h_c] + 1 \quad (2)$$

where

TT_t = total discharge time of truck queue;
TT_c = total discharge time of passenger-car queue,
h_c = saturation flow headway of all-passenger-car queue;

In addition,

- PCEs are calculated with the location of the truck ranging from Positions 1 to 10,
- Headways are measured at the point where the rear wheels of the vehicle cross the stop bar,
- Saturation flow headway (h_c) is based on stable moving queues of passenger cars at this study location (h_c was found to be 2.0), and
- Vehicle queues contain an equal number of vehicles.

During their research, Molina et al. were able to obtain hundreds of truck samples from three intersections (*5*). The left-turn research for this study was conducted on a limited budget and under a time constraint that did not allow for a large study sample. Fortunately, Molina et al. did offer guidelines on the minimum size of the sample (i.e., number of queues) to ensure that the results would be statistically correct. For the truck data to be statistically valid, it was determined that each truck position being examined must have at least five observations (*5*). Therefore, if the examination was to include 10 positions and four truck types, the minimum number of observations would be 5 × 4 × 10 = 200, plus all the passenger-car data that could be obtained. All passenger-car queues needed at

least seven cars to be usable (*5*). In addition, traffic conditions needed to be at or near capacity (saturated) for the left-turn movement. Sporadic arrivals during the green indication would not give accurate results.

STUDY PROCEDURE

General

The study procedure essentially replicates the method used by Molina et al. during their analysis. The site used in the research was a diamond interchange located at 4500 South and Interstate 15 in Salt Lake City, Utah. The interchange was in a location where heavy trucks often used the facility. One nearby traffic generator was a concrete ready-mix plant. As a result, a large portion of the truck traffic consisted of multitrailer dump trucks, combination hopper trucks, and concrete mix trucks. The abundance of these "special vehicles" allowed an opportunity to calculate which standard truck class they most closely resembled in terms of PCEs. Figure 2 shows the special truck classes observed during the data collection period. Data were collected during good weather and daylight conditions on each side of the diamond interchange during the morning and evening peak periods, as well as during midday, when sufficient traffic volumes permitted. Grade at the location is level.

Equipment

Two methods were used to collect the raw data: on-site observation and videotape. The on-site observations were recorded using a personal computer (PC) and adapting the Traffic Data Input Program (TDIP) software (*13*). The software package was intended to be used in analyzing delays at stop-controlled intersections, but it was useful in recording the discharge times (headways) between successive vehicles. The software allowed the observer to start the count at the beginning of the left-turn green indication and record when the rear wheels of each vehicle in the queue crossed the stop bar.

At the start of the green indication, a specific key was depressed on the keyboard. As the rear tire of each vehicle crossed the stop line, a second key was pressed. Pressing the keys caused the times to be recorded in an ASCII file. After the complete observation of a queue, it was noted on a field sheet whether any trucks were present and, if so, the type, number of axles, queue position, and a brief description. Keeping accurate field records was essential since they would enable the identification of the data set that matched each queue.

With the video camera, the information was recorded on tape in the field and later extracted using the PC and the TDIP program. The camera was positioned so that the stop line and as much of the standing queue as possible could be seen clearly. Since the camera position did not allow the green signal indication to appear in the viewfinder at the same time as the stop line, a simple light tree was hard-wired into the signal controller and placed in the camera's field of vision to facilitate the precise determination of the beginning time of each left-turn movement.

Data Analysis

When all available headway information was recorded in the data files, each file was loaded into a spreadsheet program for analysis.

