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16. Abstract

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17. Key Words

Passenger Car Equivalents, Large
Trucks, Intersection Capacity,
Arterial Streets, Signalization.

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PASSENGER CAR EQUIVALENCIES FOR LARGE TRUCKS AT SIGNALIZED INTERSECTIONS

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Research Report 397-2
Research Study Number 2-18-85-397
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Sponsored by the

Texas State Department of Highways and Public Transportation
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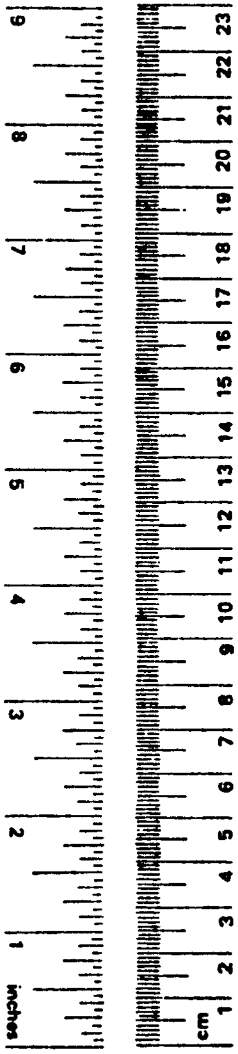
May 1987

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843

METRIC CONVERSION FACTORS

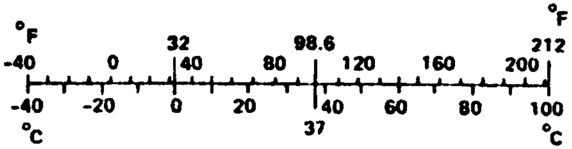
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

ABSTRACT

The objective of this report was to develop passenger car equivalents (PCE's) for trucks traveling straight through a level, signalized intersection based on vehicle type and position of vehicle in queue. Data were collected at three different sites and included: length of queue, classification of vehicles, and total travel time for each vehicle measured from start of green to the time the vehicle's rear axle crossed the stop line. An analytical model was developed to estimate PCE values based on total travel time and vehicle type. Using this model, PCE values were developed for 2-axle, single-unit; 3-axle, single-unit; 4-axle combination; and 5-axle combination trucks. An approximate equation was subsequently developed to predict the PCE's for large vehicles based on the number of axles. This research concluded that position of vehicle in queue significantly affects the PCE of the 5-axle trucks but does not affect the PCE value of the smaller single-unit trucks. It was further concluded that the PCE value used to calculate the heavy vehicle adjustment factors (Table 9-6) in the 1985 Highway Capacity Manual is inadequate for the large 5-axle combination trucks. Therefore, the PCE values generated from this study were condensed into two values; one for light trucks and one for heavy trucks. Furthermore, the heavy vehicle adjustment factor equation was modified to analyze the effects of light and heavy trucks separately using the recommended PCE values developed in this report.

KEY WORDS: Passenger Car Equivalents, Large Trucks, Intersection Capacity, Arterial Streets, Signalization

EXECUTIVE SUMMARY

The presence of large trucks at signalized intersections has a detrimental effect on the intersection's capacity. This effect must be taken into account in the signal timing process in order to optimize signal operation and reduce motorist delay. Recognizing this need, the State Department of Highways and Public Transportation (SDHPT) sponsored a cooperative research project with the Texas Transportation Institute (TTI) entitled, "Longer and Wider Trucks on the Texas Highway System." This report discusses the portion of the project concerned with the impacts of large trucks on the capacity of a signalized intersections.

This research determined the delay effects of a truck on a queue of vehicles as the position of the truck within the queue varied. The method proposed to analyze this effect was to measure the time required for a queue composed of passenger cars and one truck to cross the stop line as compared to the time required for the same size queue composed entirely of passenger cars to cross the same point. This approach was aimed at obtaining the total effect of a truck on a queue of passenger cars.

The literature indicated three factors that primarily influence the size of the PCE for a truck at a signalized intersection. Firstly, the PCE value will increase as the length of vehicle increases since the vehicle is physically occupying more roadway space which would otherwise be available to passenger cars. Secondly, the acceleration characteristics of a truck will also influence the size of the PCE. As the acceleration rate increases, the PCE value will decrease since the truck will delay the passenger cars less, and of course, the converse will result in a higher PCE value. The final factor that was found to affect the PCE is the behavior of motorists. The available information seems to indicate that drivers "shy away" from large trucks. This results in drivers following further back from the truck which increases the delay on the passenger car drivers which, in turn, results in a higher PCE value.

The development of PCE's for signalized intersections was examined in depth. The most common method used for developing the PCE at signalized intersections was found to be the headway method which assumes all of the delay due to the large trucks can be accounted for in the truck's headway. The headway method takes the ratio of the average headway for a truck and passenger car as the PCE for the truck. The PCE values developed for large trucks using this method were found to range between 1.6 to 2.3.

This research developed an equation to determine the PCE of a truck based on the total delay it inflicted on all the vehicles traveling behind it. The equation is based on the difference in total travel time between a queue with a truck in it and queue of all passenger cars. It has the following form:

$$PCE_{j_k} = [(TT_{j_k,b_i} - TT_{b_1,b_i})/h_b] + 1$$

where:

TT = total travel time measured from start of green, sec;
j = truck type;

k = position of the truck in the queue;
b_1 = passenger car in position one in the queue;
b_i = passenger car in position "i" in the queue; and
h_b = base passenger car saturation flow headway, sec.

In this equation, the PCE value was calculated at vehicle position "i" where i is the last passenger car behind the truck that has an incremental increase in delay due to the truck. Beyond this vehicle position, no additional delay is incurred by the queue of passenger cars.

In developing the PCE values, data collected for each vehicle included: the position of vehicle in queue, the size of queue the vehicle was in, the type of vehicle, and the total travel time of the vehicle from its position in queue to the stop line. This measurement was referenced to the onset of green and was measured to the point in time when the vehicle's rear axle crossed the stop line. Regression equations were developed to predict the total travel time for the vehicle of interest and the succeeding string of passenger cars. A regression equation was also developed for each vehicle type as the position of the vehicle in queue varied. As a result, PCE values were developed according to vehicle type and position of vehicle type in queue. The resulting PCE matrix was then condensed into a single PCE value for a light truck and a heavy truck class. The light truck class was selected to represent the small delivery trucks (i.e., single-unit trucks) while the heavy truck class represents the large, heavily loaded trucks (i.e., combination trucks with 5-axles or more). The PCE values for these two classes are given in the following table.

Average PCE Values for Final Two Truck Classes.

Truck Type	PCE Value
Light Truck	1.7
Heavy Truck	3.7

Once the PCE value for the two truck classes was developed, the heavy vehicle adjustment factor equation found in the 1985 HCM was modified to analyze the effects of the two truck types separately. A comparison of the capacity reduction resulting from the PCE values used in the 1985 HCM and the values recommended in this study reveal a significant difference in the estimation of an intersection's capacity. In some cases, the difference in capacity between the two methods was found to be as high as 17 percent.

An examination of the PCE values per truck class found a relationship between number of axles and the PCE value of a truck. Using this relationship, a regression equation was developed to predict the PCE value based on the number of axles. The equation used to predict PCE values has the following form:

$$PCE = 1.08 + 0.10*AXL2$$

However, this equation is limited in that it is only applicable to large vehicles. In other words, the data collection system used to obtain the average number of axles must be able to screen out passenger cars.

IMPLEMENTATION

The findings of this study should be helpful to SDHPT traffic engineers who plan, design, operate, and maintain signalized intersections. Use of the PCE values developed in this research will result in improved timing plans and substantially reduce delay costs at the approximately 12,000 signalized intersections in the State of Texas. It is estimated that, on the average, each intersection services 10,000 vehicles per day, 2 percent of which are large trucks. Thus, 2,400,000 large truck, traffic signal interactions occur on a daily basis. It is also estimated that by using a PCE of 3.7 for large trucks, the average delay per interaction will be reduced by 5 seconds. This translates to a cost savings of over $13,000 per day (3300 hours per day at $4 per day) or $3,400,000 per year (260 working days per year) for Texas motorists. These benefits can be provided at no cost to the public by simply incorporating the research results into ongoing signal retiming projects. As the project cost was approximately $20,000, the benefit to cost ratio for the 5 years it will take to retime the majority of the signals in the state is more than 500 to 1.

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DISCLAIMER

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I. INTRODUCTION

BACKGROUND

The signalized intersection is the most serious capacity constraint along an urban street. It is at this junction where two roadways share the same section of road and the capacity of both is reduced. Thus, improving the capacity and level of service (LOS) of the street system requires improving the efficiency of the intersections. This can be accomplished by geometric modifications (i.e., adding turning lanes, channelization, widening the intersection, etc.) and/or operational improvements (i.e., improving signal timing, improving progression, adding or deleting phases, etc.). Unfortunately, geometric improvements are not always feasible or practical due to physical and economical limitations. As a result, the traffic engineer is oftentimes left with only one course of action which is to improve the operational efficiency of the intersection.

Increasing the intersection's capacity by improving its operation may be realized through means such as signal timing optimization and improving progression between intersections. The methodology used to calculate the increase in capacity as a result of these improvements is based on making adjustments to some "ideal" saturation flow rate so as to reflect the prevailing traffic conditions. The "ideal" saturation flow rate for signalized intersections is based on a traffic stream consisting solely of passenger cars and is usually taken to be 1,800 passenger cars per hour of green time per lane (pcphgpl). This ideal flow rate is adjusted for conditions that are not ideal through the use of eight adjustment factors found in Chapter 9 of the 1985 Highway Capacity Manual (HCM) (1).

The introduction of a truck into the traffic stream reduces the "ideal" saturation flow rate of a particular intersection approach due to the additional roadway space occupied by trucks and their lower performance capabilities with respect to passenger cars. The 1985 HCM (1) accounts for the presence of trucks by multiplying the "ideal" saturation flow rate by a heavy vehicle adjustment factor. This factor is based on percentage of trucks and the number of passenger cars displaced by the truck, commonly known as the truck's passenger car equivalent (PCE). As the heavy vehicle adjustment factor can significantly effect an intersection's estimated capacity, it is critical that the traffic engineer uses accurate values of both components of the adjustment factor in capacity calculations. The first component, the percentage of trucks, can be easily measured in the field whereas the second component, the PCE can not.

STUDY PROBLEM STATEMENT

Since the introduction of the term PCE, much research has been done in the area. PCE's have been developed for virtually every type of facility from urban freeways, to two-lane two-way rural highways, and to signalized intersections. Past studies have yielded various estimates for the PCE value of a truck on a given facility. The reason for this variability can be directly attributed to the lack of a consistent definition of equivalency. The basis for this inconsistency lies in the lack of understanding of how trucks affect both the operating characteristics of individual vehicles and the overall performance of the traffic stream (2).

It is well known that a truck has a negative impact on the capacity of a signalized intersection. The problem is determining a way of measuring the size of this impact, and determining the number of vehicles affected by it. Therefore, this research attempted to quantitatively measure the differences in operating characteristics between passenger cars and trucks traveling straight through a level, signalized intersection. These data were used to develop PCE's for trucks at signalized intersections based on truck type and position in queue. As a result, the principal vehicle operating characteristics of interest were the vehicle's acceleration rate and its position within the queue. Turning movements, roadway grades, and other factors affecting the PCE were not examined due to time and financial constraints of the study.

STUDY OBJECTIVES

Two specific research objectives of the overall study are addressed in this report. These objectives are:

1. Develop a methodology to determine the effect of a truck on a queue of passenger cars.
2. Using the aforementioned methodology, develop PCE's for trucks at signalized intersections based on truck type and position of the truck in queue.

REPORT OVERVIEW

Past studies show a need to examine the effects of large truck operation on the capacity of signalized intersections. This report quantifies the effects of large trucks through the use of PCE's. The results presented herein are limited by the data collected, statistical analysis conducted, and practical observations made during the course of this study. The following is an overview of this report.

Chapter 2 presents a literature review of the factors affecting the PCE of a truck at a signalized intersection along with previous methods used to calculate PCE's. Based on the finding of the literature review and engineering judgement, a new model is developed to calculate the PCE of a truck based on truck type and its position in the queue.

Chapter 3 describes the study procedure. The site selection and data collection are discussed therein. A discussion of the statistical technique used to analyze the data is also given in this chapter.

The next chapter deals with study results and presents the development of the PCE's. Plots of total travel time versus position of the vehicle in queue are presented for each truck type analyzed. The implications of these PCE values on the capacity of an intersection are also discussed. In addition, an approximate method to calculate the PCE of a truck based on its number of axles is presented.

Major findings and conclusions are listed in Chapter 5. Based on these results, a list of recommendations to improve current practice is given. Recommendations for future research in the development of PCE's at signalized intersections are also contained in this chapter.

II. LITERATURE REVIEW

An exhaustive literature review was conducted to search for references pertaining to passenger car equivalents (PCE). The first section deals with the factors that affect the PCE of trucks at signalized intersections. The next section reviews the methodologies used to calculate PCE values at signalized intersections.

After reviewing the literature, a model was developed to predict the PCE for any vehicle type in any position in queue. This model was based on the additional delay a truck caused a queue of passenger cars.

FACTORS AFFECTING PASSENGER CAR EQUIVALENTS

The methodology used to compute the capacity of a signalized intersection is based on a traffic stream containing passenger cars only (1). Intuitively, the introduction of trucks into the traffic stream will negatively affect the capacity of the intersection. Therefore, the presence of trucks must be accounted for through the use of PCE's. The literature reports three main factors that influence the size of the PCE at signalized intersections. These factors are length of vehicle, acceleration characteristics, and driver behavior.

The effect of the first variable, length of vehicle, is obvious. As the length of vehicle increases, more space will be occupied; hence the PCE will increase. Past research has found that large 5-axle trucks are on the average about 3 times longer than a standard passenger car (3, 4, 5).

The second variable, acceleration characteristics, is a surrogate for vehicle performance. If a passenger car and a truck performed identically (i.e., had the same acceleration rate) the PCE of the truck would be primarily the result of its greater length. However, past research indicates that passenger cars accelerate between 2 to 3 times faster than trucks (3, 4, 5). This will tend to increase the value of the PCE. It should be noted that on level terrain over a period of time, the speeds of trucks will eventually approximate those of passenger cars. Trucks may, in fact, accelerate until they close the gap (i.e. headway) between themselves and the preceding vehicle (2, 6).

Finally, the behavior of passenger car drivers following a truck was examined. The results from one study indicate that the presence of a truck immediately in front of a passenger car tends to cause the drivers of automobiles to shy away, thereby increasing the PCE value (2).

