HEAVY VEHICLE IMPACT ON RURAL TWO LANE HIGHWAY SEGMENTS OPERATING UNDER VARIOUS LEVELS OF SERVICE CONDITIONS

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Zijian Zheng

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Transportation and Logistics

August 2014

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Heavy Vehicle Impact on Rural Two Lane Highway Segments Operating under Various Levels of Service Conditions

By

Zijian Zheng

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

PAN LU

Chair

JILL HOUGH

XIANGQING TANGPONG

Approved:

10/03/2014

Date

DENVER TOLLIVER

Department Chair

ABSTRACT

Oil boom in Western North Dakota State brings increasing number of oil trucks. The distinct characteristics of heavy vehicles such as oil trucks: low speed, large size, and slow accelerate and decelerate results in inaccuracy in traffic capacity forecasting and safety analysis. In this research, to calculate passenger car equivalent (PCE) factor of heavy vehicles, such as oil trucks, on two-lane rural highway, an improved analytical method based on headway and delay is introduced. It considers several elements that have effect on PCE factor: vehicle speed, safety passing time, headway distribution, level of service (LOS), and delay to downstream traffic. The new set of PCE factor values are classified into three groups corresponding to different LOS.

ACKNOWLEDGEMENTS

There are many people giving me help on this paper. First I want to give my gratitude to Dr. Pan Lu, my advisor. Her utmost professionalism, considerable efforts, patient, wisdom and continuous encouragement have kept me moving forward during the study. What I learnt from her is going to be a fortune in my life. A very sincere thank you is due to my committee members for their guidance and support to improve the quality of this paper. Dr. Tolliver, Dr. Tangpong, and Dr. Hough shared their experience and knowledge, and helped me to complete this paper.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1. Background

Western North Dakota is experiencing a great economic boom with continued oil industry expansion. Helms (2012), the director of North Dakota's mineral resources department, claims that in Western North Dakota, the Bakken Shale formation produced about 640,000 barrels of oil per day in May, second only to Texas' 1.7 million barrels per day. Figure 1 describes the oil production increase trend in recent years (Energy Information Administration, 2013).

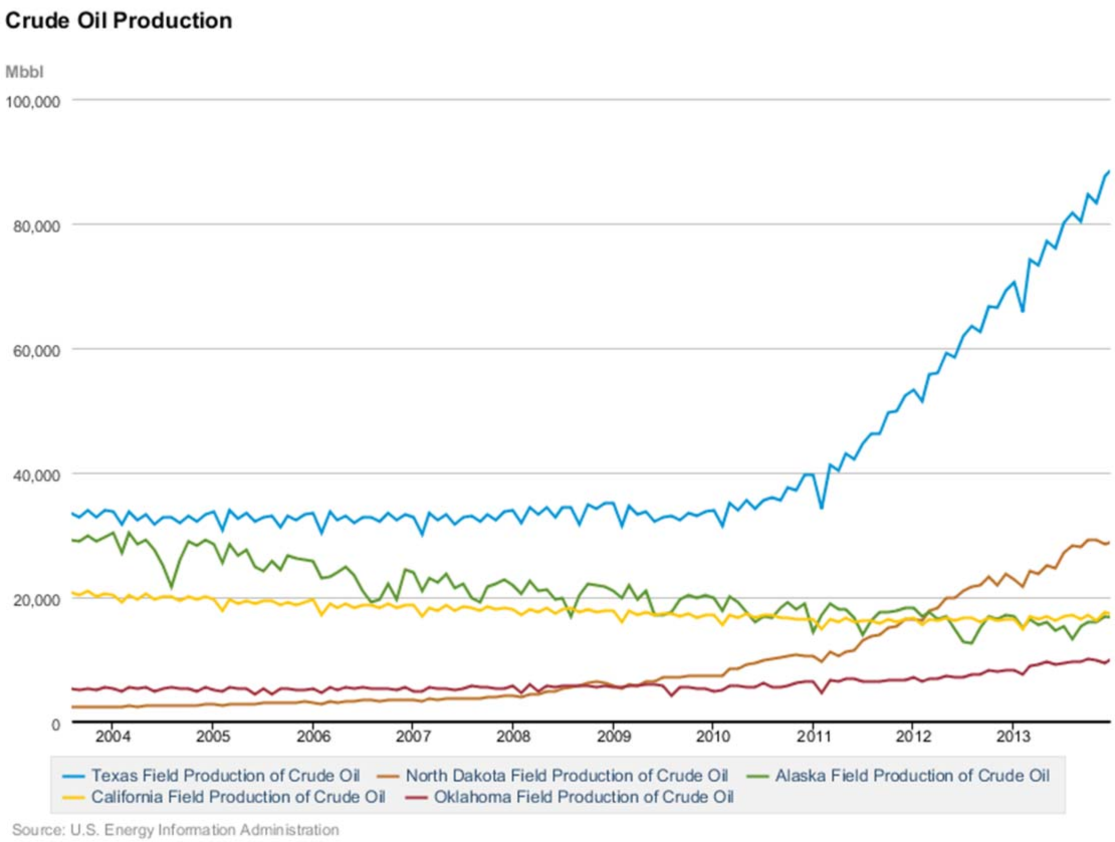

Figure 1. Monthly Crude Oil Production, in Millions of Barrels

As shown in Figure 1, North Dakota oil production has increased from less than five millions of barrels to nearly thirty millions of barrels per month. Moreover, the number of oil producing wells in North Dakota has nearly doubled during the last ten years. According to Official Portal for North Dakota State Government (2013), there were approximately 3,391 wells in North Dakota producing oil in 2005. In 2013, the number had risen to 9,723 wells (North Dakota Industrial Commission, 2013). In addition, the number of producing wells is expected to rise up to between 40,000 and 50,000 in the next 10 or 20 years (Dobb, 2013).Oil productions are mainly transported by oil trucks. Facing the increase of oil productions, more oil trucks are needed to transport sand, water, tanks, rig equipment, drilling mud, chemical, cement, pipe, scoria and gravel. Table 1 shows detailed truck movements, including inbound and outbound, for drilling each well (Tolliver and Dybing, 2010).To ship each item, origin and destination were proposed for each movement. For example, movement of drilling mud may start with an origin at a transition center and end with a destination at a drilling site. Each pair of origin and destination is connected by assigning the shortest route.

Table 1. Rig Related Movements per Well

Item	Number of trucks	Inbound or Outbound
Sand	80	Inbound
Water (Fresh)	400	Inbound
Water (Waste)	200	Outbound
Frac Tanks	100	Both
Rig Equipment	50	Both
Drilling Mud	50	Inbound
Chemical	4	Inbound
Cement	15	Inbound
Pipe	10	Inbound
Scoria/Gravel	80	Inbound
Fuel/trucks	7	Inbound
Frac/cement pumper trucks	15	Inbound
Workover rigs	1	Inbound
Total (One Direction)	1012	
Total Trucks	2024	

Based on analysis shown in Table 1, drilling each new well requires more than 2,000 large oil truck trips. This expansion has resulted in an increase in traffic, especially heavy large truck traffic. On average, about 15% traffic is truck traffic in non-oil impacted North Dakota counties while it goes up to 50% in oil-impacted counties (Tolliver and Dybing, 2010). In Table 2, the average number of trucks per day, the minimum and maximum value and the percentage of average daily traffic (ADT) for each listed major county are presented (Tolliver and Dybing, 2010). As shown in Table 2, more than 50 percentage truck ADT in half of these oil counties are introduced by large oil trucks (Tolliver and Dybing, 2010).

Table 2. Average Trucks per Day on Major County Roads

County	Minimum	Mean	Maximum	Trucks as a Percent of ADT
Billings	4	31	80	49
Bottineau	48	68	86	24
Bowman	30	125	233	62
Burke	4	22	66	43
Divide	28	96	172	54
Dunn	12	61	198	46
Golden Valley	23	38	50	42
McHenry	7	21	40	15
McKenzie	14	97	253	51
Mercer	1	3	6	14
Mountrail	12	65	252	49
Slope	7	17	34	37
Stark	9	26	62	24
Ward	24	105	217	26
Williams	10	68	312	51

This sudden increase of truck trips has contributed to a number of issues related to transportation, such as road impairment and maintenance and North Dakota oil county traffic congestion. It has been a major drive of prompting some researches on related issues.

1.2. Problem Statement

Tolliver and Dybing (2010) studied on how much the investment on highways is needed to support oil and gas production and distribution in North Dakota. Based on data collected from previous years, they analyzed traffic damage to highways and cost needed for the impairment. With the help of Geographic Information System (GIS) software, daily traffic trips were predicted based on the amount of oil production and were assigned to each road. The result reveals that fixing the impacted roads will require an investment of more than 900 million dollars from 2010 to 2030 due to the booming oil production.

Research by Tolliver and Dybing (2010) provides great insight, however, their research encounters several limitations, and one of them is the use of Passenger-Car Equivalent (PCE) factor values which are based on average PCE factors of all classes of trucks recommended by Highway Capacity Manual (HCM) 2010. It tends to underestimate the traffic.