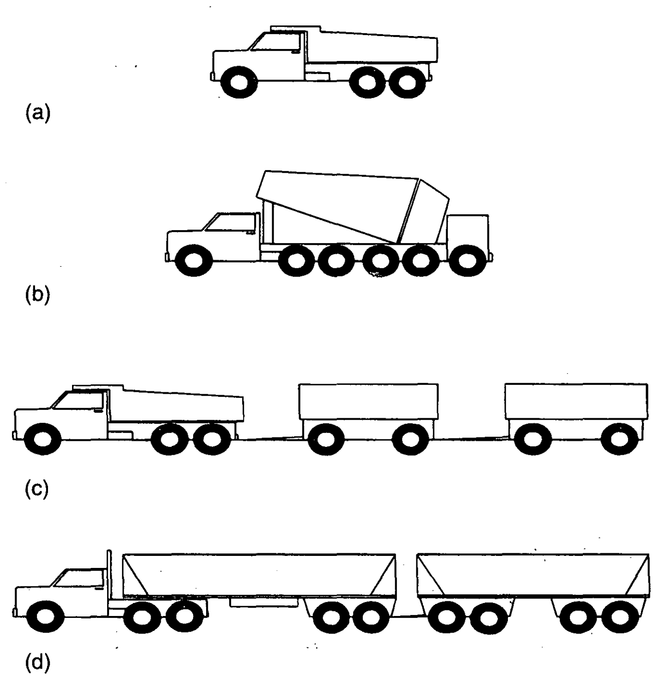

FIGURE 2 Special vehicle classes: *a*, three-axle dump truck; *b*, six-axle concrete mix truck; *c*, seven-axle dump truck with two trailers; *d*, nine-axle hopper truck with one trailer.

One column of the spreadsheet contained the times at the beginning of the green indications. A second column contained the times at which each vehicle in the queue discharged across the stop line.

The analysis procedure required that each start time be paired with the appropriate vehicle crossing times and that they be identified as to the type of truck involved, if applicable.

Once the time differences between vehicles were calculated, corresponding data sets were identified. In other words, there was one grouping for the all passenger-car queues, one for two-axle trucks in the first position, one for two-axle trucks in the second position, and so on for all trucks and their specific positions.

The next step was to compute average headways for each vehicle position in each grouping. For example, in the all passenger-car queues, the average headway was calculated for the first cars, the second, the third, and so forth. This same procedure was also done for every truck position in every different truck grouping. Unfortunately, headways for some of the truck types and some of the truck positions were not obtained because of insufficient data.

Referring to Equation 2, TT_t is the total discharge time for the truck queue being considered. It is measured as the sum of the headways from the start of the green indication to the point at which the first passenger car behind the truck reaches saturation flow headway. Figure 3 graphically illustrates the differences between the headways for some of the truck types in the first position. For the five-axle truck in the first position, saturation flow headway occurred at the seventh vehicle with the sum of the headways being 23.4 sec. The average headways were then applied to Equation 2 to determine a PCE for each vehicle class and position in the queue.

TT_c is the total discharge time for a passenger-car queue. It is measured as the sum of the headways from the start of the green indication to the same point as in the queue with the truck. In this example it occurred at the seventh vehicle, the sum being 16.0 sec.

The saturation flow headway (h_c) was already identified as occurring at the seventh vehicle; it is 2.0 sec.

Applying the equation for a five-axle truck in the first position yields

$$PCE = (23.4 - 16.0)/2.0 + 1 = 4.7$$

STUDY RESULTS

General

It was anticipated that the PCEs determined for left-turning trucks would be slightly higher than the PCEs determined by Molina et al. who examined trucks traveling in a straight path. The results from the data showed that PCEs were approximately as expected. Figure 3 shows that three-axle trucks compare closely to passenger cars. On the other hand, the heavy trucks take considerably longer to get moving.

PCEs versus Position in Queue

Table 1 gives the PCE for each truck class and position in the queue, as well as the number of truck queues in each data set. The results show that the highest PCEs occur with the truck in first position in the queue, and as the platoon of vehicles approaches saturation flow, the PCE reaches its minimum value.

It can be seen that the light trucks (two-axle truck, three-axle truck, three-axle dump truck, and six-axle concrete mix truck) have comparable PCEs. It is also evident that the heavy trucks (five-axle combination truck, seven-axle dump truck with trailers, and nine-axle combination hopper truck with one trailer) have about the same PCEs.