PASSENGER CAR EQUIVALENTS FOR SIGNALIZED INTERSECTIONS

The term "passenger car equivalent" was introduced in the 1965 HCM (7) and 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." It goes on to state that at signalized intersections, the effects of trucks on capacity varies greatly depending on the type of vehicle, its weight/horsepower ratio, and its size and turning characteristics. However, at this time, very little was known about the individual effect of each vehicle's characteristics. Therefore, the 1965 HCM (7) provided an "all-inclusive" adjustment factor to the ideal saturation flow rate. This factor appears to have been calculated with a PCE value of 2. This assumption is supported by the claim that a truck under the best conditions is equal to two passenger cars (7).

Since the 1965 HCM (7), there has been much research done in this area. Webster and Cobbe (8) adjusted for the effects of different vehicle types on the saturation flow of an intersection by assigning each vehicle type a PCE value. A straight-through heavy or medium goods vehicle was assigned a PCE value of 1.75. Miller (9) developed PCE's for through vehicles at intersections based on the additional headway a truck would require when compared to a passenger car. This was one of the first references to define equivalencies in quantitative terms. Miller found that a commercial vehicle required an additional 1.79 seconds to cross the stop line. Dividing the average headway of a truck by the average headway of a passenger car resulted in a PCE value of 1.85. Carstens (10) also used the headway approach to develop PCE's. Headways were measured from front bumper to front bumper (known as leading headway). The average headways for a passenger car and truck were found to be 2.29 seconds and 3.74 seconds, respectively. The ratio of the two (1.63) was defined as the truck's PCE where a truck was defined as any vehicle having more than four tires.

Branston and van Zuylen (11) measured the lagging headway of "saturated" vehicles as they crossed the stop line. A saturated vehicle was one that came to a complete or near stop in the queue before proceeding. The authors developed regression equations from field data based on two different counting schemes, synchronous and asynchronous. The synchronous and asynchronous methods yielded PCE's for straight-through trucks to be 1.59 and 1.74, respectively. Of the two methods, the asynchronous one was recommended because it did not require additional manipulation to correct for biases as did the synchronous method. In a later work, Branston (12) used the same technique to develop additional PCE's. For vehicles traveling straight through a level intersection, regression equations were developed from data based on the departure rate of vehicles and the length of the counting period. PCE values for medium trucks (two-axle) and heavy trucks (three axles or greater) were found to be 1.35 and 1.68, respectively. However, it must be noted that no data for trucks with five or more axles were collected. This suggests that the PCE values reported may be somewhat low for large trucks. An interesting finding of this research was that PCE's increased with increasing flow rate. This means that the PCE value fluctuated throughout the day. Holland (13) examined the effects of trucks on four signalized intersections in Dublin. Using the headway method, he calculated a PCE value of 2.26 for a truck where a truck was any vehicle with more than six tires.

A 1980 study calculated the delay for vehicles arriving at an intersection based on the difference in time needed for a single car to travel through the intersection from some point before the stop line to some point after the stop line and the time to travel the same distance at normal running speeds. The delay was calculated using actual data collected at six intersections and also estimated using a simulation model. PCE's were then developed for various vehicle types based on the ratio of the total delay measured in the field to the average delay for an all-passenger-car queue estimated by the simulation model. The results showed that single-unit trucks had a PCE value of 1.6 and tractor-trailers had a PCE of 2.8 (14).

Hu and Johnson (5) identified several factors that influenced PCE's at signalized intersections. These factors are:

1. truck percentage,
2. type of traffic control,
3. truck acceleration,
4. number of approach lanes, and
5. driver behavior.

Due to the complexity of the interrelationship of the variables and the lack of available data, the authors developed a simplified model based primarily on truck size and acceleration characteristics, and equal densities between the mixed and basic streams. The model has the following form:

$$PCE = 1 + (n + 1)[\sqrt{(R)} - 1] \qquad [2.1]$$

where:

n = number of passenger cars behind the truck; and
R = ratio of average acceleration rate of a passenger car to that of the truck.

The value for n is calculated using a probabilistic distribution of the number of trucks in N vehicles where N is the number of vehicles stopped per cycle.

The major drawbacks of this model are that it can only deal with one truck type at a time and at multilane intersections, passenger cars are assumed not to avoid trucks when selecting a lane. This latter shortcoming will tend to overestimate the PCE values (5).

The 1985 HCM (1) retains the same general methodology as its predecessor to account for the effects of trucks on the capacity of signalized intersections. A heavy vehicle adjustment factor (f_{HV}) is used to account for the extra space needed by trucks and their slower acceleration capabilities with respect to passenger cars. Although not reported, the PCE value used to arrive at the adjustment factor can be calculated using the following equation:

$$f_{HV} = 1/[1 + P_T(PCE - 1)] \qquad [2.2]$$

where:

PCE = passenger car equivalent;
f_{HV} = heavy vehicle adjustment factor; and
P_T = percent trucks.

Using the values in the heavy vehicle adjustment factor table [Table 9-6 in the 1985 HCM (1)], the PCE was calculated to be 1.5 and remains constant as the percent of heavy vehicles increases from 0 to 30. However, a heavy vehicle is defined as any vehicle having more than four tires and includes trucks, recreational vehicles, and buses. Therefore, the PCE value used to calculate this factor is not the PCE value for a truck but probably the average of the PCE values for all types of heavy vehicles operating at signalized intersections.

The Canadian Capacity Guide for Signalized Intersections (15) presents PCE's for various vehicle types developed from a least squares optimization procedure that reflects the individual vehicle type's composite effect on the traffic stream. The results from this study indicate a PCE value for a single-unit truck of 1.5 and for a combination truck of 2.5, or 3.5 if heavily loaded.

MODEL DEVELOPMENT

Traffic flow departing from a signalized intersection is depicted in Figure 1. When the signal indication turns from red to green, driver must first react to the change by taking his/her foot off the brake and placing it on the accelerator before proceeding. Consequently, the first vehicle's headway is relatively large with respect to the rest of the queue and its corresponding flow rate is low. When the second vehicle crosses the stop line, its headway is smaller than the first because the driver's perception/reaction (P/R) time partially overlaps the first driver's P/R time and the vehicle has more distance in which to accelerate. It follows that the third vehicle's headway is shorter than the second's for the same reason. After "N" vehicles pass, the effect of the initial reaction to the signal change has dissipated. At this point, all successive vehicles within the queue will have approximately the same headway and the saturation flow will reach its maximum value (1, 3). The total additional time required for the first few vehicles to cross the stop line due to perception/reaction and vehicle acceleration is known as start-up lost time, l_s, as shown in Figure 1. Greenshields et al. (16) found that the headways of successive saturated vehicles were approximately constant after the fifth vehicle where a saturated vehicle was one that arrived on red or arrived on green and came to a complete stop before proceeding through the intersection. Similarly, Leong (17) found that a constant headway occurred after the fourth vehicle in queue. This relationship is graphically depicted in Figure 2.

In determining the capacity of a signalized intersection, it is assumed that all vehicles in the traffic stream are identical and depart at a constant saturation flow headway (11). However, this is not true as there are many types of vehicles in the traffic stream whose different performance capabilities cause their headways to be vastly different from one another. To correct for this discrepancy, the saturation flow rate is expressed in terms of straight-through passenger car equivalents. In other words, each vehicle type is converted into the equivalent number of passenger cars it displaces.

There are two types of methodologies used to estimate PCE's at signalized intersections. The first method involves simulating the intersection and running a regression equation on the results. However, simulation requires that the model be accurately validated for the range of conditions studied. The second method, known as the headway method, involves measuring the actual discharge headways of the various vehicle types in the field and running a regression analysis on the resultant data set. This method seems more appropriate since the data used for the regression analysis is actual data and not generated data from a simulation model.

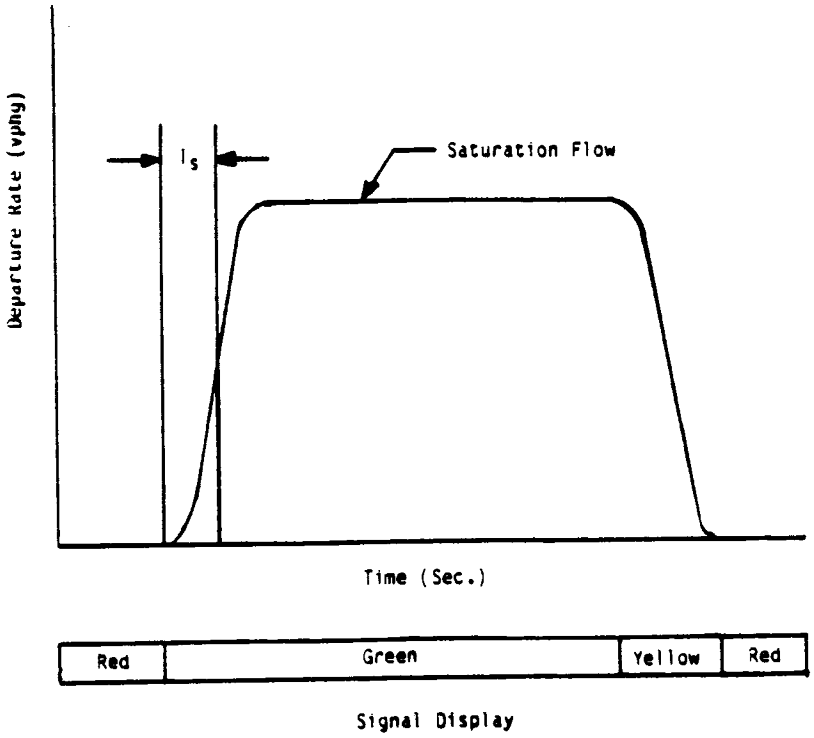


Figure 1. Departure Process at a Signalized Intersection.

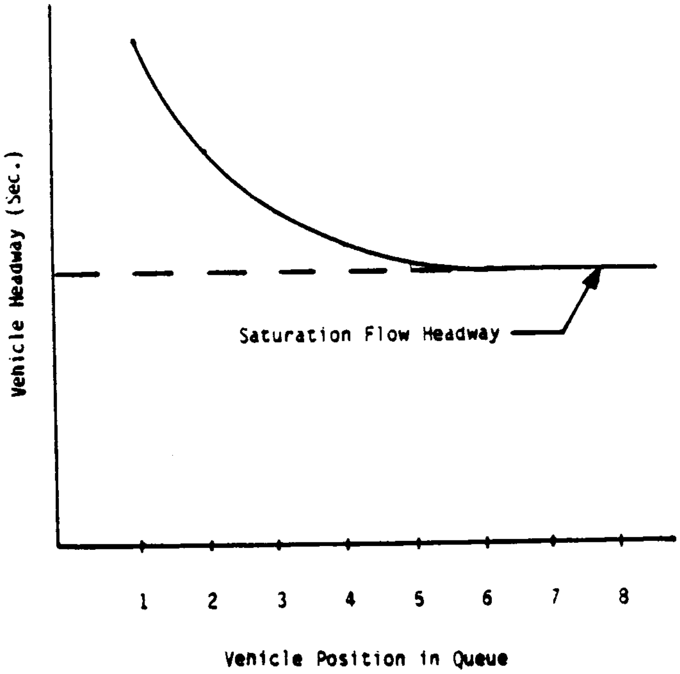


Figure 2. Headway of Vehicles in Queue.

The headway method is the most common method used to determine the PCE value of trucks and other vehicle types at signalized intersections (5, 10, 11, 12, 13). Headways are collected for all saturated vehicles as they cross the stop line and the relationship between headways and vehicle type modeled using a regression equation. The values predicted by the regression analysis are then used to generate the PCE values using the following equation:

$$PCE_i = h_i/h_b \qquad [2.3]$$

where:

PCE_i = PCE for vehicle i;
h_i = headway of vehicle of interest; and
h_b = saturation flow headway of passenger car.

Since the primary concern of this research is to develop PCE's for trucks, Equation 2.3 can be modified to:

$$PCE_t = h_t/h_b \qquad [2.4]$$

where h_t represents the truck's headway and everything else remains the same.

Equation 2.4 relates the effect of the operating characteristics and vehicle length of a truck to that of a passenger car. However, this equation does not measure the delay caused by a truck on the passenger cars immediately behind it. In other words, it does not account for the fact that the effect of a truck's lower acceleration capability will propagate down the queue and cause a number of the passenger cars following behind the truck to be delayed. Eventually, this additional delay will dissipate as the truck reaches the normal speed of the traffic stream at which time the headways of the passenger cars behind the truck will be the same as the headways of the passenger cars in an all-passenger-car queue. For example, the effect of a truck in the first position in queue can be expressed as follows:

$$\Delta H = \sum_{n=2}^{i} (\Delta h_n) \qquad [2.5]$$

where:

ΔH = the total additional delay to the queue by the truck;
n = position in queue of a passenger car following the truck;
i = position of last passenger car affected by the truck; and
Δh = the incremental delay to a passenger car due to the truck.

Therefore, Equation 2.4 needs to be modified to reflect this additional effect. The resulting equation is:

$$PCE_t = (h_t + \Delta H)/h_b \qquad [2.6]$$

Unlike h_b and h_t which are relatively easy to measure in the field, there is no known method of directly measuring ΔH. Determining the value of ΔH would require measuring the incremental increase in the headways of the succeeding passenger cars behind the truck and knowing how many passenger cars are affected by the truck. To circumvent this, a better method would be to measure the total travel time of a queue of passenger cars with a truck in the queue and compare it to the total travel time for the same size queue consisting solely of "i" passenger cars. The "i"th passenger car is the queue position of the last passenger car behind the truck which experienced an incremental increase in delay due to the truck's lower acceleration rate. After the "i"th passenger car, succeeding passenger cars in the queue will not experience additional delay. This relationship is graphically depicted in Figure 3 in which the travel times for an all-passenger-car queue are compared to the travel times for a queue of passenger cars with a truck in position one. Therefore, to make use of this relationship the PCE equation needs to be restated in terms of total travel time.

The total travel time for a passenger car in position "i" with a truck at the front of the queue is given by the equation:

$$TT_{t_1,b_i} = L_t + h_t + \sum_{n=2}^{i}(h_{bn}) + \sum_{n=2}^{i}(\Delta h_n) \qquad [2.7]$$

where:

TT = total travel time measured from start of green, sec;
t_1 = truck in position one in queue;
b_i = passenger car in position "i" in queue; and
L_t = total lost time for the queue containing a truck.

Altering this equation for an all-passenger car queue would yield:

$$TT_{b_1,b_i} = L_b + \sum_{n=1}^{i}(h_{bn}) \qquad [2.8]$$

where:

b_1 = passenger car in position one in queue;
b_i = passenger car in position "i" in queue; and
L_b = lost time for the all-passenger-car queue.

Equations 2.7 and 2.8 imply that the lost times for a queue with a truck and an all-passenger-car queue are different. Since lost time is a function of driver perception and reaction to the signal change and vehicle acceleration, the lost time of a truck with respect to a passenger car would only be different because of the different operating characteristics of the two vehicles. Therefore, truck lost time, L_t, will be refined as:

$$L_t = L_b + h_a \qquad [2.9]$$

where:

h_a = incremental lost time due to a truck being in the queue.