The 1965 HCM first introduced the concept of PCE and defined it as the number of passenger cars displaced in traffic flow by a large vehicle, under the prevailing roadway and traffic conditions (HCM, 1965). Under the same traffic condition and during the same period, PCE factors can be calculated by counting the number of vehicles in different traffic flow consisting of all passenger cars and mixed vehicles. For example, under the same traffic condition, during an hour, for a traffic flow consisting of only passenger cars, there are one hundred passenger cars passing by a traffic counter. However, for a traffic flow consisting of one truck and passenger cars, there are ninety-seven vehicles passing by the traffic counter.

Thus, the PCE factor of this truck category under current traffic condition is calculated by one hundred minus ninety-seven and divided by one truck. The result is three. It means that under this traffic condition, effect of one truck on capacity equals to that of three passenger cars.

Moreover, in Tolliver and Dybing's analysis (2010), daily traffic trips were assigned by an all-or-nothing method. The all-or-nothing method assigns traffic on the shortest route between traffic analysis zones. Using this method, after reaching the capacity of the shortest route, the model will continue to assign traffic on the second shortest route until trips between traffic analysis zone pairs have all been assigned. It is clear that their method highly depends on the accuracy of the calculated capacity of each highway segments which in turn is affected by PCE values. The following section will illustrate how PCE affect capacity with HCM method in detail.

In HCM (2000), the capacity of a facility is defined as the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions (HCM, 2000). It also describes the stated capacity for a given facility as a flow rate that can be achieved repeatedly for peak periods of sufficient demand. The absolute maximum flow rate can vary from day to day and from location to location. Thus, capacity is not only a theoretical value, but also a practical value since it often comes from field observation and data collection. To determine the capacity of a facility, different types of vehicles need to be transferred to equivalent numbers of passenger cars by using PCE factors.

However the value of PCE factor presented by HCM has some shortfalls including the values only reflect average values of various classes of trucks. In their model, PCE factor is calculated by dividing the theoretical number of passing of one truck by the theoretical number of passing of one passenger car. Theoretical passing could be defined as the overtaking process by a faster vehicle and a slower vehicle, and both of these two vehicles keep their mainstream speed during the passing period on road section. In HCM’s model, only speed and traffic volume were taken into account. Therefore, in their model, overtaking action is considered to be successfully performed when two vehicles has different speeds. It is correct when it refers to low traffic volume, for example, under level of service A. Under that traffic conditions, overtaking process won’t be affected by other factors, such as traffic from opposite direction. However, when a road gets crowded, not only speed of vehicles will be affected, but also passing process will be interrupted by other vehicles: vehicles in front of the slow vehicle in the same lane and traffic from the opposite lane. Thus, theoretical passing number will be much higher than actual passing number, if only speed and traffic volume are considered as criteria.

To improve previous model, in this paper, a new model is proposed to develop a new set of PCE factors. The model is based on two main criteria: delay and headway. In section 2, previous methods used to calculate PCE factors are discussed. In section 3, methodology of this paper is introduced. Section 4 analyzes parameters in this model. Results of this model are discussed in section 5. Finally, summary and conclusion are stated in section 6.

CHAPTER 2. LITERATURE REVIEW

2.1. HCM 1965 Method

While the HCM 1965 first defined the concept of PCE factor, it also proposed a model to calculate PCE factor for two-lane highways. It suggested that PCE factor could be calculated by one criterion: average speed. By comparing average speed, the model can be described by Equation (1) (HCM, 1965):

$$P_p = \sum_{i=1}^{m-1} \sum_{j=2}^{m} C_i \cdot C_j \left(\frac{1}{v_i} - \frac{1}{v_j}\right) \tag{1}$$

Where

P_p is the total number of theoretical passenger cars passing within one kilometer during a given period.

v_i, v_j are travel speeds of slower and faster passenger cars, respectively.

C_i, C_j are numbers of vehicles having respective speeds v_i or v_j for the given period.

i, j respectively represent index of passed and passing vehicles.

m is one-direction passing-car volume for the given period.

To get the average theoretical number of passing of one passenger car, P_{kp}, the total number of theoretical passenger-car passing, P_p, is divided by m, one-direction passing-car volume. The equation is stated as:

$$P_{kp} = \frac{P_p}{m} \tag{2}$$

Similarly, the theoretical number of passing of one truck can be calculated by Equation (3):

$$P_{kt} = \sum_{l=1}^{m} C_l \left(\frac{1}{v_t} - \frac{1}{v_l}\right) \tag{3}$$

Where

P_{kt} is theoretical number of passing of one truck within one kilometer during a given period.

v_l is travel speed of a passenger vehicle.

C_l is the number of vehicles having a speed of v_l.

v_t is travel speed of the truck.

l is the passenger car index.

The PCE factor was calculated by the ratio of the theoretical number of passing of one truck to the theoretical number of passing of one passenger car, as given by Equation (4):

$$E = \frac{P_{kt}}{P_{kp}} \tag{4}$$

Where

E is PCE factor of trucks.

The method to determine PCE is straight forward and easy to follow; however, it assumes that the opposite-traffic volume was low, which means that opposite-traffic had no effect on the passing procedure. This method provided a persuasive result for divided highway, but it is not appropriate to be applied in two-lane highway, especially when the opposite lane is congested.

2.2. HCM 1985 Method

In HCM (1985), previous methods in PCE factor calculation for two-lane highway was revised, and a conclusion was demonstrated that mean speed cannot reflect realistic passing times precisely. Furthermore, a new model was developed to measure PCE factor, named "percent time delay." Percent time delay is the proportion of the cumulative travel time that a driver spends on following other vehicles to the entire travel time. Apparently, when more long-enough gaps show in the opposite lane, passing demand can be satisfied, which results in decreasing in percent time delay. On the contrary, when traffic condition can only allow fewer passing demands, percent time delay will increase.

Another essence in the study is that the capacity of a two-lane highway was proved to be a function of the directional split of traffic, ranging from a capacity of 2,800 pc/h in both directions of traffic combined for a 50 to 50 directional split to 2,000 pc/h for a 100/0 split.

Table 3 shows PCE factor value in HCM (1985) used in general terrain segment. As type of terrain change from level to mountainous, value of PCE factor increases exponentially. This indicates that when grade of highway increases, large vehicles have more effect on capacity. Furthermore, for each vehicle type, under LOS B and C, PCE factor value reaches its peak value under each type of terrain.

Table 3. Passenger-Car Equivalents of Heavy Vehicle in General Terrain Segment

Vehicle type	Level of service	Type of terrain		
		Level	Rolling	Mountainous
Trucks, E_T	A	2.0	4.0	7.0
	B and C	2.2	5.0	10.0
	D and E	2.0	5.0	12.0

2.3. HCM 2000 Method

After revising HCM 1985 method, in Archilla's research, he questioned the result got by HCM 1985 and stated that the directional split factors used in HCM 1985 Chapter 8 appeared to be overestimated (as cited in Douglas, Harwood, May, Anderson, and A. Ricardo, 1999). When Archilla conducted his research in TWOPAS using an uneven directional split factor, the operational performance (space mean speed, traffic delay rate, and percent time delay) is better than 50/50 split, which considered by HCM (1985) to be the ideal conditions to get the best operational performance. Both Krumins and Archilla got the similar conclusion that the PCE factor values in HCM (1985) were too high (as cited in Douglas, Harwood, May, Anderson, and A. Ricardo, 1999). Krumins (1991) reached his conclusion from field data, while Archilla's from traffic simulation software with TWOPAS model.

HCM (2000) used TWOPAS and UCBRURAL to calculate PCE factor. TWOPAS is developed as a two-lane highway traffic operation computer simulation model. UCBRURAL is a companion user interface, which provides a user-friendly environment to specific data input for TWOPAS and to display and analyze output data. Field data were collected to get practical results in twenty sites in four states and one province in Canada (as cited in Douglas, Harwood, May, Anderson, and A. Ricardo, 1999). These data included traffic volume, speed, and platooning data on high volume two-lane highways, comparison of speeds upstream and downstream of shoulder width transitions on two-lane highways, collection of truck crawl speeds on a steep upgrade, and evaluation of traffic operations on a steep downgrade.

Compared with old version, the newer revised TWOPAS model used in HCM 2000 has several big improvements (as cited in Douglas, Harwood, May, Anderson, and A. Ricardo, 1999), such as:

1. Updates to incorporate changes in driver and vehicle characteristics
   (1) Update acceleration and speed maintenance capabilities of vehicle population
   (2) Update reduction in speeds selected by drivers on horizontal curves
2. Other TWOPAS/UCBRURAL improvements
   (1) Allow interface to take advantage of TWOPAS capability to model vertical curves at changes of grade
   (2) Generate driven desired speeds for correct distributions when more than one vehicle category is present

These improvements allow providing a new set of PCE factor for more vehicle categories and under more types of terrain. Table 4 shows the vehicle performance data used by TWOPAS as input data in TWOPAS model (as cited in Douglas, Harwood, May, Anderson, and A. Ricardo, 1999). Compared with the old one, revised edition lowers weight to net horsepower ratio resulting from new technology on braking, which reduces braking time for vehicles to stop.