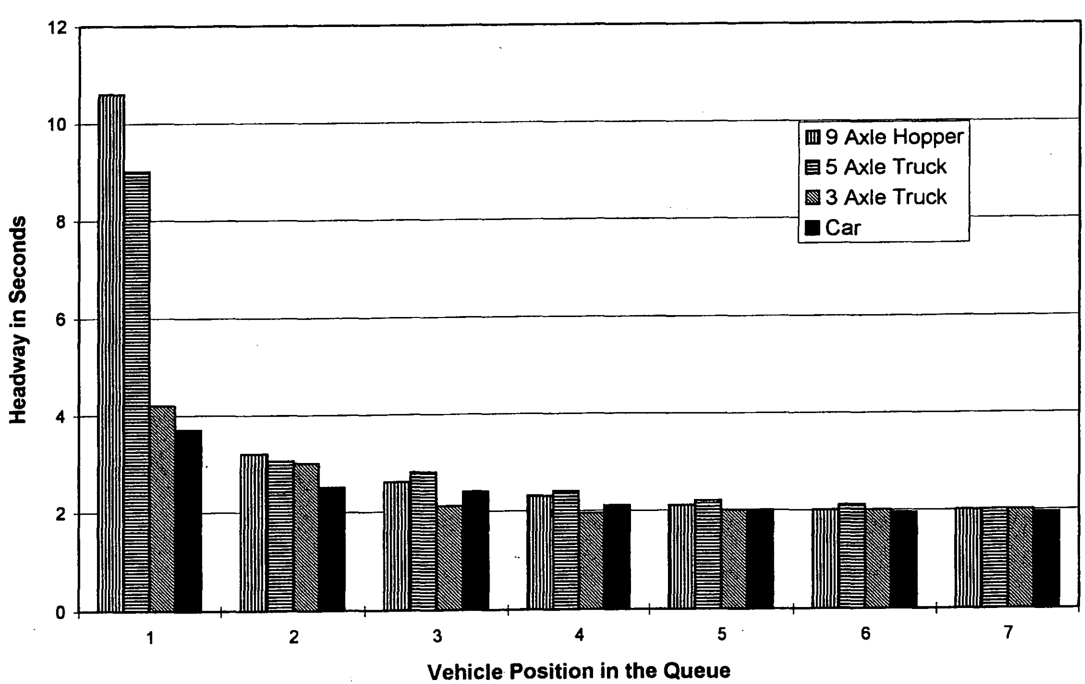

FIGURE 3 Headways for various trucks in first position versus passenger-car headways.

TABLE 1 PCEs versus Truck Position in Queue

Truck Class	Queue Position	Number of Observations	PCE
2-Axle Single	1	13	2
	2	12	1.8
	3	11	1.7
	4	14	1.7
	5	14	1.6
	6	11	1.6
	7-10	*	**
3-Axle Single	1	13	2.1
	2	11	2
	3	12	1.8
	4	11	1.7
	5	12	1.6
	6	11	1.6
	7-10	*	**
5-Axle Combination	1	17	4.7
	2	12	4.7
	3	13	4.5
	4	17	4.3
	5	12	4
	6-10	*	**
3-Axle Dump Truck	1	13	2.2
	2	*	*
	3	*	*
	4	12	1.7
	5	11	1.6
	6-10	11	1.6
7-Axle Dump Truck w/ 2 Trailers	1	14	5.7
	2	12	5
	3	11	4.1
	4	*	**
	5	11	3.5
	6-10	*	**
6-Axle Concrete Mix Truck	1	12	2.8
	2	13	2.5
	3	*	**
	4	*	**
	5	*	**
	6	11	1.7
	7-10	*	**
9-Axle Combination Hopper Truck w/ 2 Trailers	1	15	5
	2	12	4.9
	3	13	4.4
	4	*	**
	5	11	4.1
	6	11	4
	7-10	*	**

* Insufficient number of observations to calculate PCE.

** No PCE calculated due to insufficient number of observations.

Because of similarities in PCEs, the truck types were grouped into two categories. Grouping the PCEs is logical since it is doubtful that anyone performing a traffic count would have the resources to apply a separate PCE for each truck type and for each position in the queue.