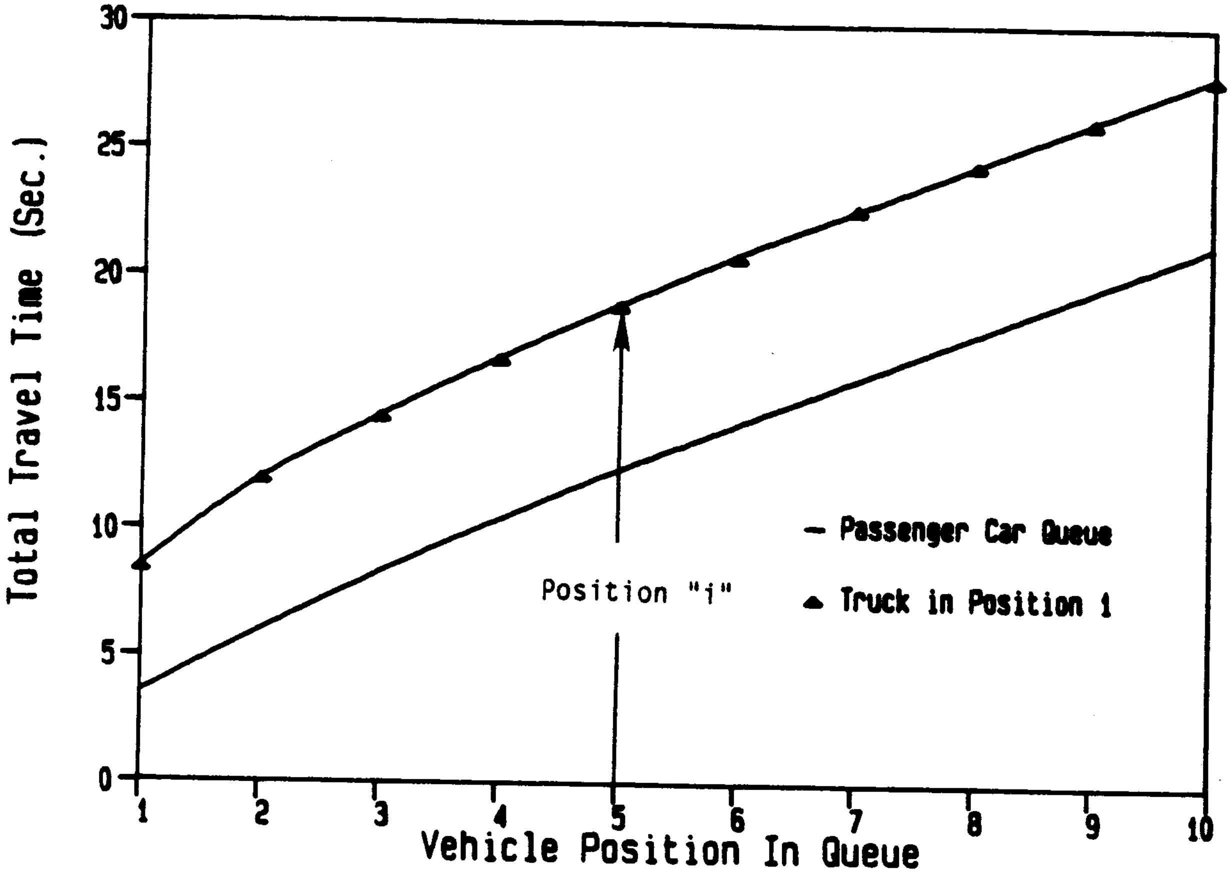


Figure 3. Travel Times for a Queue of All-Passenger Cars and a Queue of Passenger Cars with a Truck in Position 1.

Since this incremental lost time is, in fact, an effect of the truck and adds delay to the queue, it can be considered part of the total truck effect ΔH. Therefore, Equation 2.5 can be modified to include h_a as follows:

$$\Delta H = \sum_{n=2}^{i} (\Delta h_n) + h_a \qquad [2.10]$$

Substituting Equations 2.9 and 2.10 into Equation 2.7 yields:

$$TT_{t_1,b_i} = L_b + h_t + \sum_{n=2}^{i} (h_{bn}) + \Delta H \qquad [2.11]$$

Rewriting equation 2.8 as follows:

$$TT_{b_1,b_i} = L_b + h_b + \sum_{n=2}^{i} (h_{bn}) \qquad [2.12]$$

Substituting Equation 2.12 into 2.11 and solving for ΔH yields:

$$\Delta H = TT_{t_1,b_i} - TT_{b_1,b_i} + h_b - h_t \qquad [2.13]$$

Finally, substituting Equation 2.13 into 2.6 will result in the following:

$$PCE_t = [(TT_{t_1,b_i} - TT_{b_1,b_i})/h_b] + 1 \qquad [2.14]$$

Therefore, PCE's are based on the difference between the total travel time for the last passenger car affected by the truck and the total travel time for a passenger car in the same position in an all-passenger car queue. Since the incremental effect of the truck has dissipated at this vehicle position, PCE values calculated from the travel times of any succeeding vehicles should remain constant if "i" really is the last vehicle affected.

Equation 2.14 can be modified to determine the PCE for any truck type in any position in queue. However, this equation implicitly assumes that there is only one truck in the queue. If there is more than one truck in the queue, the additional travel times produced by the extra truck(s) will result in a larger travel time. The additional travel time produced by a second truck will result in larger delays, but not necessarily twice the delay produced by one truck. Furthermore, the PCE value is affected by the position of the trucks in the queue. To avoid reporting results for all possible combination of trucks in various positions within queue, which would have little practical use, PCE's are generated for only one truck in a queue with the position of the truck varying from one to ten. Therefore, if the truck is in a queue position other than the first, the vehicles in front of the truck must be passenger cars for the results to be valid.

Figure 4 illustrates the relationships between the arrival times of a queue of passenger cars with a truck in the first position; a queue of passenger cars with a truck in the fifth position; and a queue consisting solely of passenger cars. The difference in travel times at queue position "i" is the PCE of the truck. Notice that the "i"th position is not the same for the two truck queues. The general form of the equation used to calculate the PCE is:

$$PCE_{j_k} = [(TT_{j_k,b_i} - TT_{b_1,b_i})/h_b] + 1 \qquad [2.15]$$

where:

j = type of truck (i.e., S.U., 5-axle, etc.); and
k = the position of the truck in the queue.

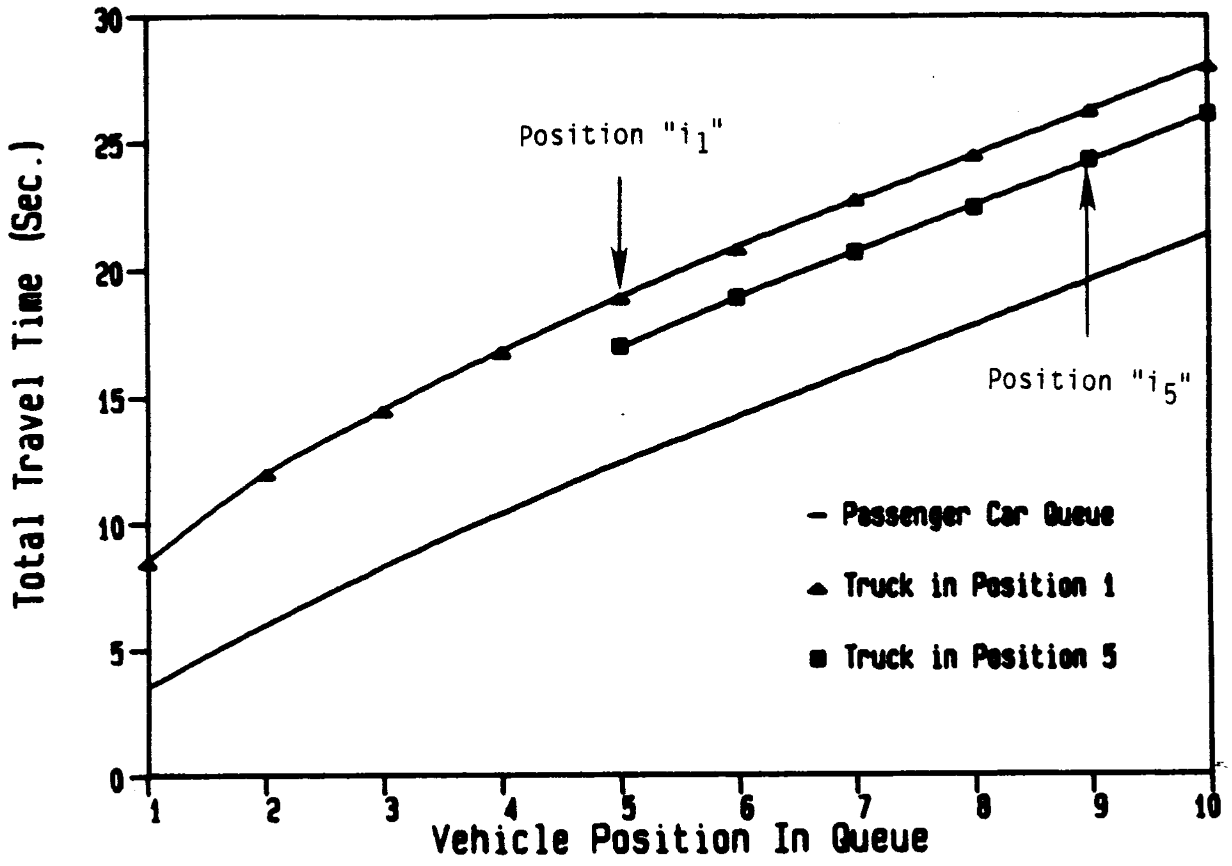


Figure 4. Travel Times for a Queue with a Truck in Position 1 and a Truck in Position 5.

III. STUDY PROCEDURE

BACKGROUND

The objective of this research was to study the effects of trucks on the delay at signalized intersections. However, delay is a difficult parameter to measure; therefore, the intervehicular spacing (i.e., headway) was measured as a surrogate for delay using a data collection system developed at the Texas Transportation Institute (TTI). The data used in this research were collected at three sites in Texas.

The following sections describe the automatic data collection system, the selection of the study sites, the data collection process, and the data analysis procedures.

AUTOMATIC DATA COLLECTION SYSTEM

The traffic flow data were collected using the automatic data collection system illustrated in Figure 5. The main component of this system was a Golden River Corporation Environmental Computer (EC). Other components of the system included: a 6-foot by 6-foot temporary inductive loop, a temporary roadway instrumentation switch (tapeswitch), a loop box, a photoelectric cell, and a Zenith Z-170 PC microcomputer. This system was used to measure the following variables for each vehicle:

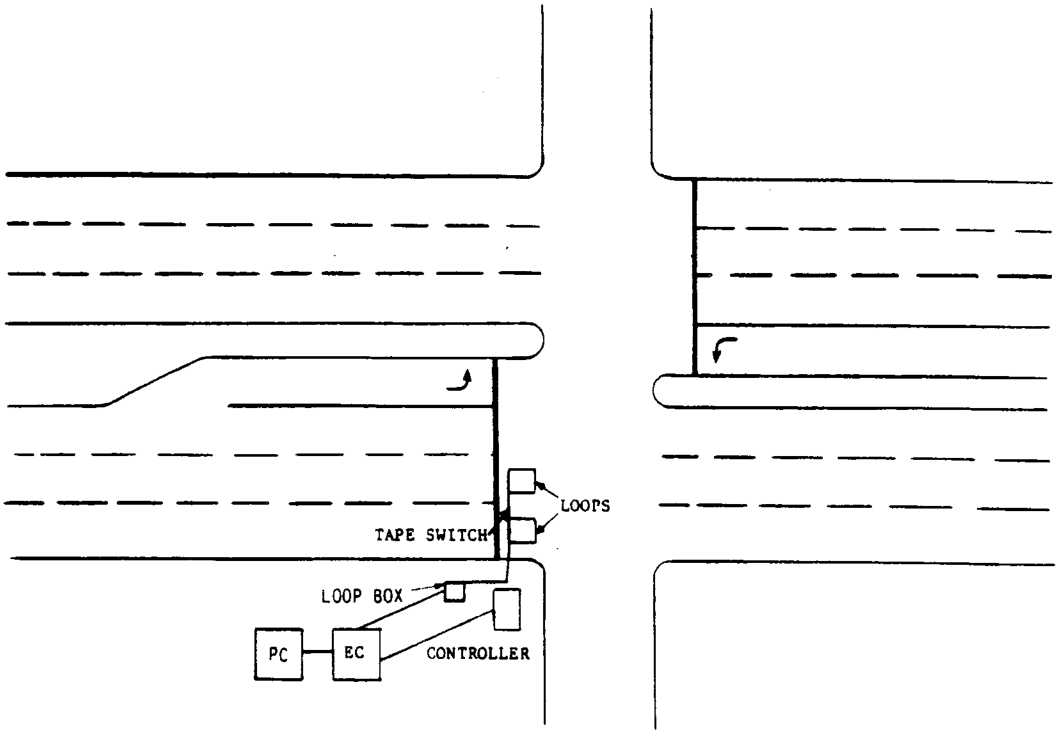
1. Elapsed time from the start of green;
2. Occupancy time; and
3. Number of axles.

The loop and tapeswitch inputs were used concurrently to classify vehicles by counting the number of axles while the loop was occupied. The in-house built loop box contained a loop detector card and a power supply housed in a small waterproof box. Its purpose was to amplify the signal from the loop before transmitting it to the EC. The photoelectric cell was used to provide time-base coordination between the traffic signal and the EC. Finally, the Zenith was used to process the field data using a software package developed at TTI. The processed data were then stored on 5 1/4 inch floppy diskettes.

SITE SELECTION

Based on previous experience, it was felt that three sites would supply a sufficient amount of different conditions for this study. To avoid demographic biases and since financial limitations made it impractical to leave the state, one site was selected from each of the following Texas cities: Austin, Houston, and Dallas. A preliminary list of potential sites in each city was obtained from traffic counts and suggestions made from city and state traffic engineering personnel. Each potential location was initially screened by TTI personnel using the following criteria:

SCHEMATIC OF LAYOUT



FIELD DATA COLLECTION

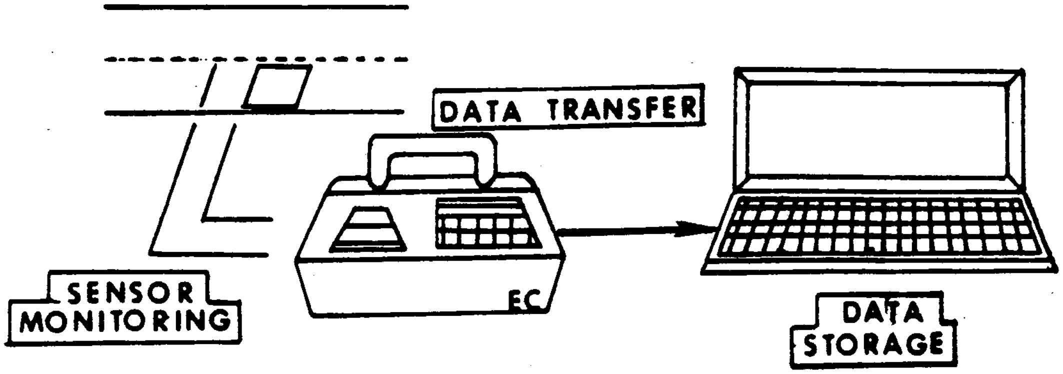


Figure 5. Illustration of the Automatic Data Collection System.