Table 4. TWOPAS Input Data

<table>
<tr><td rowspan="2">Vehicle category</td><td rowspan="2">TWOPAS vehicle type</td><td rowspan="2">Percent of truck population</td><td colspan="2">Weight to net horsepower ratio (lb/hp)</td><td colspan="2">Weight to projected frontal area ratio (lb/ft^2)</td><td rowspan="2"></td></tr>
<tr><td>Old</td><td>New</td><td>Old</td><td>New</td></tr>
<tr><td rowspan="4">Truck</td><td>1</td><td>12.0</td><td>266</td><td>228</td><td>620</td><td>682</td><td>Lowest performance truck</td></tr>
<tr><td>2</td><td>25.6</td><td>196</td><td>176</td><td>420</td><td>462</td><td></td></tr>
<tr><td>3</td><td>34.0</td><td>128</td><td>140</td><td>284</td><td>340</td><td></td></tr>
<tr><td>4</td><td>28.4</td><td>72</td><td>76</td><td>158</td><td>174</td><td>Highest performance truck</td></tr>
<tr><td rowspan="2">Vehicle category</td><td rowspan="2">TWOPAS vehicle type</td><td rowspan="2">Percent of PC population</td><td colspan="2">Maximum acceleration (ft/sec^2)</td><td colspan="2">Maximum speed (ft/sec)</td><td rowspan="2"></td></tr>
<tr><td>Old</td><td>New</td><td>Old</td><td>New</td></tr>
<tr><td rowspan="5">Passenger car</td><td>9</td><td></td><td>9.277</td><td>11.17</td><td>109.14</td><td>112.8</td><td>Lowest performance PC</td></tr>
<tr><td>10</td><td></td><td>9.766</td><td>11.99</td><td>114.89</td><td>117.8</td><td></td></tr>
<tr><td>11</td><td></td><td>10.089</td><td>12.77</td><td>118.69</td><td>121.1</td><td></td></tr>
<tr><td>12</td><td></td><td>10.429</td><td>13.22</td><td>122.69</td><td>127.0</td><td></td></tr>
<tr><td>13</td><td></td><td>11.201</td><td>14.10</td><td>131.78</td><td>142.7</td><td>Highest performance PC</td></tr>
</table>

Based on the results of simulation runs with the TWOPAS model, PCE values for trucks (E_T) is calculated by Equation (5) and Equation (6) using ATS and PTSF respectively, based on data for a traffic stream containing a specified percentage of trucks.

$$E_T = \frac{P_T(v/f_G) + ((ATS_{tr/grade} - ATS_{pc/grade})/-0.0125)}{P_T(v/f_G)} \tag{5}$$

$$E_T = \frac{P_T(v/f_G) + ((PTSF_{tr/grade} - PTSF_{pc/grade})/(0.879e^{-0.000879v/f_G}))}{P_T(v/f_G)} \tag{6}$$

Where:

v is flow rate (veh/h).

P_T is proportion of trucks in the traffic stream, expressed as a decimal.

f_G is grade adjustment factor.

$ATS_{tr/grade}$ is average travel speed for the mixed flow in non-level terrain or on a specific grade (km/h).

$ATS_{pc/grade}$ is average travel speed for the all passenger-car flow in non-level terrain or on a specific grade (km/h).

$PTSF_{pc/grade}$ is percent time spent following for the mixed flow in non-level terrain or on a specific grade.

All the values of the factors were decided by the shapes of the fundamental speed-flow and PTSF-flow curves displayed in Figure 2 and Figure 3 (HCM, 2010).

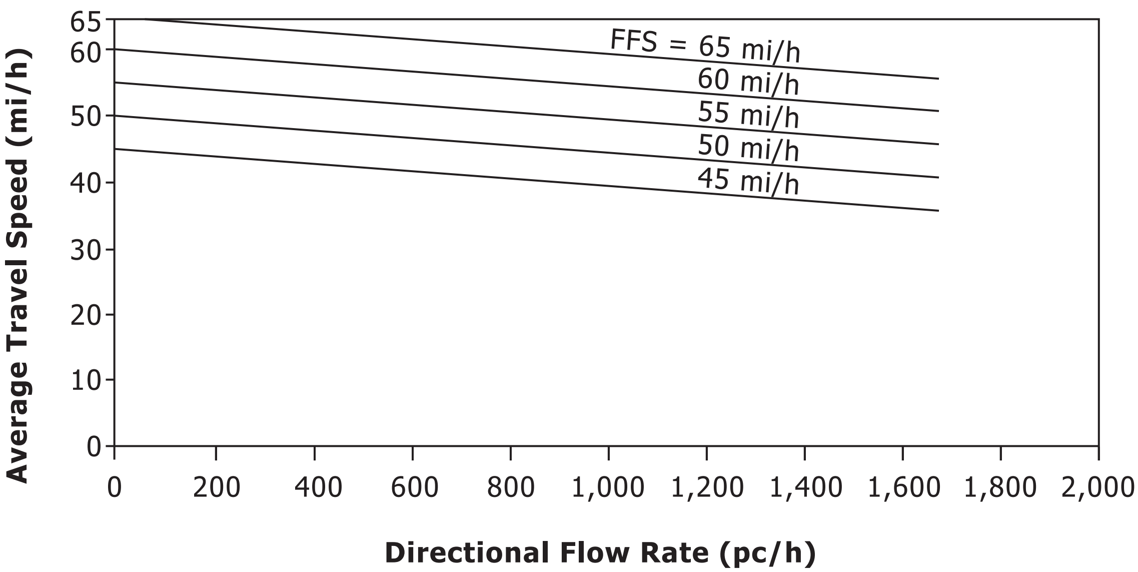

Figure 2. Speed-Flow Relationships Used in Two-Way Segment

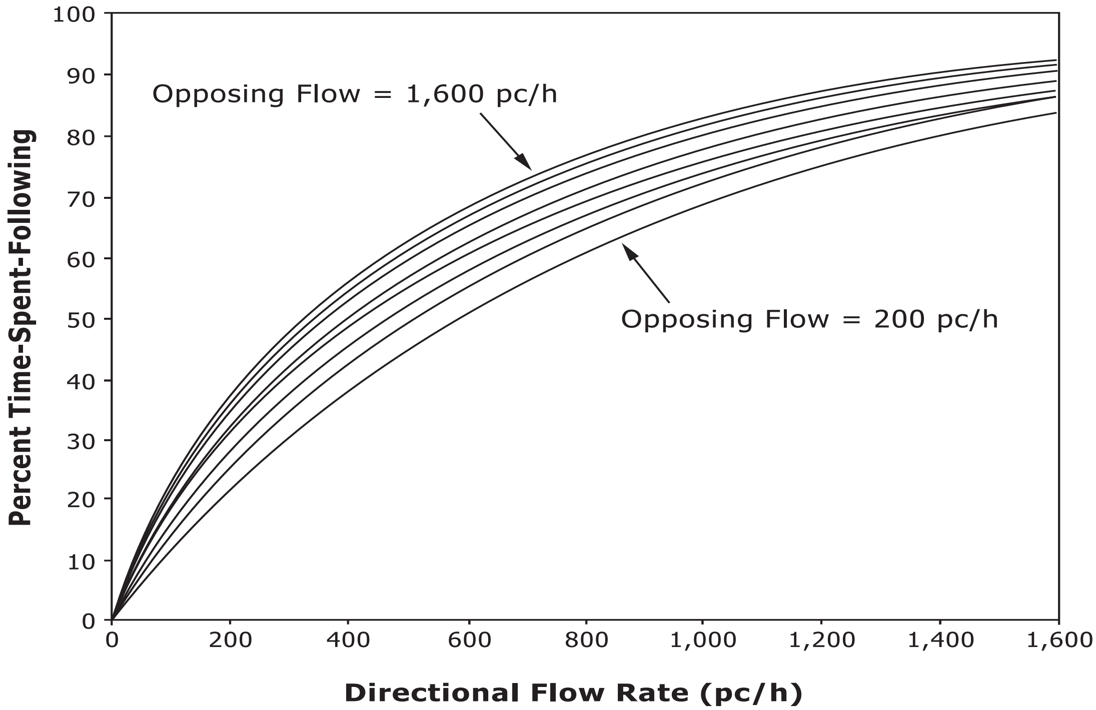

Figure 3. PTSF-Flow Relationship Used in Two-Way Segment

Equation (5) indicates that the slope of the speed-flow line in Figure 2 does not vary with flow rate. Similarly, Equation (6) presents the slope of each PTSF-flow shape. It can be observed that the slope decreases as flow rate increases.

Table 5 presents PCE factor values for trucks in level terrain by HCM (2000).