For the location used in this research, it was appropriate to calculate a weighted average for both the light and heavy truck groups and include the special vehicles unique to the study site (Table 2). Doing so produced a left-turn PCE of 1.9 for the light trucks and a PCE of 4.5 for the heavy trucks. These values are averages for all queue positions. If this information is used elsewhere, the weighted average PCE should be based only on those types of trucks that use the facility and whether the intersection geometrics are similar to the study location. If the special trucks are excluded from the data set (i.e., not present), the weighted average left-turn PCE is 1.7 for light trucks and 4.4 for heavy trucks.

If the results are to be used in traffic applications other than at this location, note that certain geometric factors unique to this interchange are reflected in the results. The approximate inside radii for the left-turn movements were 15 to 18 m (50 to 60 ft). Interchanges with three lanes in each direction along the arterial road would probably have an even larger turning radius. The larger-radius turns should allow trucks to negotiate the turns at higher speeds, which would lower the PCE.

The PCEs reflect a mix of loaded and unloaded trucks. No rigid effort was made to note which trucks were carrying a load, but general observation of the traffic mix conditions indicates that about half the trucks were loaded.

A comparison of these results with those of Molina et al., who recommended using PCEs of 1.7 for light trucks and 3.7 for heavy trucks for a through movement on level grade, suggests that light trucks are relatively unaffected by the left-turn maneuver whereas heavy trucks are slowed by it. The difference may at first seem small, but if many trucks are in the traffic stream, using an inappropriate PCE can make a significant difference in capacity calculations.

APPLICATION OF RESULTS

General

The PCE results are intended to be used in computer modeling and analysis techniques that evaluate intersection capacity and level of service. The information is also expected to be helpful to traffic engineers who design, maintain, and operate signalized intersections. PCEs for left-turn movements at modern SPUIs appear to approximate those for through movements at intersections because of the much larger turning radii provided. Analysis of left turns at compressed diamond interchanges should reflect the higher PCEs resulting from the shorter-radius left turns. The left-turn PCEs determined in this paper are just that—PCEs for left-turning trucks with an inside radius of turn of 15 to 18 m (50 to 60 ft).

CONCLUSIONS AND RECOMMENDATIONS

General

The conclusions and recommendations in this paper are intended to serve as a model for further research. They are to encourage a procedure for obtaining more accurate truck influence information using relatively simple procedures and equipment.

Conclusions

- As initially expected, PCEs for trucks turning left are higher than those for trucks traveling in a straight path.
- Light trucks have only a small effect on the traffic stream because of their good performance characteristics. A low weight-to-horsepower ratio allows for the trucks to accelerate quickly up to saturation flow speed.
- Heavy trucks have a large influence on the traffic stream, especially when turning left, because of (*a*) their high weight-to-horsepower ratio, which causes them to take longer to accelerate, and (*b*) their limited ability to negotiate sharp turns. It was noted that after the heavy trucks did get moving, the PCE decreased noticeably.
- Concrete mix trucks and single-unit dump trucks closely resemble the PCE for lightweight trucks.
- Multitrailer dump trucks and hopper trucks with trailers have PCEs approximately the same as heavy trucks.
- Left-turning PCEs for standard light and heavy trucks should be 1.7 and 4.4, respectively.
- If many special trucks are present in the traffic stream, the above PCEs should be modified as described in this paper.

Recommendations

- More data collection and study are recommended to calculate PCEs for other specialty vehicles.
- Similar studies are recommended at SPUIs to allow further comparisons between interchange types.
- More studies are recommended to determine the effect on PCE values of two or more trucks in a queue.

TABLE 2 Weighted Average PCEs for Each Truck Class

Truck Class	Weighted Average PCE
2-Axle Single	1.7
3-Axle Single	1.8
3-Axle Dump Truck	1.8
6-Axle Concrete Mix Truck	2.4
5-Axle Combination	4.4
9-Axle Combination Hopper Truck w/ 2 Trailers	4.5
7-Axle Dump Truck w/ 2 Trailers	4.7

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