1. High traffic volumes;
2. Long cycle lengths;
3. High truck volumes;
4. Level terrain;
5. Left-turn bay;
6. Right-turn lane; and
7. Ease of set up.

Sites that met this criteria insured that the data collected would meet the requirements for this study. The three sites selected were: State Highway 183 at Georgian in Austin, State Highway 6 at Farm Road 529 in Houston, and Irving Boulevard at Mockingbird Lane in Dallas.

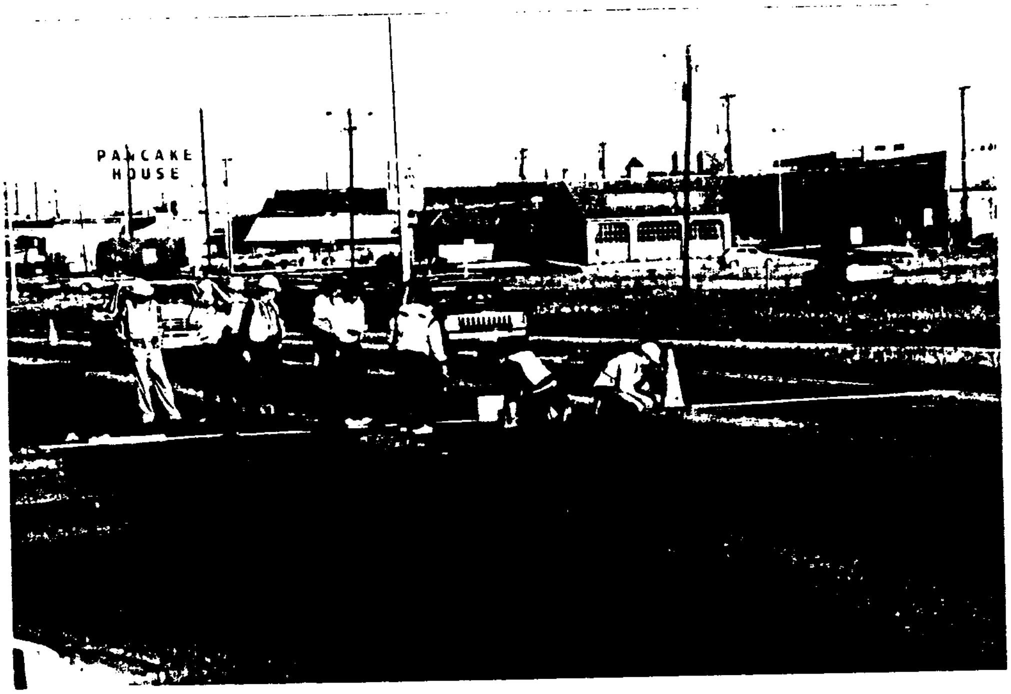
DATA COLLECTION

At each of the study sites, two EC systems (one per lane) were installed along with pushbutton boxes for manual classification. Data were collected for eight hours on two consecutive days. Data collection was divided into four 2-hour periods; 2 hours in the AM peak, 4 hours in the off-peak, and 2 hours in PM peak. Except for approximately 15 minutes of light rain in Houston, all the data were collected under dry weather conditions.

Setting up for this study was a rather long and detailed process which can be subdivided into two phases. The first phase was the installation of the roadway and signal components of the system. These components remained in place until the end of the study and included: the tapeswitches, the loops, and the photoelectric cell. This activity required traffic control to be provided by either the SDHPT or the city's transportation engineering department. The second phase was conducted approximately 30 minutes before each AM data collection session. These activities consisted of setting up the EC's and Zeniths in the back of the van and then connecting them to the loops and tapeswitches with specially prepared connectors. Figure 6 shows the installation of the loops and tapeswitches, and Figure 7 shows the arrangement of the equipment in the van.

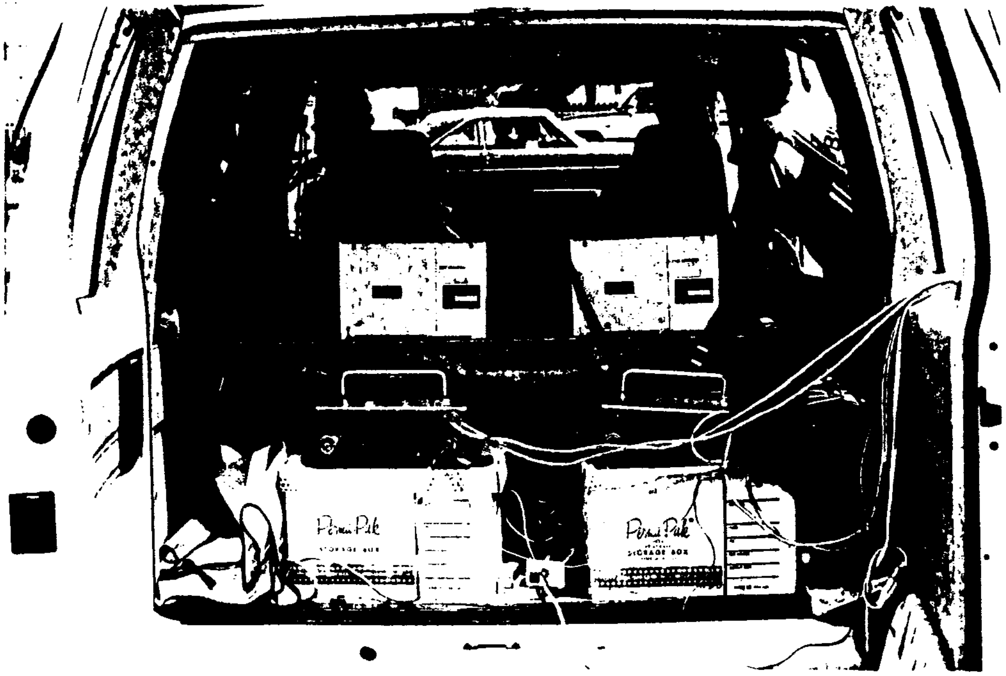
During each study period, data were collected for each cycle individually (i.e., each cycle provided one observation for the final data set). At the start of green, the photoelectric cell triggered the beginning of the data collection for each cycle. Data collection was stopped by manually pushing the "stop" button located on the pushbutton box whenever the last vehicle in queue crossed the loop. Data were only collected for saturated vehicles traveling straight through the intersection. Therefore, if a vehicle performed any maneuvers other than proceeding through the intersection (i.e., a lane change or a right turn), the data collection for that cycle would be terminated at the vehicle immediately in front of the one performing the maneuver. In addition to the automatic classification, the vehicles were also being manually classified. The manual classification served two purposes: it provided a check on the automatic classification thereby reducing the chances of vehicle being misclassified, and it allowed different types of vehicles with the same number of axles to be distinguished from one another. This particular scheme required a minimum of three persons with two operating the pushbutton boxes and the third noting the last vehicle in queue.

Placing Loop in Inner Lane.



Connecting Lead-In Wires to Tapeswitch in Inner Lane.

Figure 6. Installation of Loops and Tapeswitches for Field Study.



Golden River Corporation Environment Computer.

Zenith Z-170 PC Microcomputers.

Figure 7. Arrangement of Equipment in the Van.

DATA ANALYSIS

This section will discuss the methodology and techniques used to analyze the data. The purpose of this analysis was to determine a truck's effect on a queue of vehicles. The basic methodology decided upon was to measure the elapsed time, at the stop line, from the start of green to the arrival of each queued vehicle's rear axle.

The objectives of this section are two fold: (1) develop a regression equation from the data set to predict total travel time; and (2) use the predicted values to estimate the PCE values for various truck classes. The sections that follow will describe the manipulation and statistical analysis of the data. The development of the PCE values will be discussed in a subsequent chapter.

Data Reduction

The data stored on floppy diskettes were transferred to the main computer system at Texas A&M University so as to take advantage of its large storage capacity and high speed processing. Once on the mainframe, the data were analyzed using the SAS statistical computer program. This program was the workhorse throughout the data analysis phase of the study. SAS was used to retrieve and store data, to modify and edit the data, and to perform several statistical tests on the data.

The data were first sorted according to the type of vehicles within the queue. A total of five classes were defined and included: passenger cars; 2-axle, single-unit trucks; 3-axle, single-unit trucks; and 4- and 5-axle combination trucks. These vehicles are shown in Figure 8. The next step was to divide each vehicle class into 10 subclasses with the queue position of the vehicle of interest varying from position one to ten. The passenger car data set was not broken down into subsets since the criterion was to have the vehicle of interest in a different queue position (from 1 to 10) in each subset with the rest of the vehicles in the subset being passenger cars. For example, the first subset for the 5-axle truck class would contain the vehicle of interest (5-axle truck) in queue position one with the rest of the vehicles in the queue being passenger cars. This is to be consistent with the methodology that will be used to determine the PCE's.

At this time, the data were nearly ready for the statistical analysis phase. However, before proceeding to that step, it was felt that a manual review of the data was in order so that any erroneous data could be identified and removed before conducting any statistical analyses. The data were checked for the following errors:

1. The occupancy time was greater than the elapsed time. This condition was only possible when the vehicle's front tires had crept over the tapeswitch prior to the onset of green. If this was the case, then all the elapsed time measurements for that cycle were in error. Therefore, all of these observations were removed from the sample.

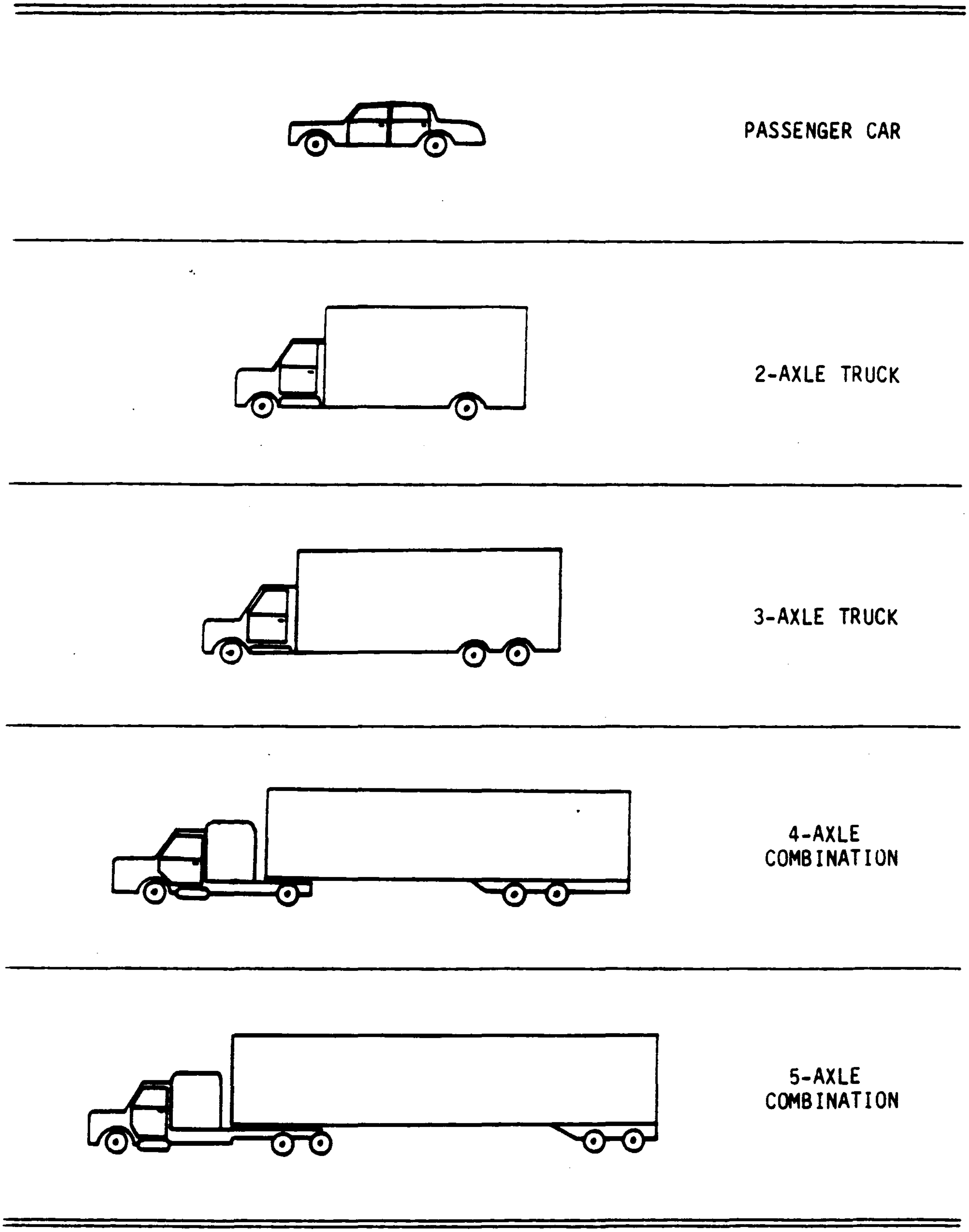


Figure 8. Typical Vehicles Used for Analysis.

2. The elapsed time for the vehicle within the queue was lower than the previous vehicle's elapsed time. This error occurred when the observer failed to stop the data collection for the previous cycle. At the beginning of the next cycle, the existing queue of vehicles was added to the previous queue; this resulted in the elapsed time appearing to decrease in the middle of the queue. All the data in the cycle from the point the elapsed time decreased were removed, thereby retaining the observations prior to the error.

3. Incremental differences in elapsed times began to increase. This error occurred whenever the observer failed to stop the data collection until the end of the cycle. In this case, the vehicles arriving after the end of the queue were not saturated vehicles and would bias the results if included in the final data set. These vehicles were easily identified and removed because they were not manually classified.

These error checks were performed for each of the 10 subclasses in every vehicle category. Upon their completion, the total amount of data available for statistical analysis were as listed in Table 1.

Table 1. Data Available for Analysis.

Vehicle Category	Total Number of Cycles	Total Number of Vehicles
Passenger Car	1530	10,105
2-Axle, Single-Unit	280	1687
3-Axle, Single-Unit	130	771
4-Axle Truck	25	135
5-Axle Truck	160	927

Note: For the truck categories, the total number of cycles corresponds to the total number of trucks in the data set with the rest of the vehicles being passenger cars.