Table 5. PCE Factor Values for Trucks in Level Terrain

Two-way flow rate (PC/h)	Directional flow rate (PC/h)	ATS (km/h)	PTSF
		E_T	E_T
0-600	0-300	1.7	1.1
>600-1,200	>300-600	1.2	1.1
>1,200	>600	1.1	1.0

As Krumins and Archilla mentioned above, value of PCE factor calculated by newer model in HCM 2000 is lower than that provided by HCM 1985 (as cited in Douglas, Harwood, May, Anderson, and A. Ricardo, 1999). Also it makes values of PCE factor more precise than previous method. However, there are still limitations to use this set of PCE value for oil trucks operating on two-lane rural highway in western North Dakota for the following reasons:

1. PCE factors value in HCM 2000 are calculated by using Equation 5 and 6, however the equations are developed empirically. As stated by Archilla (as cited in Douglas, Harwood, May, Anderson, and A. Ricardo, 1999, p. 131), “the vehicle mix used to determine E_T consisted of 14 percent trucks and 86 percent passenger cars was selected because the HCM suggests a truck proportion of 14 percent as a default value for rural two-lane highways.” However, in western North Dakota oil area, oil trucks takes up average 42% of average daily traffic (Andrew and Kimberly, 2012) Also, all data used in TWOPAS model were collected in four states (California, Florida, Missouri, and Oregon) and one province in Canada (as cited in Douglas, Harwood, May, Anderson, and A. Ricardo, 1999). It may not practical for ND.
2. This set of values is the average value for all truck categories, not for one specific truck category. However, truck length can vary from 23 feet to more than 80 feet and most oil trucks are 85 feet in length. Passing longer trucks requires more time and the probability to fulfill this requirement is lower than that to pass a smaller truck. On two-lane highway, larger trucks will block more vehicles and cause longer delay. It is hardly convincing to use average value to represent an extreme value.

3. Criteria used in TWOPAS model is average travel speed and flow rate in unit miles per hour and vehicles per hour, respectively. What the model calculates is the average space occupied by each vehicle on highway under prevailing condition. And compare that between trucks and passenger-cars. It is reciprocal of density that dividing flow rate by average travel speed. However, it overlooked a fact that trucks will have an effect on following traffic flow. HCM method measured this effect only in study time period, and at some cases, it will underestimate and overestimate the PCE value. For example, assume that the study period is n hour, and there are i vehicles passing the counter during this period, which is shown in Figure 4.

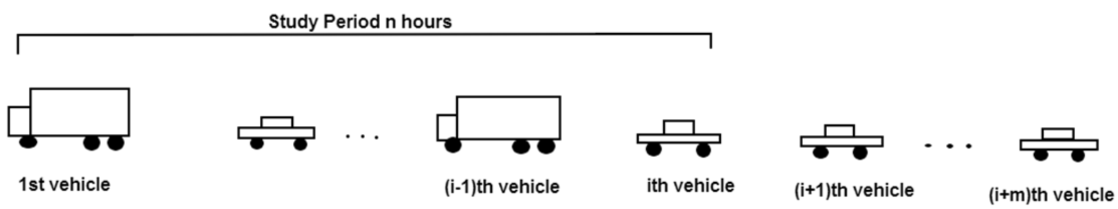

Figure 4. Traffic Flow in Study Section

Say, under certain condition, only the first i/2 traffic are affected by the first truck, which means that trucks in the first i/2 traffic occupy less space than trucks in the other half. In this case, calculating average space occupied by one truck in study period will overestimate PCE value of trucks in the first i/2 traffic and underestimate PCE value of trucks in the other half. Another case that HCM2000 model ignored is that when the effect of trucks exceeds the study period. For example, under certain condition, trucks in the study period time n have effect on all the (i+m) vehicles, as shown in Figure 4. In HCM 2000, the model did not take the m vehicles that exceed study period into account. In other words, the predefined study period may underestimate PCE by omitting delay effect.

2.4. Delay Based Method

Craus, Abishai and Itzhak (1980) revised the method the HCM proposed in 1965, and developed another model specific to two-lane highway. They studied characteristic of two-lane highway that opposite traffic has considerable impact of passing procedure, and the headway distribution characteristic. In their model, PCE factor could be generated from the ratio that delay time caused by one truck to the delay by one passenger car, as stated by Equation (7):

$$E = \frac{d_{kt}}{d_{kp}} \tag{7}$$

Where

d_{kt} is delay caused by one truck.

d_{kp} is delay caused by one passenger car.

They pointed out that when headway from opposite traffic was not long enough to allow a vehicle to overtake, delay would happen, until there was headway from the other lane long enough to allow the overtaking action. Headway, defined by HCM, is the time, in seconds, between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles. If vehicle arrival follows some pattern given by the counting distribution, there is also a distribution of headways of these successive vehicles. In their study, they assumed that headways between vehicles are distributed exponentially. The possibility that overtaking action could happen was calculated based on minimal gap that enabled the completion of a passing maneuver and headway distribution of opposite lane. Total delay was the result of multiplying the duration of headways that less than the minimal gap and the number of such headways.

This model presents a new idea to calculate PCE factor, however it is only reasonable when level of service is A and B. Before their model was built, they assumed that headway was exponential distributed. It is only valid when traffic arrival follows Poisson distribution. Poisson distribution is used to describe discrete events that are truly random, and only under level of service A and B, traffic arrival can happen truly randomly. Therefore, when traffic gets crowded, traffic will get interrupted by each other, and arrival can’t be assumed as random.

2.5. Spatial Headway Based Method

Spatial headway method was considered as the most appropriate for level freeway segments by Krammes and Crowley (2008). They believed that the variable used to determine PCE factor must reflect three factors: (1) trucks are larger than passenger cars, (2) trucks have operating capabilities that are inferior to those of passenger cars. It means that more braking distance is needed, which results in longer distance when trucks follow other vehicles, and so is when other vehicles follow trucks, and (3) trucks have both physical and psychological impact of nearby vehicles and drivers. Based on these thoughts they calculated

PCE factor as the ratio of the space a passenger car needed to pass a truck and the space it needed to pass a passenger car, and stated as Equation (8):

$$E_T = [(1 - P_T) H_{TP} + p H_{TT}] / H_P \tag{8}$$

Where

P_T is the proportion of trucks.

H_{TP} is the headway of a truck when it follows a passenger car in the mixed vehicle stream.

H_{TT} is the headway of a truck when it follows a truck in the mixed vehicle stream.

H_P is the headway of a passenger car following either vehicle type in the mixed vehicle stream.

This method considered the effects of trucks on other vehicle drivers when trucks were followed and being passed, which is quite inspiring, however, Krammes and Crowley ignored an important effect, delay effect. The regular vehicles and large trucks will cause the different delay effect on the following traffic flow under certain condition.

2.6. Density Based Method

Recently, with the advanced computer technology, numbers of studies about PCE factor utilized simulation software. Aiming to analyze the impact of a variety of traffic, design, and vehicle characteristics on PCE factor, Nathan and Elefteriadou (1997) used Freeway Simulation (FRESIM) estimated PCE factor based on traffic density. The method was based on density and consisted of six steps:

(1) A base curve is first generated, whose x axle is flow and y axle is density, by simulating an all-passenger-car traffic stream.

(2) Generate another flow-density curve, called mix curve, with traffic stream consisting of passenger car and trucks.

(3) Substitute a certain number of passengers in the mixed vehicle traffic stream with an equal number of trucks. The proportion of vehicles replaced is 5%.

(4) At a selected traffic flow rate, qs, simulate this mixed traffic from step 3, and record the traffic density output.

(5) Project a horizontal line from the density point in step 4 and intersect with the mix curve at point B to get the flow rate qM; then intersect with the base curve at point A to get the flow rate qB.

(6) PCE factor for trucks is calculated by using following Equation (9), developed by Sumner et al., 1984:

$$PCE = \frac{1}{\Delta p}[\frac{qB}{qs} - \frac{qB}{qM}] + 1 \qquad (9)$$

Where

Δp is the proportion of the trucks that is added to the mix traffic stream.

qB is the based vehicle flow at a constant traffic density.

qM is the mixed vehicle flow at a constant traffic density,

qs is the truck flow at a constant traffic density.

Following the six steps above, relation between PCE factor and more variables were tested: highway grade, highway length of grade, number of lanes per direction, free-flow operating speed of traffic, percentage of trucks in the traffic stream, and traffic flow rate. The result of their research provided a new set of PCE values, and it represented a function of PCE factor and traffic variables that had impacts on it.

2.7. Simulation Software Based Method

Ahmed, Younghan, and Hesham (2005) developed a new set a PCE factor using simulation software. Their method was straight forward, and could be described as:

$$PCE = (\text{actual field capacity in pcph} - \text{number of PCs})/\text{number of trucks} \qquad (10)$$

By reviewing previous researches, they indicated that except the report by Al-Kaisy et al. (2005), there were no studies about the impact of heavy vehicles during oversaturated condition. Their study was conducted to answer the question of "does the effect of heavy vehicles remain the same when a highway facility operates at different level of service?" In their research, queue discharge flow (QDF) capacity was utilized as the criterion in developing the congested PCE factor. Actual field capacity data was collected at two study sites. After calibration and validation simulation model, they generated PCE factor for heavy vehicles under congested conditions, and studied the effect of proportion of trucks, length of grade, and percentage of upgrade on PCE factors. They found that heavy vehicles' behavior during congestion mainly determines PCE values. Also, they pointed out that using HCM values under oversaturated condition would involve a significant amount of error.