Statistical Analysis

The purpose of this analysis was to develop a regression equation that predicted total travel time based on the position of the vehicle in the queue. In this analysis, total travel time is the time for a vehicle's rear axle to cross over the roadway instrumentation from its position in queue. This measurement has been previously referred to as the vehicle's elapsed time.

The first step in this analysis was to analyze the passenger car data set. Past research suggests that the headways of passenger cars departing from a signalized intersection start off at a high value and eventually drop down to a constant value (16, 17). Since the total travel time is actually cumulative headways of the vehicles in queue, the total travel time should be increasing at a constant rate at some point within the queue (i.e., the difference between successive travel times becomes a constant headway value, h_b). In other words the values for total travel time will be increasing at a nonlinear rate with the values for the first vehicles increasing at a greater rate than the later ones.

An analysis of the means of the headways for the passenger car data set indicated that the means were statistically identical after the seventh position in queue (i.e., the headway was constant after the seventh position). The average headway was calculated to be 1.79 seconds and rounded to 1.8 seconds (2000 pcbhqpl). Therefore, for the first seven queue positions, a second order polynomial line was fitted using the SAS program. Since the variability in headways was increasing with queue position, a weighted regression was used to account for this phenomenon. The resulting regression equation had an R^2 of 0.907 which indicates that the model fit the data extremely well. The model has the following form:

$$ELP = B_0 + B_1 * VEH + B_2 * VEH^2 \qquad [3.1]$$

where:

ELP = total travel time for the queue;
VEH = position of vehicle in the queue; and
B_0, B_1, B_2 = regression coefficients.

To be consistent, this same methodology was applied to the all truck data sets. A regression equation was developed for each position analyzed from the position where the truck was located towards the end of the queue. Since the data sets analyzed were much smaller than the passenger car data sets, it was not possible to determine statistically when the headways of the passenger cars, behind the truck, reached a constant headway. However, it was critical to this study to determine the exact position when the headways reached a constant value (i.e., position "i") because it is at this vehicle position that the travel time values were taken to calculate the PCE of the truck. Therefore, it was assumed that passenger cars traveling behind a truck would eventually reach the same constant headway value as the passenger cars traveling in an all-passenger-car queue. Therefore, when the regression equation predicted that the headways between passenger cars would reach a constant headway value of 1.8 seconds (i.e., the saturation flow headway), the PCE was calculated at that position.

In developing the regression equations, the question arose as to how little data could be used to develop a regression equation with any degree of confidence. This proved to be a difficult question. To resolve the issue, it was decided that the truck position that was being examined must contain at least five observations. In addition, the succeeding three passenger car positions must have a combined value of at least 15 observations with the smallest value per position being no less than four observations. This was done so that the equations developed could reasonably predict the travel time for a passenger car at least three positions behind the truck in the queue. These data were needed so that the effect of a truck on passenger cars behind the truck could be analyzed. Table 2 lists the fit of each regression model developed from the different data sets that were analyzed.

Table 2. Regression Fit for the Truck Data.

Truck Class	Position of Truck in Queue	Weighted R^2	No. of Trucks in the Data	Total No. of Vehicles
2-Axle, Single-Unit	1	.9572	71	329
	2	.9470	52	228
	3	.9210	50	199
	4	.9501	35	127
	5	.8779	37	112
	6	.7290	21	63
	7	.7649	13	41
	8-10	--	--	--
3-Axle, Single-Unit	1	.9256	28	97
	2	.8291	28	110
	3	.9445	23	113
	4	.9299	21	80
	5	.6798	19	51
	6	.8412	12	47
	7-10	--	--	--
4-Axle Combination	1	.8778	14	61
	2	--	--	--
	3	.8962	11	52
	4-10	--	--	--
5-Axle Combination	1	.8095	39	130
	2	.9395	36	145
	3	.8426	23	67
	4	.7779	27	89
	5	--	--	--
	6	--	--	--
	7	.7067	15	45
	8-10	--	--	--

Note: -- means insufficient data to develop a regression equation.

IV. STUDY RESULTS

This chapter focuses on the development of the PCE values for various truck categories and then compares them to the values currently being used by the 1985 HCM (1). The development of PCE values for each truck class and for several queue positions within each truck class are discussed in the first section. The second section discusses an approximate method of predicting the PCE of a truck based on its number of axles. The final section examines the impacts the proposed PCE values on the capacity of a signalized intersection and then compares the resultant capacity estimates to capacity estimates using the PCE's in the HCM (1).

PASSENGER CAR EQUIVALENTS

Using the regression equations developed for the passenger car data set and the truck data sets in Chapter 3, the PCE for each type of truck at various positions in the queue can be determined. The PCE was calculated using Equation 2.15 which was developed in Chapter 2 and shown here:

$$PCE_{j_k} = [(TT_{j_k,b_i} - TT_{b_1,b_i})/h_b] + 1 \qquad [4.1]$$

where:

j = truck type;
k = position of the truck in the queue;
TT = total travel time measured from start of green, sec;
b_1 = passenger car in position one in the queue;
b_i = passenger car in position "i" in queue; and
h_b = saturation flow headway, sec.

As stated in Chapter 2, the PCE is based on the difference in total travel time between a queue with one truck in it and a queue of an all-passenger-cars. Since, the proposed method of determining the PCE is based on total delay inflicted by a truck on the succeeding passenger car stream, the PCE equation must be applied at the vehicle position where the effect of the truck's lower acceleration performance has dissipated. After this vehicle position, the PCE value should remain approximately constant, reflecting the effects of the constant accumulated delay and the truck's greater length. This vehicle position is referred to as position "i" and, except for the truck, the queue is composed solely of passenger cars. Therefore, to determine the PCE of a given truck type in a given queue position, the total travel time of a passenger car in position "i" behind the truck is compared to the travel time for a passenger car in the equivalent position in an all-passenger-car queue. The problem with this methodology was in determining position "i". Since this is the point where the performance-related effects of a truck have dissipated, the headways beyond this point should be approximately the same as the headways for an all-passenger-car queue. Therefore, by comparing the headways of the queue being analyzed to the all-passenger-car queue and noting the position at which they are the same, position "i" was determined.

The first truck class that was analyzed was the 5-axle combination truck class. Figure 9 shows the regression lines for a queue of all-passenger-cars and a queue with a 5-axle truck in position one. As illustrated in the figure, the difference in travel time grows larger with each succeeding vehicle in queue. However, the incremental increase in the travel times between the two queues is growing smaller. At approximately position nine, the incremental increase in travel time between the two queues is zero (i.e., the lines are parallel). At this queue position, the passenger car in the queue with a truck is not incurring any additional delay. Therefore, this position was defined as position "i" for the case where a 5-axle truck is in position one. Figure 10 shows a graph similar to Figure 9, but with an additional regression line for a queue with a 5-axle truck in position three. In this case, the regression line for the all-passenger-car queue and the regression line for the 5-axle truck in position three become parallel at about queue position six. Thus, the "i"th position for a 5-axle truck in position three is queue position six. This same procedure was used for the remainder of the regression lines in the 5-axle combination truck class.

This same technique was used for the 4-axle truck class to determine the "i"th position. However, due to the scarcity of data, regression lines were only developed for a queue with a truck in position one and position three. Figure 11 shows the regression line developed for a queue with a 4-axle truck in queue position one and the regression line developed for a queue of all-passenger-cars. It is apparent from this figure that the two regression lines are not parallel. Since they are not, the "i"th position cannot be determined or reasonably estimated. Therefore, in order to give the best possible estimate of the PCE, the last queue position (position 6) was used as a surrogate for position "i".

Finally, the 2- and 3-axle, single-unit truck classes were analyzed. Figure 12 compares the regression line for a queue of all-passenger-cars to the regression lines for queues with 2-axle, single-unit trucks in positions one, three, and five. An interesting observation here is that regardless of the position of the truck in the queue, the total travel time after the eighth position in queue is approximately equal for each line. This means that the PCE value calculated from these lines will be nearly identical. Figure 13 shows a similar graph for 3-axle, single-unit trucks. Although not as obvious as in the 2-axle truck class, this figure also indicates that queue position has very little influence on travel times and consequently, the PCE values for this truck class.

After examining all of the regression lines and determining the "i" position for each one, PCE values were calculated using Equation 4.1. The value used for saturation flow headway, h_b, was 1.8 seconds and was determined during the development of the all-passenger-car regression line. The resultant PCE values are listed in Table 3.

As a final step, a regression analysis was conducted on the PCE values developed for each truck class. The purpose was two fold: (1) determine if the values generated were statistically different from each other; and (2) if so, develop an equation which could interpolate the PCE values for the positions where there was insufficient data to develop a value. The latter part was only applicable to the 5-axle truck class.

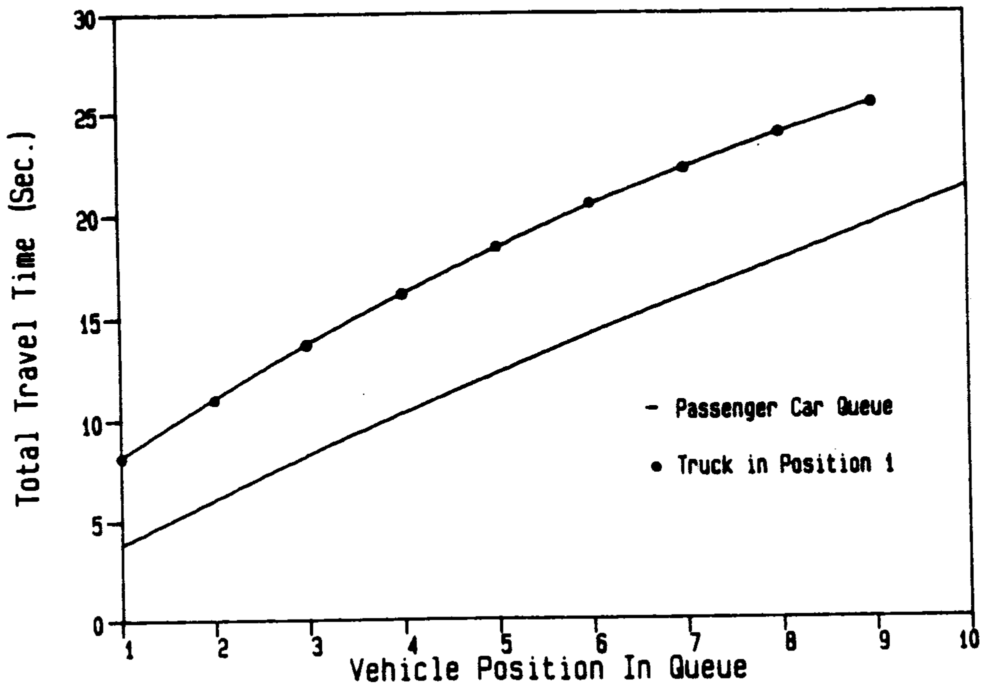


Figure 9. Regression Lines for All-Passenger Car Queue and 5-Axle Truck in Position 1.

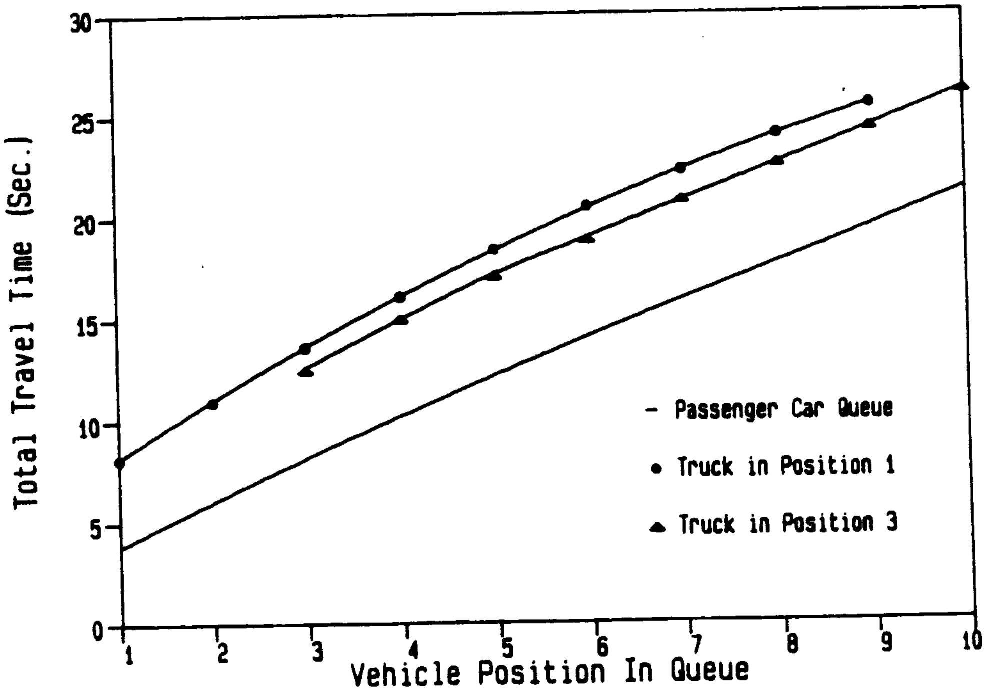


Figure 10. Regression Lines for All-Passenger Car Queue and 5-Axle Trucks in Position 1 and 3.

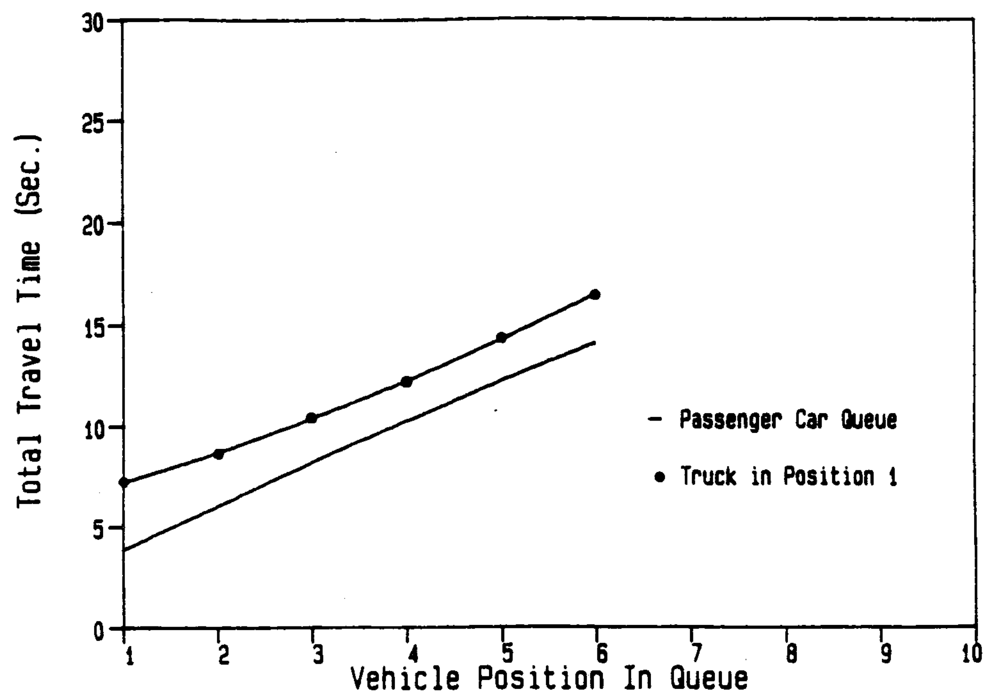


Figure 11. Regression Lines for All-Passenger Car Queue and 4-Axle Truck in Position 1.