Their result was from actual field data, so it could be the closest value to real PCE factor value. However, their result is site-specific, which means that PCE factor developed by their study is not suitable for other places. And plus their research is dedicated for Multi-lane freeway condition only. Moreover, since their method is site-specific, to generate PCE factor for entire highway system needs numerous sensors, which can be very costly.

2.8. Truck Percentage Based Method

Sun, Lv, and Paul (2008) started a study on PCE values within highway work zones. Because of the distinct characteristics of highway work zones, traditional method (the ratio of the headway) usually underestimated PCE values for highway work zones. Therefore, they established a closed loop method based on both speed and truck percentage, stated as:

$$V_E = V_M(1 - P_t) + V_M \times P_t \times E_t \qquad (11)$$

Where

V_E is the base volume (only consisting of passenger cars).

V_M is the mixed volume (including both passenger cars and trucks).

P_t is the percentage of trucks.

E_t is PCE factor.

Figure 5 shows the flow chart of a closed-loop calibration at the j th step.

Their result was shown in three dimensional charts to display the change of PCE factor with other criteria: speed and percentage of trucks.

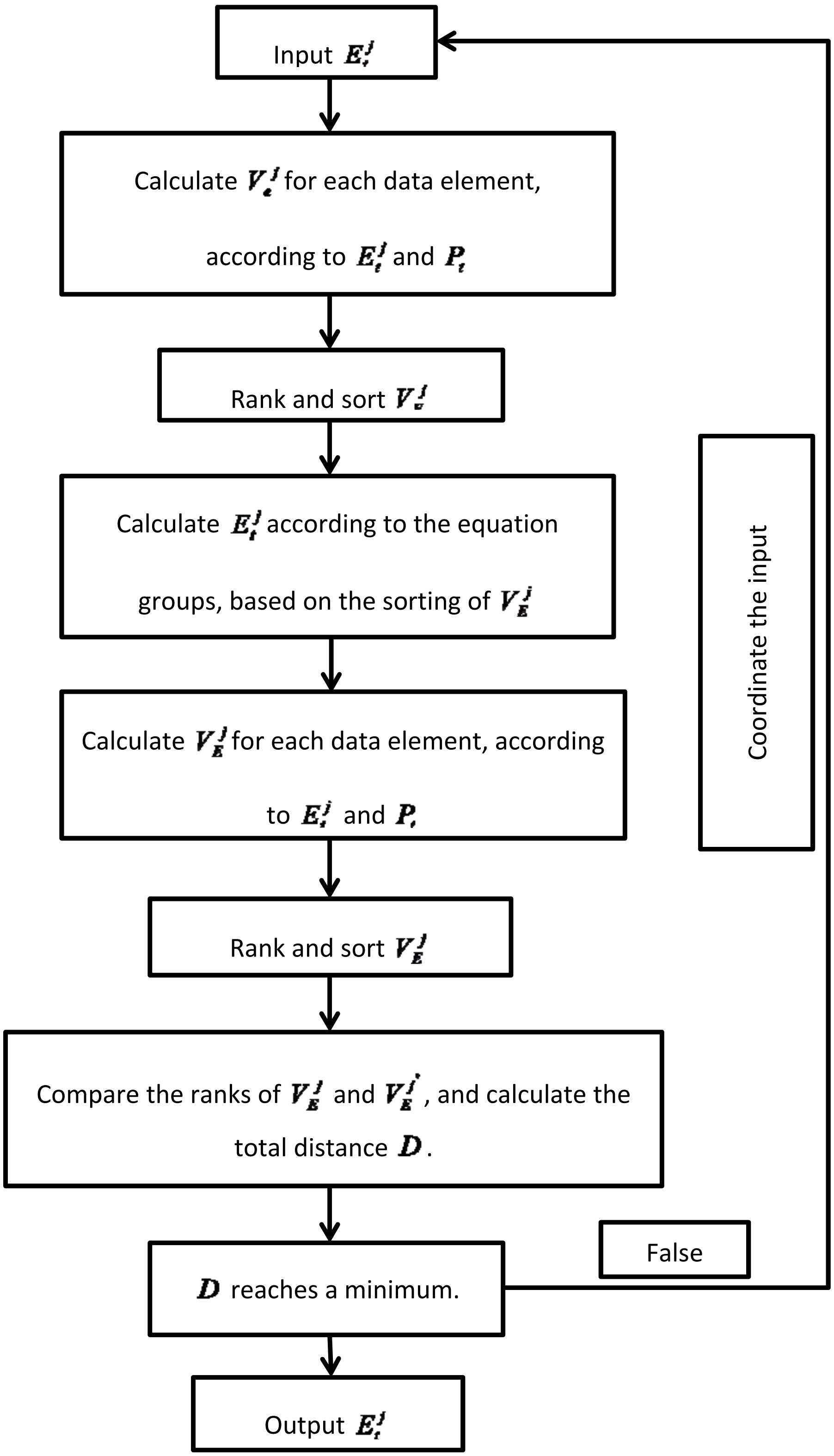

Figure 5. Flow Chart of a Closed-Loop Calibration

Comparing all these models and methods, simulation method is more prominent in simulating driver behaviors and traffic flow performance. However, expenses spent on software have to be considered when conducting a research. On the other hand, an analytical model computes PCE factor values by building analytical mathematical models and simulating driver and traffic flow behavior in mathematical way. Using an analytical model, it is easier and useful to visualize, understand and discover influence of each factor in the model on PCE factor value. For example, PCE factor is affect by traffic volume, average travel speed and some other factors. In an analytical model, it is easy to control the value of each factor, and to visualize the fluctuation of PCE factor value when each variable changes. Thus, in this paper, an analytical model is chosen to develop and compute PCE factor over simulation model.

CHAPTER 3. METHODOLOGY

3.1. Introduction

As mentioned in introduction, western North Dakota state is experiencing oil boom, which results in increasing oil truck traffic to transport oil products, 55% of which happens on two-lane rural highway. Such a great number of large truck volume experienced on rural highway provokes numbers of issues such as pavement maintenance and rehabilitation needs study. PCE factor is one of key factors in analyzing and estimating these issues. However, previous studies provided few useful information regarding PCE factors for large trucks, such as oil truck, on two-lane rural highway under various congestion levels. In this paper, a model will be developed to understand and estimate PCE factors for large truck on two-lane rural highway under various LOS conditions.

PCE factor is defined by HCM (1965) as the number of passenger cars displaced in traffic flow by a truck, under the prevailing roadway and traffic conditions. In another words, PCE factor is the ratio of effect of one truck on highway traffic flow to that of one passenger-car has on highway traffic flow, in this case, two-lane rural highway. A wrong impression about PCE factor is that PCE factor is computed as the number that one truck can be replaced by consecutive passenger-cars with zero headway between them. On the contrary, PCE factor is supposed to be the number of successive passenger-cars that can replace one truck in prevailing road condition. As mentioned above, another mis-understanding about trucks on two lane highway is that they only have impact on adjacent vehicles. In fact, trucks on two lane highway will affect traffic flow behind them. Because of low deceleration rate of trucks, truck drivers tend to keep a long distance when a truck follows a passenger car than when a passenger-car follows a passenger-car. Moreover, special characteristic of two-lane highway limits passenger-car drivers' ability to overtake one slow truck. When traffic flow is stuck by a truck, the impacted platoon will travel as the truck speed, which reduces operation efficiency of a highway, as average travel speed of trucks is lower than that of passenger-cars. Thus, to estimate PCE factor, in this model, two criteria will be considered, headway between passenger-cars and one slow vehicle, and delay caused by the slow vehicle. Here, slow vehicle refers to one slow passenger-car or one oil truck. The headway criteria takes into consideration trucks' physical impact of the nearby vehicles and drivers while the delay criteria takes account of trucks' physical impact of vehicles in the following traffic stream under various traffic conditions. In this model PCE factor is computed by comparing the total impacted length of traffic that one oil truck caused to the one that one slow passenger-car caused. The model can be expressed as Equation (12) and each factor are defined below and shown in Figure 6:

$$PCE = \frac{Tlength_T}{Tlength_{PC}} = \frac{queue_T + headway_T}{queue_{PC} + headway_{PC}} \tag{12}$$

Where

$Tlength_T$ is total impacted length caused by a truck, including space occupied by the truck and the queue length of following traffic affected by the truck.

$Tlength_{PC}$ is total impacted length caused by one slow passenger-car with the same travelling speed as the slow truck, including the space occupied by the slow passenger-car and the queue length of following traffic affected by the slow passenger-car.

$headway_T$ is space between the passenger-car in front of the truck and the one follows right behind the truck.

$headway_{PC}$ is headway between a passenger car a slow passenger car.

$queue_T$ is the length of queue of number of n1 passenger-cars caused by the truck.