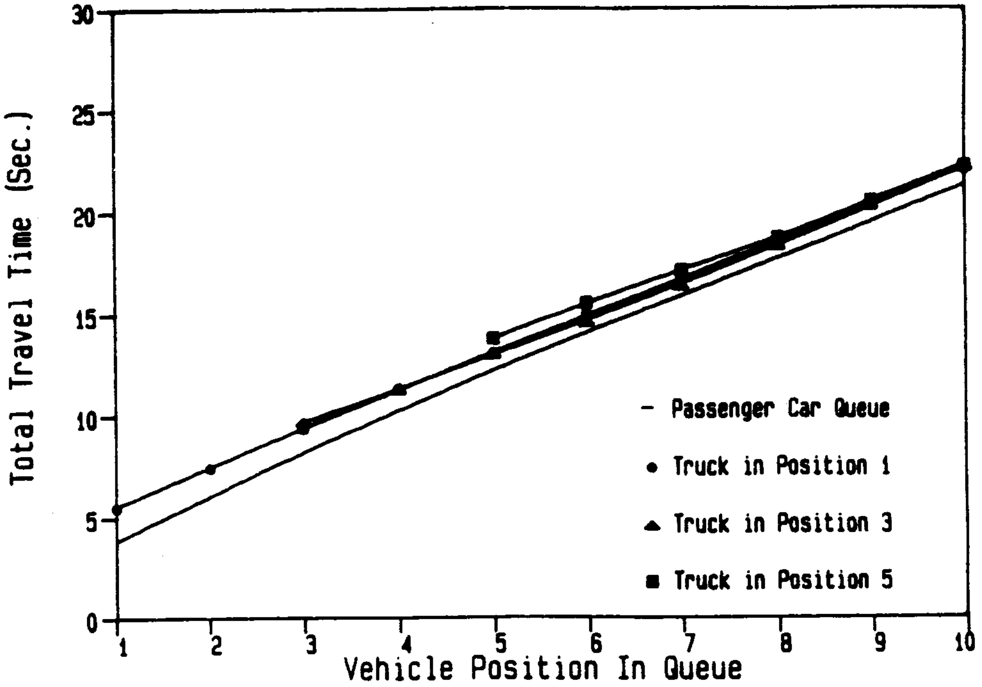


Figure 12. Regression Lines for 2-Axle Truck Class.

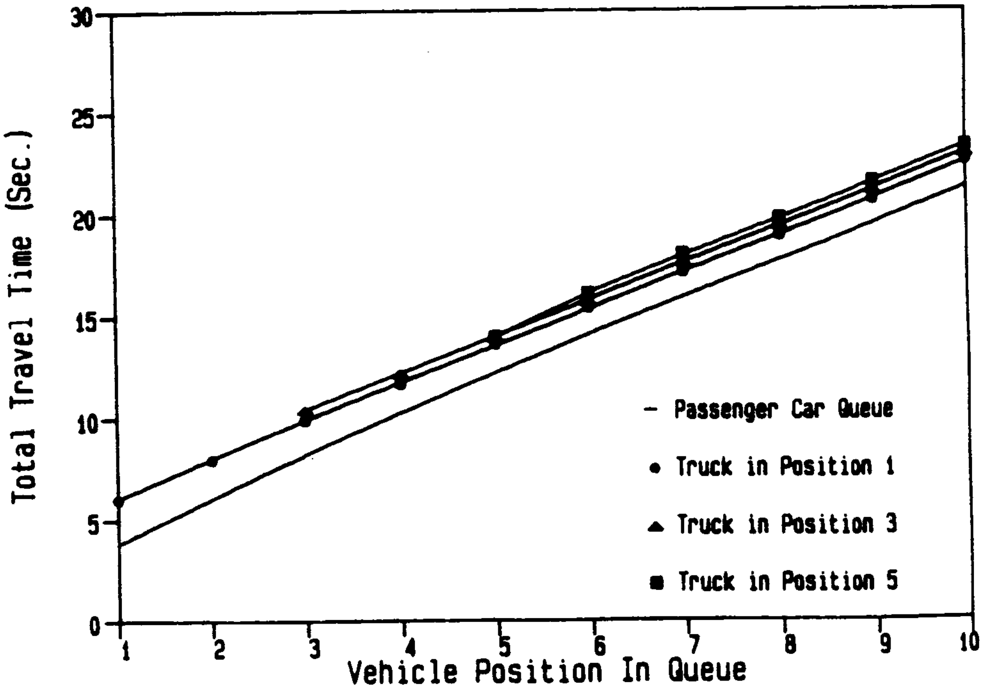


Figure 13. Regression Lines for 3-Axle Truck Class.

Table 3. Observed PCE Values for Various Truck Types.

Truck Type	Truck Position in Queue						
	1	2	3	4	5	6	7
2-Axle, Single-Unit	1.5	1.8	1.5	1.6	1.6	1.4	1.7
3-Axle, Single-Unit	1.7	2.3	1.9	1.9	2.1	2.1	-
4-Axle Truck	2.3	-	2.5	-	-	-	-
5-Axle Truck	4.3	3.9	3.7	3.3	-	-	3.2

Note: - signifies that there was insufficient data to develop a PCE.

A first order linear regression was performed on the 2-axle, single-unit truck class. The probability of the F-test indicated that the nonintercept term was zero (Prob.>F of 0.9786). This confirmed an earlier suspicion that the PCE values for this truck class were not influenced by the position of the truck in the queue. Furthermore, this also suggested that each of the PCE values was statistically identical; therefore, the average of these values was used as the PCE values for each position in queue.

The same procedure was applied to the 3-axle, single-unit truck class. Once again, the probability of the F-test indicated that the nonintercept term was zero, although the evidence was not as strong (Prob.>F of 0.4415). As before, this test suggested that the values were statistically identical which means that the average of the PCE values can be used in place of the actual values.

No analysis was performed on the 4-axle truck class because of the scarcity of points to regress upon. Therefore, the PCE values were left unaltered.

A first order linear regression equation was fitted to the PCE values for the 5- axle truck class. The model had an adjusted R^2 value of 0.7874 indicating that 78.74 percent of the variability was explained by the model. Furthermore, the F-test indicated that the nonintercept term was significant. This appeared to be a good model, but the PCE values appeared to follow an exponential curve. Therefore, the independent variable was transformed by taking its logarithm. Using the transformed value for the independent variable, another first order regression equation was fitted to the PCE values. The resulting adjusted R^2 value of 0.8180 indicated that this was a better fitting model. Table 4 lists the PCE values developed by these regression analyses. The outputs from the SAS program used in the final analyses are provided in the Appendix.

Table 4. Predicted PCE Values for Various Truck Types.

Truck Type	Truck Position in Queue						
	1	2	3	4	5	6	7
2-Axle, Single Unit	1.6	1.6	1.6	1.6	1.6	1.6	1.6
3-Axle, Single Unit	2.0	2.0	2.0	2.0	2.0	2.0	-
4-Axle Truck	2.3	-	2.5	-	-	-	-
5-Axle Truck	4.1	3.9	3.7	3.6	3.4	3.2	3.1

Note: - signifies that there was insufficient data to develop a PCE.

EFFECTS ON CAPACITY

For the practicing engineering community, the matrix of PCE values listed in Table 4 is of little use. Seldom do city or state traffic engineers have the time or manpower to determine the percentage of trucks at an intersection much less the time or manpower to determine the percentage of trucks based on truck type and position in queue. A practical solution would be to condense the values in Table 4 into two values; one for light trucks (i.e., delivery trucks) and one for heavy trucks (i.e., 18-wheelers).

The first step in this process was to determine the make up of the new truck classes. Figure 14 illustrates the difference in travel time between a queue of all passenger cars; and a queue with a 2-axle truck, a 3-axle truck, and a 5-axle truck all in the first queue position. As can be seen by this illustration, the difference in operating characteristics of 2- and 3-axle single-unit trucks is slight compared to that of the 5-axle truck. Therefore, due to similarities in performance capabilities, size, and usage; the two single-unit truck classes were combined to form the light truck class. This class was selected to represent the light-cargo hauling truck population typically found in urban areas. The heavy truck class composed of the 5-axle combination truck class was selected to represent the large tractor trailer combinations typically used for long distance hauling. Since there was very little data for the 4-axle truck class, this class was not used.

Light Trucks

To determine the PCE for the light truck class, the weighted average based on the proportion of trucks in each of the single-unit classes was used. A total of 482 2-axle, single-unit trucks and 255 3-axle, single-unit trucks were observed. The proportion of the total observations in each truck class was multiplied by its PCE to obtain the average PCE as follows:

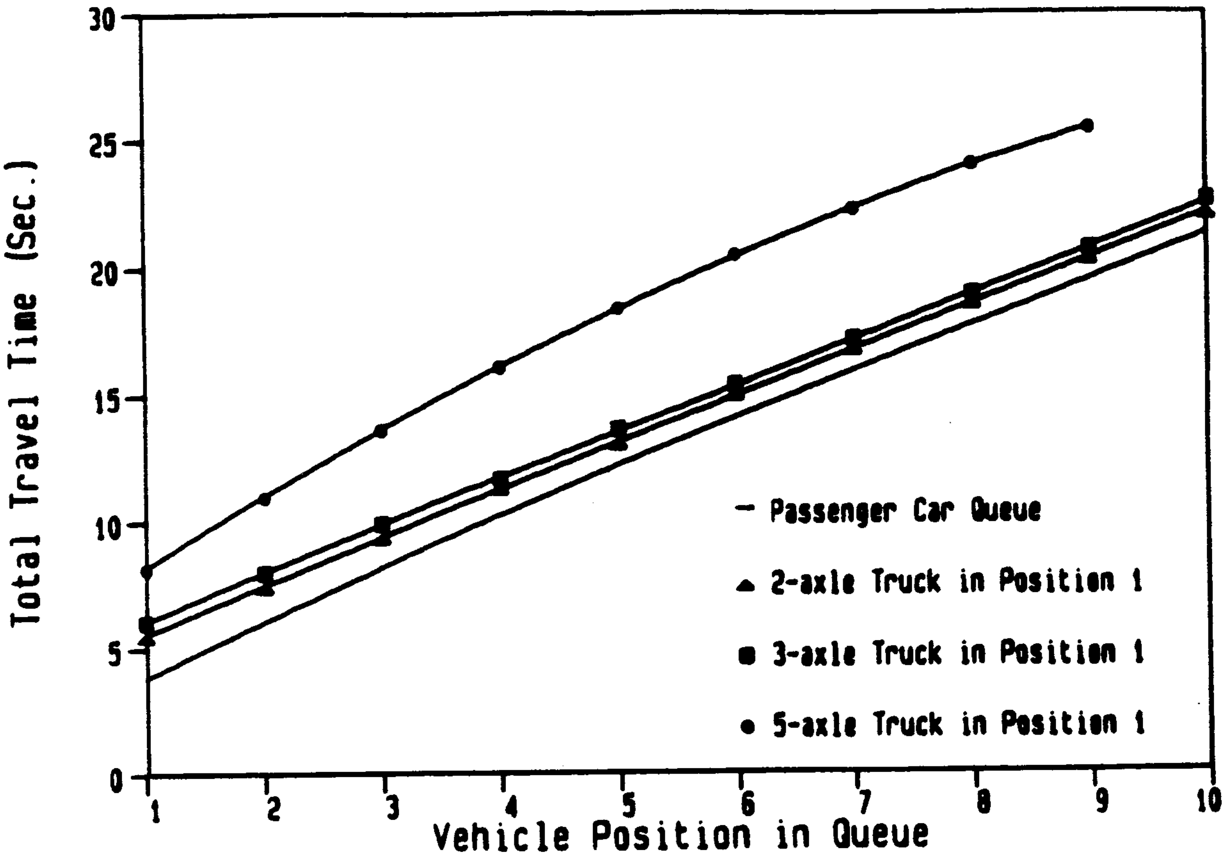


Figure 14. Comparison of Travel Times for an All-Passenger-Car Queue and Various Truck Types in Position 1.

$$\text{Light Truck PCE} = (482/737)*1.6 + (255/737)*2.0 = 1.7. \qquad [4.2]$$

Heavy Trucks

The PCE value for the heavy truck class was determined in a similar fashion. The proportion of trucks in each queue position was multiplied by its respective PCE, and then summed to arrive at an average weighted PCE value. Table 5 lists the number of 5-axle trucks and their PCE values per queue position used to calculate the PCE. The average PCE for the heavy truck class was calculated as follows:

$$\text{Heavy Truck PCE} = (42/220)*4.1 + . . . + (23/220)*3.1 = 3.7. \qquad [4.3]$$

Table 5. Number of Trucks and PCE per Queue Position.

Queue Position	Number of Trucks	Average PCE
1	42	4.1
2	41	3.9
3	43	3.7
4	40	3.6
5	19	3.4
6	12	3.2
7	23	3.1

Heavy Vehicle Adjustment Factor

The previous sections have discussed the major findings of this research; most importantly of which is that heavy trucks should be considered a separate category from light trucks for capacity analysis purposes due to the differences in their operating characteristics. This means that the PCE values for the two truck types must be combined in such a way as to accurately reflect the actual traffic conditions.

The 1985 HCM (1) uses a heavy vehicle adjustment factor to modify the capacity of a signalized intersection so as to account for the presence of trucks. For other classes of facilities, the 1985 HCM (1) accounts for trucks, buses, and recreational vehicles. Applying this methodology to signalized intersections, an equation to combine the PCE of the three different vehicle types can be written as follows:

$$f_{HV} = 1/[1 + P_T(E_T - 1) + P_R(E_R - 1) + P_B(E_B - 1)] \qquad [4.4]$$

where:

P = percent of vehicle type in the traffic stream;
E = passenger car equivalent of the vehicle type;
T = truck;
R = recreational vehicle;
B = bus; and
f_{HV} = heavy vehicle adjustment factor.

Expanding this methodology to account for light trucks and heavy trucks separately, the following equation was developed:

$$f_{HV} = 1/[1 + P_{HT}(E_{HT} - 1) + P_{LT}(E_{LT} - 1) + P_R(E_R - 1) + P_B(E_B - 1)] \qquad [4.5]$$

where:

P = percent of vehicle type in the traffic stream;
E = passenger car equivalent of the vehicle type;
HT = heavy truck;
LT = light truck;
R = recreational vehicle;
B = bus; and
f_{HV} = heavy vehicle adjustment factor.