$queue_{PC}$ is the length of queue of number of n2 passenger-cars caused by the slow passenger-car.

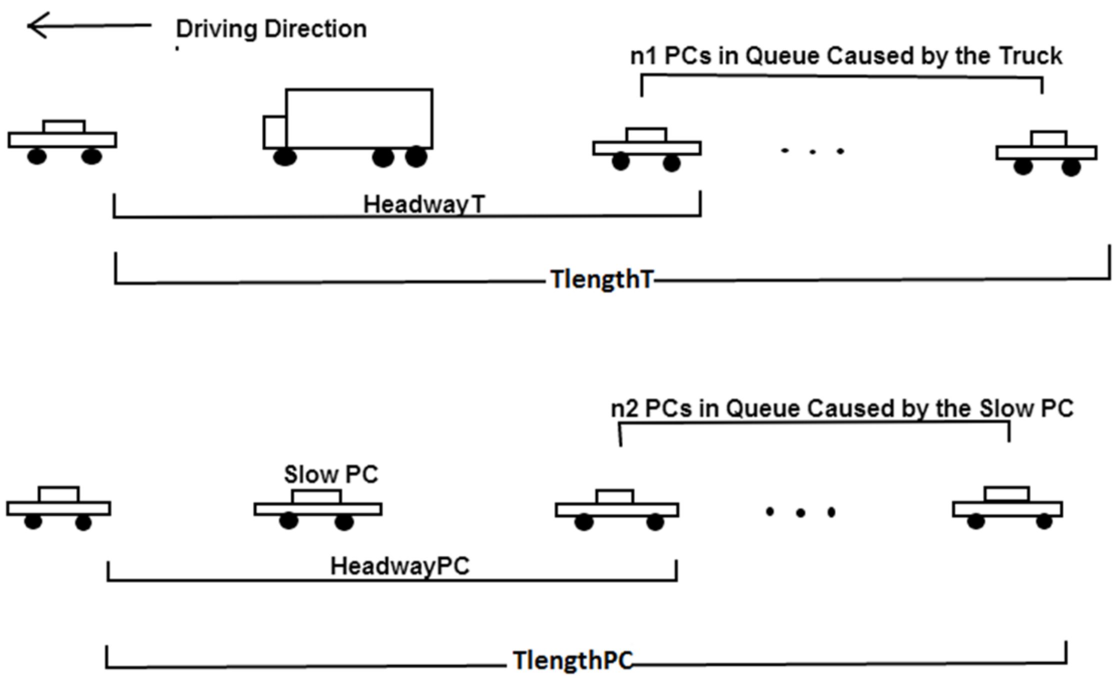

Figure 6. PCE Factor Model Introduction

3.2. Queue Length Model

3.2.1 Introduction

Because of the distinctive characteristic of two-lane highway, passing maneuver can only be completed when there is enough space between two successive vehicles from the opposite lane, and passing a large oil truck will take longer time than passing a passenger-car. In addition, the huge bulk of oil trucks blocks drives eyesight, which makes safety passing distance is greater when a passenger-car overtakes an oil truck than it passes a passenger-car. Passing a truck requires a longer passing distance, which means that it needs a longer gap showing up from the opposite lane. Therefore, for a passenger-car, to pass a truck is less possible than to pass a passenger-car. When passing maneuver cannot be acted, vehicles are forced to follow behind the slow vehicle with a lower speed, until safety passing distance shows up from the other lane. Thus, time spent on following a truck is usually longer than following a passenger-car. In other words, more vehicles will be impacted by a slow truck than a slow passenger-car under the same condition. While vehicles waiting for the gap that longer enough to allow passing maneuver, a queue is generated. The queue length is depended on arrival rate of following traffic and the LOS of the opposite lane. In other words, when arrival rate of following traffic holds constant, queue length is cumulated with LOS of opposite lane getting worse. Also, if LOS of the opposing lane is constant, queue length will increase when there are more vehicles coming in the unit time. The following section will introduce the model to calculate the rate of incremental of queue length.

Before develop the model, some assumptions should be made:

(1) This model is specifically based on characteristics of oil trucks and two-lane rural highway condition.

(2) There is no passing-lane considered in studied segments.

(3) Type of terrain of road sections studied in this model is level. Rolling and mountain terrains are not studied in this model.

(4) Studied traffic platoon only consists of passenger cars and one oil truck, and the only one truck leads the traffic flow.

(5) Only one event happens at one time. It means that only two vehicles get involved in the process of overtaking, the slow one and the fast.

To control variables, only vehicles characteristics are considered as changing variables, except of which, road condition and vehicle performance are considered as the same when comparing $headway_T$, $headway_{PC}$, $queue_T$, $queue_{PC}$. It means that to compare the difference of impact between a truck and a passenger-car, both of them will be assumed to travel with the same speed, which is considered as a lower speed compared with average mainstream speed under each LOS. In addition, weather and road type are assumed to be the same and all vehicles are operating rationally. To control variable, only one truck and one slow passenger car are in studied traffic flow. PCE factor is the number of passenger cars that can substitute with one truck. Therefore, this model measures the impact that one truck brings to the entire traffic flow and the impact that one slow passenger-car brings to the entire traffic flow. Thus, the ratio of these two impacts will be the value of PCE factor, which represents the number of passenger-cars, can be used to substitute one truck.

As mentioned above, delay caused by a slow vehicle is determined by the frequency that the safety passing distance is showing up in the opposite lane. Due to the large size of oil trucks, more time and longer passing distance is required for passenger-cars to overtake them. Therefore, the delay caused by oil trucks is longer than that brought by passenger-cars.

Under different Level of Service (LOS), vehicle travel speed, traffic density, traffic volume, vehicle headway distribution, and vehicle arrival rate are different. In this paper, LOS will be divided into three groups based on traffic performance and headway distribution: LOS A and B, LOS C and D, and LOS E and F. Under LOS A and B, traffic travels with little interruption. Drivers feel comfortable and convenient under these two levels. Thus, traffic arrives randomly, and headway is negative exponential distributed (Wolfgang, Louis, and William, 1982). Travel speed of vehicles is mainly limited by geometric design features, other than traffic flow. Under LOS C and D, average travel speed decreases, because traffic volume increases. Traffic density is higher than that under LOS A and B. However, traffic flow is still operating stable. There are some restrictions on drivers' ability to maneuver, which results in poor level of comfortable. Therefore, headway distribution cannot be expressed by negative exponential distribution, which will be described more in following sections (Wolfgang, Louis, and William, 1982). Under LOS E and F, highway capacity is reached or exceeded. Traffic flow condition is unstable and any traffic accident will cause extensive queuing and even break down.

In following sections, queuing length value will be calculated corresponding to different LOS group.

3.2.2 Under LOS A and B

According to Wolfgang, Louis, and William (1982),under LOS A and B, headway distribution and vehicle arrival distribution can be seen as truly random, and can be described by negative exponential distribution and Poisson distribution respectively.

The negative exponential distribution is stated as:

$$P(q \geq \alpha) = e^{-\lambda\alpha} \tag{13}$$

Where:

q = headway of traffic in each direction (s);

α = a given headway (s);

λ =mean arrival rate (veh/s);

P = the probability of a headway, q being greater than or equal to α seconds.

To compare delay that truck and slow passenger-car result in, model M/M/1 based on queuing theory is introduced here. In this model, the truck and the slow passenger-car are seen as service channel with their own speed V_T. When truck and slow passenger car are seen as standing service channel, the rest traffic (original speed denoted as V_C) in the same lane moves with a relative velocity:

$$V_R = V_C - V_T \tag{14}$$

The traffic density (K) remains the same, however, the relative average rate of arrival (λ_R) would change to

$$\lambda_R = V_R \times K = (V_C - V_T) \times K \tag{15}$$

To calculate average queue length, model M/M/1 queue is introduced here. M/M/1 queue model is used to calculate queue length in a system with a single server. Arrival rate has Poisson distribution, and service rate has an exponential distribution. In M/M/1 queuing model, relative average rate of arrival is seen as queue birth rate. When a passenger-car follows a truck or slow passenger-car, it can be seen as being served. Time spent on following slow vehicles can be seen as service time. According to Craus, Abishai and Itzhak (1979), time spent by one passenger-car following slow vehicle is given by:

$$d = \left(\frac{1-e^{-\lambda\alpha}}{\lambda e^{-\lambda\alpha}} - \alpha\right) \cdot \left(\frac{u}{u+v}\right) \tag{16}$$

Where

u is the speed of average of opposite traffic;

v is the speed of the slow vehicle;

The rest parameters are defined above.

If upstream traffic arrival rate λ_R is smaller than service rate d , average queue length E_{m1}: the average number of units waiting to be served (average queue length) is calculated by Equation (17), suggested by Wolfgang, Louis, and William (1982):

$$E_{m1} = \frac{\lambda_R^2}{d(d-\lambda_R)} \tag{17}$$

Where

λ_R is arrival rate of upstream traffic calculated by Equation (15);

d is calculated in Equation (16).

If upstream traffic arrival rate λ_R is bigger than service rate d , queue length is calculated by Equation (18) purposed by Henk and Francesco (n.d.):

$$E\{Q(t)\} = E\{Q(t-\Delta t)\} + q\Delta t \tag{18}$$

Where: $E\{Q(t)\}$ is queue length at time t ; Δt is a small time period; $E\{Q(t-\Delta t)\}$ is queue length at time $t-\Delta t$; q is the coming traffic arrival rate in veh/h. Based on this equation, when queue death rate is less than birth rate, the increasing rate of the queue equals to queue birth rate subtracting queue death rate. When traffic flow encounters a bottleneck, which is the oil truck or the slow vehicle in this case, traffic is forced to slow down because of lower speed of the slow vehicle. Unless there are more vehicles leaving the bottleneck than the coming vehicles, the queue will cumulate infinitely. Because safety passing distance to passing passenger-car is shorter than that for a truck, it is more likely to pass a passenger-car than to pass a truck under same condition. Thus, with the same queue birth rate, however less death rate, the growth rate of the queue caused by trucks is higher. With LOS getting worse, queue growth rate gets fast. Taking two extreme conditions as example, under LOS A, the number of traffic got impacted by the slow vehicle is only a small number, which could be one or two vehicles. On the other extreme condition, which is under LOS F, there is hardly any possibility that safety passing distance showing up in the opposite lane, so the queue grows with a high rate and increases infinitely. However, the statement is not always true. In reality, peak hour traffic only last a few hours, which means that queue length will start to decrease when LOS gets better.

3.2.3 Under LOS C and D

Under LOS C and D, traffic condition is more congested than under LOS A and B. Headway distribution is no longer random. Vehicle headway distribution is affected by other vehicles, because more weaving is occurring and vehicles starts to have effects on each other. Thus, headway distribution cannot be described as negative exponential distribution under LOS C and D. As mentioned above, increasing traffic volume lower the possibility that allows vehicles to take overtaking action. For this condition, queue birth rate exceeds queue death rate, which generate infinite queue. Thus, M/M/1 queuing model cannot be used here.

According to this situation, M3 headway distribution model is suggested for LOS C and D (Vasconcelos, Silva, Seco, Alvaro and Silva, 2012):

$$F(t) = (1-\theta)e^{-\lambda(t-\Delta)},\ t \geq 0 \tag{19}$$

Where:

λ = flow rate in vehicle/s;

Δ = minimum headway between bunched vehicles;

θ = the proportion of constrained vehicles;

t = headway;

$F(t)$ = probability distribution of headways.

The probability that the headway q is less than t is given by Equation (20):

$$F(q < t) = 1-(1-\theta)e^{-\lambda(t-\Delta)} \tag{20}$$

Where all the parameters are defined above.

For the opposite lane headway distribution, the probability, $F(t)$, for delay by n failed overtaking, and the $n+1$ trial is performed is given by:

$$F(t) = [1-(1-\theta)e^{-\lambda(t-\Delta)}]^n (1-\theta)e^{-\lambda(t-\Delta)} \tag{21}$$

Where

n is the number of headways smaller than α.

The mean expected value of n may be calculated by a summation of the multiplication of number of headways by their probabilities, as given by Equation (22):

$$\bar{n} = \sum_0^\infty n[1-(1-\theta)e^{-\lambda(t-\Delta)}]^n (1-\theta)e^{-\lambda(t-\Delta)} = \frac{1-(1-\theta)e^{-\lambda(t-\Delta)}}{(1-\theta)e^{-\lambda(t-\Delta)}} \tag{22}$$

Where

$\bar{n}$ is the expected value of n.

The number, N, of headways smaller than t seconds is given by:

$$N = \lambda[1-(1-\theta)e^{-\lambda(t-\Delta)}] \tag{23}$$

The duration of time occupied by such headways is given by:

$$H = 1-(1-\theta)e^{-\lambda(t-\Delta)}(\lambda t + 1) \tag{24}$$

Proof process is stated as follows:

Assume the intervals of lengths lying between t and $t+dt$, and for the duration we are dealing with a period of one hour (3600 seconds).

In one hour, the expected number of headways greater than t is,

$$T(1-\theta)e^{-\lambda(t-\Delta)} \tag{25}$$

Where

T =vehicles per hour= 3600λ .

Similarly, during the same time the expected number of headway greater than $t+dt$ is,

$$T(1-\theta)e^{-\lambda(t+dt-\Delta)} \tag{26}$$

The number of headway of lengths between t and $t+dt$ is,

$$T(1-\theta)e^{-\lambda(t-\Delta)}(e^{-\lambda dt}-1) \tag{27}$$

According to Greenshields and Weida (1952),

$$T(1-\theta)e^{-\lambda(t-\Delta)}(e^{-\lambda dt}-1)=\lambda T(1-\theta)e^{-\lambda(t-\Delta)}dt \tag{28}$$

The length of all such intervals could be taken as t.

Therefore, the total time in seconds of these intervals is,

$$\lambda Tt(1-\theta)e^{-\lambda(t-\Delta)}dt \tag{29}$$

By integrating Equation (29) between t and infinity, we can get the time occupied by all these intervals greater than t during one hour,

$$\begin{aligned}&=\lambda T(1-\theta)e^{\lambda\Delta}\int_t^{\infty} te^{-\lambda t}dt=3600\lambda^2(1-\theta)e^{\lambda\Delta}(te^{-\lambda t}/\lambda+e^{-\lambda t}/\lambda^2)\\&=3600(1-\theta)e^{\lambda\Delta}e^{-\lambda t}(\lambda t+1)\end{aligned} \tag{30}$$

Now the total time considered is 3600 seconds, so that the proportion of time occupied by intervals over t seconds is,

$$(1-\theta)e^{\lambda\Delta}e^{-\lambda t}(\lambda t+1)=(1-\theta)e^{\lambda(\Delta-t)}(\lambda t+1) \tag{31}$$

In turn, the proportion of time occupied by intervals less than t is,

$$1-(1-\theta)e^{-\lambda(\Delta-t)}(\lambda t+1) \tag{32}$$

The ratio, R, of H to N represents the average duration of such headways:

$$R = \frac{H}{N} = \frac{1}{\lambda} - \frac{\alpha(1-\theta)e^{-\lambda(t-\Delta)}}{1-(1-\theta)e^{-\lambda(t-\Delta)}} \tag{33}$$

The average time that a passenger car follows a truck or a slow passenger car is obtained by multiplying Equation (33) by Equation (22):

$$d_2^{'} = R \times \bar{n} = \frac{1-(1-\theta)e^{-\lambda(t-\Delta)}}{\lambda(1-\theta)e^{-\lambda(t-\Delta)}} - t \tag{34}$$

Since the two vehicles are travelling in opposite direction, $d_2^{'}$ has to be adjusted by the ratio of the average speed of opposite traffic to the sum of average speed of opposite traffic and the speed of the slow vehicle. The adjusted time that a passenger-car follows a truck or a slow passenger-car is stated as:

$$d_2 = R \times \bar{n} = \left(\frac{1-(1-\theta)e^{-\lambda(t-\Delta)}}{\lambda(1-\theta)e^{-\lambda(t-\Delta)}} - t\right) \cdot \left(\frac{u}{u+v}\right) \tag{35}$$

Where all parameters are already defined above. d_2 is the expected time that a passenger-car follows a slow vehicle. It can also be interpreted as the frequency that coming vehicles overtake the slow vehicle, which is the queue death rate.

Calculation of queue death rate is similar to the calculation under LOS A and B using the same model. Equation (18) is used to describe the relationship between queue length and time.

3.2.4 Under LOS E and F

Under LOS E and F, highway reaches the capacity and headway between vehicles totally depends on vehicles other than randomly distributed. There is no enough space appearing in opposite lane, so overtaking maneuver cannot be performed for safety issue.

Thus, queue death rate is closed to zero, and queue growth rate equals to queue birth rate. In this case, queue birth rate is equal to traffic arrival rate, which is nonrelated with type of vehicles. Therefore, delay caused by the truck and the slow passenger-car is the same.

3.3. Headway Model

In the studied platoon shown in Figure 5, calculation for $headway_T$ and $headway_{PC}$ is presented in headway model. The most outstanding difference between a truck and a passenger-car is their configuration. An oil truck is much longer than a passenger-car. As shown in Figure 7 (Commercial Transport Regulation, 2011), overall length of an oil truck is 26 meters (85 feet), compared with average length of a passenger-car 4.2 meters (14 feet). Since PCE factor reflects the number of passenger-cars that can substitute one truck under prevailing road condition, it is important to take account of both vehicle's length and headways between vehicles. The space between a truck and a passenger-car must be considered as an important criterion. Therefore, $headway_T$ and $headway_{PC}$ are necessary in the model.