When using this methodology, the PCE recommended for heavy trucks (E_{HT}) is 3.7 and for light trucks (E_{LT}) is 1.7. The PCE values for recreational vehicles and buses were not examined in this research, but the value recommended for light trucks can be assumed to apply to buses and recreational vehicles since all these vehicle types are of similar size and operating characteristics. This assumption is further supported by a recent Canadian study which reported a PCE value of 1.75 for buses (15).

Using Equation 4.5, the effects of light trucks and heavy trucks can be combined (along with other vehicle types) according to the proportion of these vehicle types in the traffic stream. The net result is a determination of the impact of an "average" truck on the capacity of the intersection.

Capacity Reduction at a Signalized Intersection

Figure 15 shows a graph of the capacity reduction due to different truck percentages and PCE values. Capacity has been reduced from the ideal value for one lane by using the adjustment factor calculated from Equation 4.5. The four

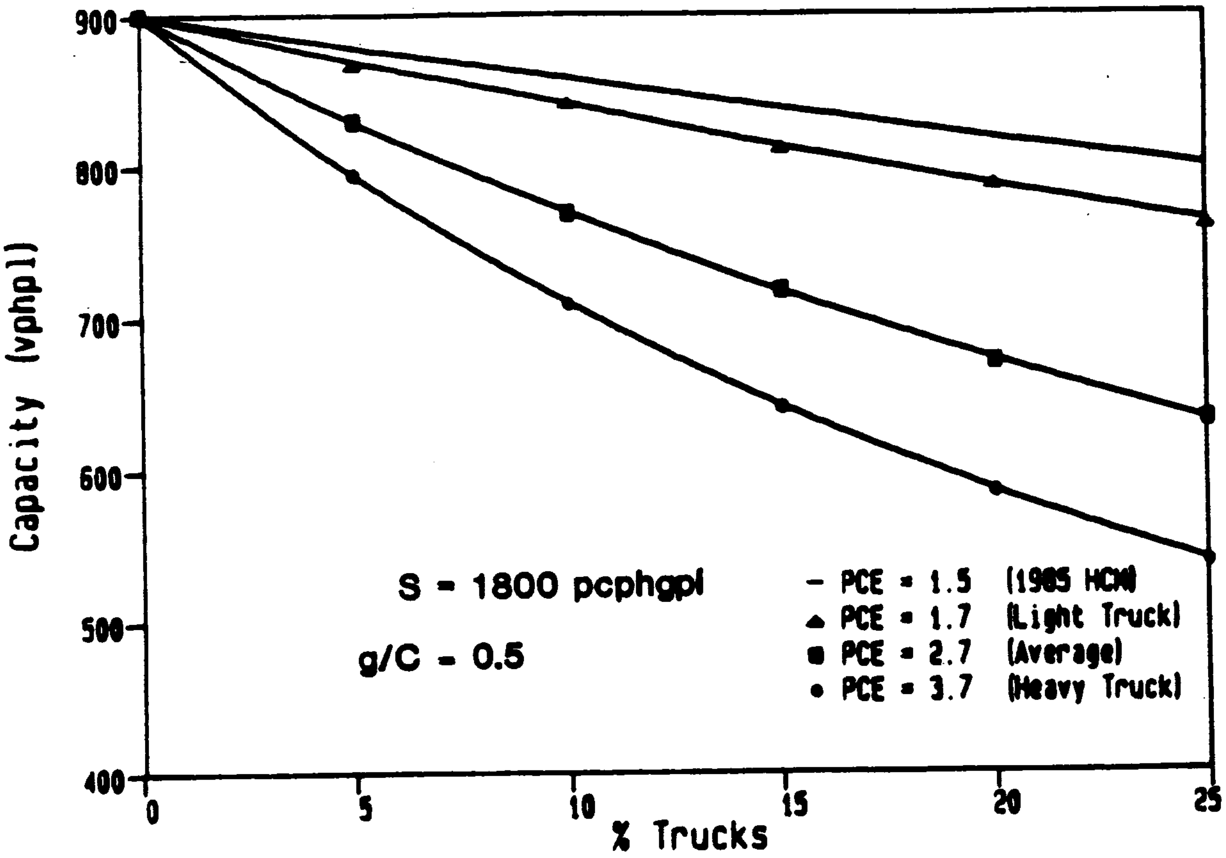


Figure 15. Comparison of Capacity Reduction Resulting from Various PCE Values.

lines show the difference in capacity reduction between the PCE value of 1.5 used in the 1985 HCM (1), the PCE value of 1.7 proposed in this study for a light truck population, the PCE value of 3.7 proposed in this study for a heavy truck population, and an average PCE value of 2.7 shown to represent a traffic stream containing an even mixture of light and heavy trucks.

For a typical urban intersection with 10 percent trucks and a truck population consisting mainly of light trucks, the difference in capacity which would result if the PCE value in the 1985 HCM (1) were used as opposed to the light truck PCE value would be a mere 2 percent. Stated differently, the 1985 HCM (1) PCE value predicts 2 percent more capacity at the intersection than actually exists. This small overestimation of capacity is within tolerable limits and would not appear to warrant a revision of the current PCE value used in the HCM. However, if the intersection has an even mixture of heavy and light trucks, an average PCE value of 2.7 can be used. Under these conditions, the overestimation of capacity by using the HCM values would be 11 percent. For the extreme case where the truck population consists solely of heavy trucks,the overestimation of capacity would be more than 17 percent.

Thus, if the adjustment factors found in the 1985 HCM (1) are used, the resulting saturation flow will produce an inflated capacity value. Furthermore, since the green splits are based on the saturation flow, the resulting green splits will not accurately reflect the existing traffic conditions. This may lead to long queues and large delays on some phases and underutilization of other phases.

PREDICTING PCE'S FROM NUMBER OF AXLES

Using the results from this study, the capacity of an intersection can be accurately adjusted for the presence of large trucks. Adjusting the capacity will require obtaining information about the traffic mix, in particular the percentage of single-unit and combination trucks. Unfortunately, city and state traffic engineers may not have this data readily available nor may they have the manpower or time to collect data of this detail. Therefore, it would be desirable to predict the capacity reducing effect of trucks (i.e., determine the PCE of the "average" truck) based on data already available or that can be easily collected. This can be accomplished by using other data that are strongly correlated to the PCE value.

As was previously noted, length of vehicle and acceleration characteristics play an important part in determining the PCE value of a truck. Furthermore, acceleration rate of a truck is strongly dependent on the amount of weight the truck is hauling. It can be argued that the PCE value of a truck type is primarily the function of its weight and length. The problem is that determining the weight and length of a truck is more troublesome than obtaining the original data needed to make the more precise calculations. However, there is a third measurement, number of axles, which is related to truck weight and length. Therefore, it was logical to assume that the PCE value of a truck could be reasonably predicted from its number of axles.

Figure 16 shows a plot of PCE value versus number of axles for a truck in position one and a truck in position three both in queues of passenger cars. This graph indicates that the PCE of a truck increases with its number of axles. Therefore, using regression analysis, a relationship was developed to predict the PCE from the number of axles. From Figure 16, it was obvious that the relationship between PCE and number of axles was not a linear one. Since there is no existing theory to suggest the shape of this line, a simple second-order linear model was selected to model the relationship. This relationship had the following form:

$$PCE=B_0+B_1*AXL^2 \qquad [4.6]$$

where:

AXL^2 = the square of the truck's axles; and
B_0, B_1 = regression coefficients.

Using this model form, a regression line was fitted to data for a truck in position one and a truck in position three. The two predicted lines are shown in Figure 17.

As illustrated in Figure 17, the two lines have similar trends and characterstics. However, the PCE values for a queue with a truck in position one are slightly high while the PCE values for a queue with a truck in position three are more representative of the average truck. Therefore, the regression line generated from the queue with a truck in position three was selected as the most appropriate. The equation for this line was:

$$PCE = 1.08 + 0.10*AXL^2. \qquad [4.7]$$

Using this equation, the PCE of all trucks in the traffic stream can be estimated to within 10 percent of the actual value. The value used for axles would be the average number of axles for the trucks found in the data. Since this equation was developed from the PCE of 2-axle, 3-axle, 4- axle, and 5-axle trucks, it should only be used for trucks whose total number of axles fall in this range. Otherwise, the predicted value may be over or underestimated.

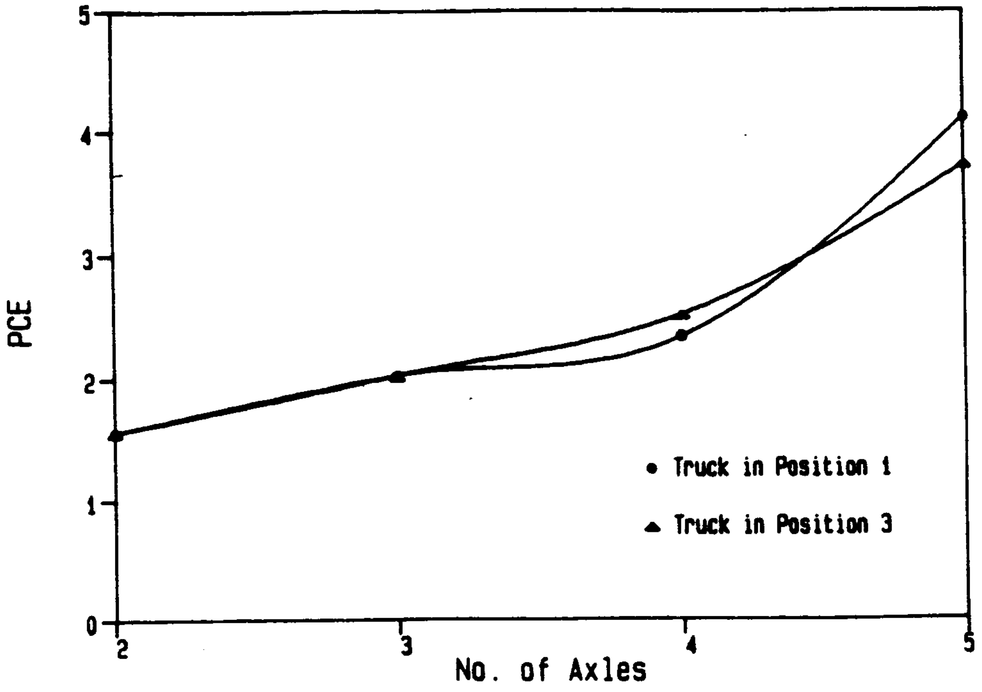


Figure 16. Actual PCE Versus Number of Axles for Various Truck Types.

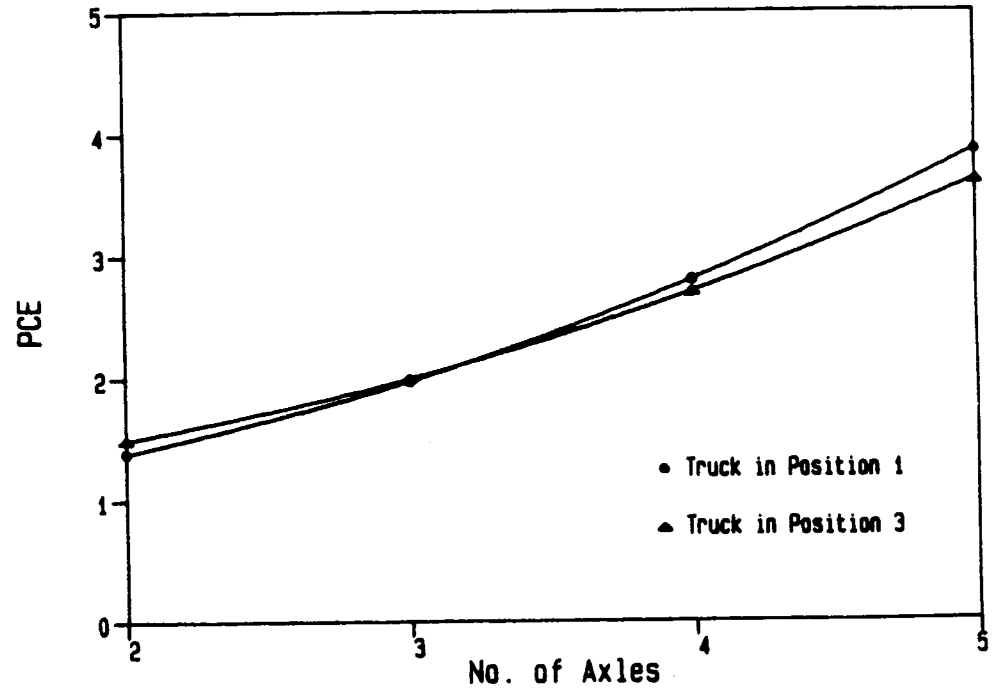


Figure 17. Predicted PCE Versus Number of Axles for Various Truck Types.

V. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This study looked at the effect of a truck on the saturation flow of a signalized intersection and developed PCE's for four truck types. Based on the results of this study, the following can be concluded:

1. Truck type affects the size of the PCE. The smaller 2-axle, single-unit trucks had a lesser impact on delay than the larger 5-axle combination trucks.

2. Position of vehicle in queue was not found to significantly affect the PCE value for the 2- and 3-axle, single-unit trucks typically found in urban areas. This is because trucks of this size are not typically hauling a great deal of weight with respect to the power of their engine. Therefore, the acceleration characteristics of these trucks are close enough to a passenger car's that their position in queue has very little effect on the PCE value.

3. Position of vehicle in queue has a very pronounced effect on the PCE value for large 5-axle combination trucks. These trucks are typically heavily loaded in addition to their greater length with respect to passenger cars. These two factors result in a large initial PCE value; however, as the position of the truck is further back in the queue, the truck has the opportunity to accelerate up to speed thereby reducing its PCE value.

4. The position of the last vehicle incrementally affected by the truck varies with truck type and position of the truck in the queue. Generally, for the first two positions in queue, the last vehicle affected by the truck can be up to eight vehicle positions behind the truck, or in other words, the "shadow" of the truck can extend up to 200 feet (assuming 25 feet per passenger car). If the truck is located after the second position in queue, its "shadow" is usually no further than three vehicle positions or approximately 75 feet.

5. The number of axles of a truck can be used to approximate its PCE values. The PCE of a truck was found to be fairly well correlated to its number of axles.

RECOMMENDATIONS

The results from this study indicate that there is a need to distinguish between different truck types when analyzing the capacity of a signalized intersection. Large, 5-axle truck combinations were found to have a significantly higher effect on the capacity of an intersection than the smaller single-unit trucks. The 1985 HCM (1) accounts for the presence of heavy vehicles (i.e., trucks, buses, and recreational vehicles) through the use of a heavy vehicle adjustment factor. This factor is based on a PCE of 1.5 which is assumed to be the average PCE for trucks, buses, and recreational vehicles. When the traffic stream contains a significant number of heavy trucks, a larger PCE effect would be expected. This effect should be accounted for in the estimation of the intersection's capacity. Based on the results of this study, the following are recommended:

1. The heavy vehicle adjustment factor equation should be modified to analyze the effects of both light and heavy trucks in addition to buses and recreational vehicle. Therefore, it is recommended that Equation 4.5 (page 36) of this report be used.
2. PCE values of 3.7 and 1.7 should be used for heavy and light trucks, respectively, when using Equation 4.5 to calculate the heavy vehicle adjustment factor for estimating capacity at a signalized intersection.

Further research into the development of PCE's for large trucks at signalized intersections is recommended. The effects of turning maneuvers and grades on the PCE value of large trucks needs to be examined as they were outside of the scope of this study. In addition, future research should study the effects of heavily loaded vehicles as compared to lightly loaded vehicles in the development of PCE's.

With regard to the methodology used in this study, a more precise method of determining the position of the "i"th vehicle is needed. This may be accomplished by collecting both headway data and spot speed data. The spot speed data would be used to determine when the queue of passenger cars behind a large truck reached saturation flow speed. Saturation flow speed would be the speed reached by the all-passenger-car queue at saturation flow headway. Position "i" would be defined as the vehicle position of the first passenger car to achieve saturation flow speed. This method would add more accuracy to the determination of the "i"th position than the procedure used in this research.

VI. REFERENCES

1. Highway Capacity Manual. Special Report 209, Transportation Research Board, Washington D.C., 1985.

2. Krammes, R.A. Effects of Trucks on the Capacity of Level, Basic Freeway Segments. Ph.D. dissertation, Pennsylvania State University, 1985.

3. Sumner, Roy, David Hill, and Steven Shapiro. Segment Passenger Car Equivalent Values for Cost Allocation on Urban Arterial Roads. Transportation Research, Vol. 18A, No. 5/6, Oct/Dec 1984, pp. 399-406.

4. Keller, Eric L. and James G. Saklas. Passenger Car Equivalents from Network Simulation. Journal of Transportation Engineering: ASCE, Vol. 110, No. 4, July 1984, pp. 397-411.

5. Hu, Yi-Chin, and Ralph D. Johnson. Passenger-Car Equivalents of Trucks in Composite Traffic. Report No. FHWA/PL/81/006, CounselTrans Inc., Rockville, MD, Feb. 1981.

6. Linzer, Elliot M., Roger P. Roess, and William R. McShane. Effect of Trucks, Buses, and Recreational Vehicles on Freeway Capacity and Service Volume. TRB, Transportation Research Record 699, 1979, pp. 17-26.

7. Highway Capacity Manual. Special Report 87, Highway Research Board, Washington D.C., 1965.

8. Webster, F.V. and B.M. Cobbe. Traffic Signals. Road Research Laboratory, Road Research Technical Paper No. 56, HMSO, London, 1966.

9. Miller, A.J. The Capacity of Signalised Intersections in Australia. Australian Road Research Board, Bull. No. 3, March 1968.

10. Carstens, Robert L. Some Traffic Parameters at Signalized Intersections. Traffic Engineering, Vol. 41, No. 11, Aug. 1971, pp. 33-36.

11. Branston, David and Henk van Zuylen. The Estimation of Saturation Flow, Effective Green Time and Passenger Car Equivalents at Traffic Signals by Multiple Linear Regression. Transportation Research, Vol. 12, No. 1, Feb. 1978, pp. 47-53.

12. Branston, David. Some Factors Affecting the Capacity of Signalized Intersections. Traffic Engineering and Control, Vol. 20, No. 8/9, Aug/Sept 1979, pp. 390-396.

13. Holland, T.J. Delay Effects of Trucks at Traffic Signals. Foras Forburtha Teoranta, Dublin (Ireland), RT-213, Nov. 1980.

14. Sosin, Janusz A. Delays at Intersections Controlled by Fixed-Cycle Traffic Signals. Traffic Engineering and Control, Vol. 21, No. 8/9, Aug/Sept 1980, pp. 407-413.

15. Teply, S. Highlights of the Canadian Capacity Guide for Signalized Intersections. Transportation Research Board, TRR 1005, 1985, pp. 20- 28.

16. Greenshields, B.D., D. Shapiro, and E.L. Erickson. Traffic Performance at Urban Intersections. Bureau of Highway Traffic, Technical Report No. 1, 1947.

17. Leong, H.J.W. Some Aspects of Urban Intersection Capacity. Australian Road Research Board, Proceedings, Vol. 2, Part 1, 1964, pp. 305-338.

VII. APPENDIX

```
1          SAS(R) LOG   OS SAS 5.15          VS2/MVS JOB PCE      STEP SAS                            13:14 MONDAY, SEPTEMBER 29, 1986

NOTE: COPYRIGHT (C) 1984 SAS INSTITUTE INC., CARY, N.C.  27511, U.S.A.
NOTE: THE JOB PCE HAS BEEN RUN UNDER RELEASE 5.15 OF SAS AT TEXAS A&M UNIVERSITY (01452001).

NOTE: CPUID   VERSION = 82  SERIAL = 000261  MODEL = 0580 .

NOTE: SAS OPTIONS SPECIFIED ARE:
       SORT=4

1          DATA DATAPCE;
2            INPUT VEH PCE;
3            CARDS;

NOTE: DATA SET WORK.DATAPCE HAS 7 OBSERVATIONS AND 2 VARIABLES. 953 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.03 SECONDS AND 96K.

11         ;
12         DATA AUSTIN2;
13           SET DATAPCE;
14           LPCE = LOG(PCE);

NOTE: DATA SET WORK.AUSTIN2 HAS 7 OBSERVATIONS AND 3 VARIABLES. 680 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.04 SECONDS AND 100K.

15         PROC REG DATA=AUSTIN2;
16           MODEL PCE = VEH;
17           OUTPUT OUT=A P=PRED;
NOTE: THE DATA SET WORK.A HAS 7 OBSERVATIONS AND 4 VARIABLES. 529 OBS/TRK.
NOTE: THE PROCEDURE REG USED 0.08 SECONDS AND 444K AND PRINTED PAGE 1.

18         DATA AUSTIN3;
19           SET A;

NOTE: DATA SET WORK.AUSTIN3 HAS 7 OBSERVATIONS AND 4 VARIABLES. 529 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.03 SECONDS AND 96K.

20         PROC PRINT;
21           VAR VEH PCE PRED;
22           TITLE 'ACTUAL AND PREDICTED PCE VALUES';
NOTE: THE PROCEDURE PRINT USED 0.06 SECONDS AND 180K AND PRINTED PAGE 2.
NOTE: SAS USED 444K MEMORY.

NOTE: SAS INSTITUTE INC.
      SAS CIRCLE
      PO BOX 8000
      CARY, N.C. 27511-8000
```

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                                          SAS                    13:14 MONDAY, SEPTEMBER 29, 1986   1

DEP VARIABLE: PCE
                                       ANALYSIS OF VARIANCE

                                   SUM OF          MEAN
               SOURCE     DF      SQUARES        SQUARE       F VALUE       PROB>F

               MODEL       1  0.000014286   0.000014286         0.001       0.9786
               ERROR       5   0.09015714    0.01803143
               C TOTAL     6   0.09017143

                   ROOT MSE     0.1342812      R-SQUARE        0.0002
                   DEP MEAN      1.564286      ADJ R-SQ       -0.1998
                   C.V.          8.584183

                                       PARAMETER ESTIMATES

                              PARAMETER         STANDARD     T FOR HO:
          VARIABLE  DF         ESTIMATE            ERROR   PARAMETER=0      PROB > |T|

          INTERCEP   1       1.56714286       0.11348829        13.809          0.0001
          VEH        1    -0.000714286        0.02537675        -0.028          0.9786
```

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ACTUAL AND PREDICTED PCE VALUES                13:14 MONDAY, SEPTEMBER 29, 1986    2

 OBS      VEH      PCE       PRED

   1        1      1.46    1.56643
   2        2      1.75    1.56571
   3        3      1.49    1.56500
   4        4      1.62    1.56429
   5        5      1.57    1.56357
   6        6      1.40    1.56286
   7        7      1.66    1.56214
```

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1         SAS(R) LOG   OS SAS 5.15          VS2/MVS JOB PCE      STEP SAS                                11:46 MONDAY, SEPTEMBER 29, 1986

NOTE: COPYRIGHT (C) 1984 SAS INSTITUTE INC., CARY, N.C.  27511, U.S.A.
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NOTE: CPUID   VERSION = 82  SERIAL = 000261  MODEL = 0580 .

NOTE: SAS OPTIONS SPECIFIED ARE:
       SORT=4

1          DATA DATAPCE;
2            INPUT VEH PCE;
3            CARDS;

NOTE: DATA SET WORK.DATAPCE HAS 6 OBSERVATIONS AND 2 VARIABLES. 953 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.03 SECONDS AND 96K.

10         ;
11         DATA AUSTIN2;
12           SET DATAPCE;
13           LPCE = LOG(PCE);

NOTE: DATA SET WORK.AUSTIN2 HAS 6 OBSERVATIONS AND 3 VARIABLES. 680 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.04 SECONDS AND 100K.

14         PROC REG DATA=AUSTIN2;
15           MODEL PCE = VEH;
16           OUTPUT OUT=A P=PRED;
NOTE: THE DATA SET WORK.A HAS 6 OBSERVATIONS AND 4 VARIABLES. 529 OBS/TRK.
NOTE: THE PROCEDURE REG USED 0.08 SECONDS AND 444K AND PRINTED PAGE 1.

17         DATA AUSTIN3;
18           SET A;

NOTE: DATA SET WORK.AUSTIN3 HAS 6 OBSERVATIONS AND 4 VARIABLES. 529 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.03 SECONDS AND 96K.

19         PROC PRINT;
20           VAR VEH PCE PRED;
21           TITLE 'ACTUAL AND PREDICTED PCE VALUES';
NOTE: THE PROCEDURE PRINT USED 0.06 SECONDS AND 180K AND PRINTED PAGE 2.
NOTE: SAS USED 444K MEMORY.

NOTE: SAS INSTITUTE INC.
      SAS CIRCLE
      PO BOX 8000
      CARY, N.C. 27511-8000
```

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                                                  SAS                      11:46 MONDAY, SEPTEMBER 29, 1986    1

DEP VARIABLE: PCE
                                            ANALYSIS OF VARIANCE

                                         SUM OF          MEAN
                      SOURCE      DF    SQUARES        SQUARE        F VALUE       PROB>F

                      MODEL        1  0.03171571    0.03171571         0.728       0.4415
                      ERROR        4  0.17416762    0.04354190
                      C TOTAL      5  0.20588333

                         ROOT MSE       0.208667       R-SQUARE       0.1540
                         DEP MEAN       2.008333       ADJ R-SQ      -0.0574
                         C.V.           10.39006

                                            PARAMETER ESTIMATES

                                     PARAMETER         STANDARD      T FOR HO:
                  VARIABLE  DF        ESTIMATE            ERROR    PARAMETER=0       PROB > |T|

                  INTERCEP   1      1.85933333       0.19425838          9.571           0.0007
                  VEH        1      0.04257143       0.04988095          0.853           0.4415
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ACTUAL AND PREDICTED PCE VALUES               11:46 MONDAY, SEPTEMBER 29, 1986    2

 OBS     VEH     PCE        PRED

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  2       2      2.28     1.94448
  3       3      1.94     1.98705
  4       4      1.93     2.02962
  5       5      2.13     2.07219
  6       6      2.08     2.11476
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1          SAS(R) LOG   OS SAS 5.15          VS2/MVS JOB PCE      STEP SAS                              10:56 MONDAY, OCTOBER 6, 1986

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NOTE: CPUID   VERSION = 82  SERIAL = 000261  MODEL = 0580 .

NOTE: SAS OPTIONS SPECIFIED ARE:
       SORT=4

1          DATA DATAPCE;
2            INPUT VEH PCE;
3            CARDS;

NOTE: DATA SET WORK.DATAPCE HAS 7 OBSERVATIONS AND 2 VARIABLES. 953 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.03 SECONDS AND 96K.

11         ;
12         DATA AUSTIN2;
13           SET DATAPCE;
14           LPCE = LOG(PCE);

NOTE: MISSING VALUES WERE GENERATED AS A RESULT OF PERFORMING
      AN OPERATION ON MISSING VALUES.
      EACH PLACE IS GIVEN BY: (NUMBER OF TIMES) AT (LINE):(COLUMN).

      2 AT 14:10

NOTE: DATA SET WORK.AUSTIN2 HAS 7 OBSERVATIONS AND 3 VARIABLES. 680 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.04 SECONDS AND 100K.

15         PROC REG DATA=AUSTIN2;
16           MODEL LPCE = VEH;
17           OUTPUT OUT=A P=LPRED;
NOTE: THE DATA SET WORK.A HAS 7 OBSERVATIONS AND 4 VARIABLES. 529 OBS/TRK.
NOTE: THE PROCEDURE REG USED 0.08 SECONDS AND 444K AND PRINTED PAGE 1.

18         DATA AUSTIN3;
19           SET A;
20           PRED = EXP(LPRED);

NOTE: DATA SET WORK.AUSTIN3 HAS 7 OBSERVATIONS AND 5 VARIABLES. 433 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.03 SECONDS AND 100K.

21         PROC PRINT;
22           VAR VEH PCE PRED;
23           TITLE 'ACTUAL AND PREDICTED PCE VALUES';
NOTE: THE PROCEDURE PRINT USED 0.07 SECONDS AND 180K AND PRINTED PAGE 2.
NOTE: SAS USED 444K MEMORY.

NOTE: SAS INSTITUTE INC.
      SAS CIRCLE
      PO BOX 8000
      CARY, N.C. 27511-8000
```

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                                              SAS                        10:56 MONDAY, OCTOBER 6, 1986     1

DEP VARIABLE: LPCE
                                                ANALYSIS OF VARIANCE

                                          SUM OF           MEAN
                  SOURCE      DF         SQUARES         SQUARE        F VALUE          PROB>F

                  MODEL        1      0.05329226     0.05329226         18.975          0.0224
                  ERROR        3     0.008425471    0.002808490
                  C TOTAL      4      0.06171773

                     ROOT MSE         0.05299519       R-SQUARE         0.8635
                     DEP MEAN            1.29671       ADJ R-SQ         0.8180
                     C.V.               4.086896

                                                PARAMETER ESTIMATES

                                  PARAMETER          STANDARD       T FOR HO:
               VARIABLE  DF        ESTIMATE             ERROR     PARAMETER=0         PROB > |T|

               INTERCEP   1      1.46717813        0.04575063          32.069             0.0001
               VEH        1     -0.05013767        0.01150982          -4.356             0.0224
```

```
ACTUAL AND PREDICTED PCE VALUES                     10:56 MONDAY, OCTOBER 6, 1986    2

 OBS      VEH      PCE        PRED

   1        1     4.33     4.12489
   2        2     3.87     3.92318
   3        3     3.71     3.73133
   4        4     3.32     3.54886
   5        5      .       3.37532
   6        6      .       3.21026
   7        7     3.17     3.05327
```