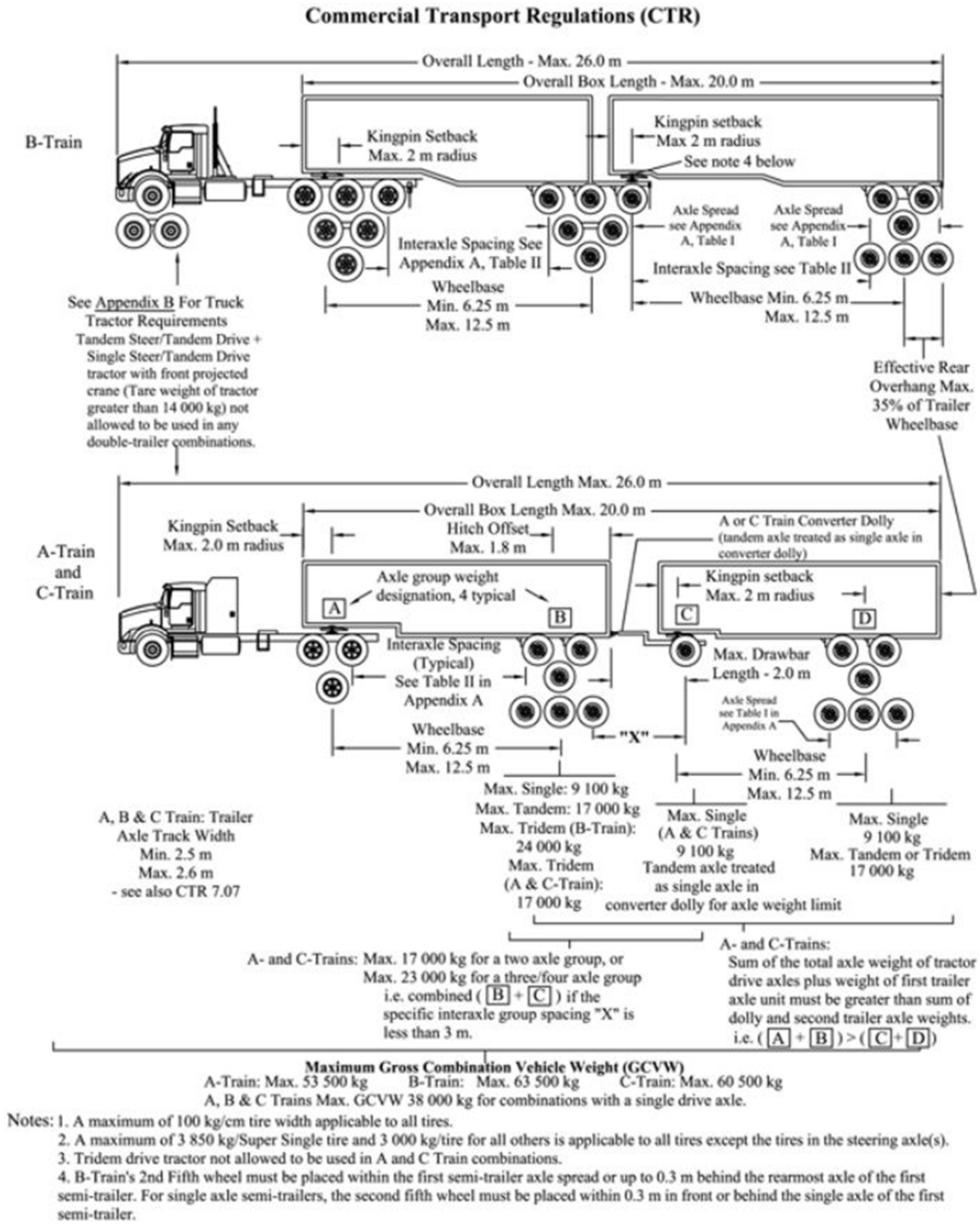

Figure 7. Oil Truck Configuration

Deceleration difference between trucks and passenger-cars makes safety distance (minimal headway) different. Because of huge weight of trucks and low deceleration rate, they need more distance and time to stop. That means when a passenger-car follows a truck, distance between them would be longer than a passenger-car follows a passenger-car.

In this model, classic linear car-following theory is adopted to calculate safety distance. Consider the vehicle $(n+1)$ following vehicle n in heavy traffic flow and no condition allowed to change lanes or pass, as shown in Figure 8 (Wolfgang, Louis, and William, 1982). Safety distance $S(t)$ is that vehicle n and vehicle $(n+1)$ keep, so that if the front vehicle brakes suddenly, the behind vehicle can stop without rear-ends with the front one. T is the response time when the following driver realizes the front vehicle slows down and he needs to hit the brake. Equation (36) is used to calculate safety distance.

$$S(t) = d_1 + d_2 + L - d_3 \tag{36}$$

Where:

$S(t)$ = at time t headway between two following vehicles;

d_1 = during response time T, moving distance of behind vehicle;

d_2 =stop distance for the behind vehicle;

d_3 =stop distance for the front vehicle;

L =safety distance when these two vehicles stop.

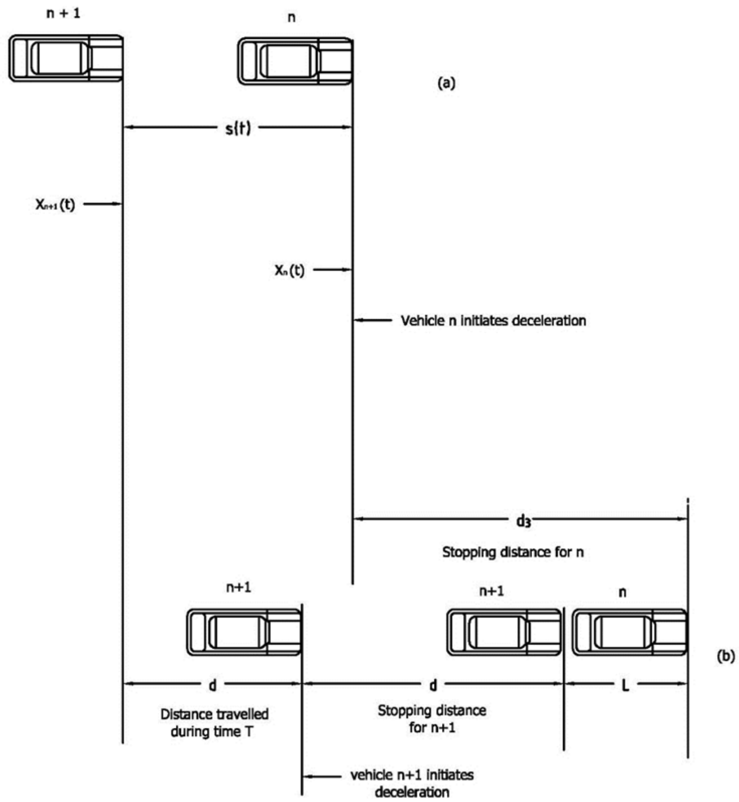

Figure 8. Safety Distance in Car Following Model

Using this model, two scenarios are studied: $headway_T$ and $headway_{PC}$. Both of these two factors are split into two parts: the slow vehicle following a regular passenger-car and a regular passenger-car following the slow vehicle. In this model, difference between the truck and the slow passenger-car are: vehicle length, driver reaction time, and deceleration rate. In addition, travel speed decides stopping distance. Therefore, corresponding to calculation in queue length model, calculation of $headway_T$ and $headway_{PC}$ is separated into three groups: LOS A and B, LOS C and D, and LOS E and F.

3.4. PCE factor

According to Equation (12), $Tlength$ equals to space that first three vehicles occupied plus queue length caused by the slow vehicle. Value of PCE factor is the ratio of the total length of traffic affected by the truck and the total length of traffic impact by the slow passenger-car. Combining queue length model and headway model, equation to calculate the value of PCE factor is presented below, under three groups:

Finite queue for both types of vehicles: such as both of direction are under LOS A or B:

$$PCE = \frac{Tlength_T}{Tlength_{PC}} = \frac{queue_T + headway_T}{queue_{PC} + headway_{PC}} \tag{37}$$

All variables are defined in the previous chapters.

Under good travel condition, such as LOS A or B, only small amount of passenger-cars can be blocked by slow vehicles. Therefore, queue will not expand infinitely. That is, as long as travel condition keeps consistent, and queue birth rate lower than queue death rate, queue length will not exceed a fixed value (Wolfgang, Louis, and William, 1982). In this case, PCE values will not change with LOS lasting time.

Infinite queue for both types of vehicles: such as both of direction are under LOS C and D:

$$PCE = \frac{Tlength_T}{Tlength_{PC}} = \frac{queue_T + headway_T}{queue_{PC} + headway_{PC}} = \frac{(\lambda_R - d_{2T}) \cdot \Delta t + headway_T}{(\lambda_R - d_{2PC}) \cdot \Delta t + headway_{PC}} \tag{38}$$

Where d_{2T} and d_{2PC} are the time that a passenger-car follows the truck and the slow passenger-car calculated in section 3.2.2, respectively. λ_R is relative arrival rate with the slow vehicles as reference. Arrival rate data is collected from a standing point. However, in queue length model, slow vehicles are selected as reference, which is not a static point, but a moving reference. Therefore, relative arrival rate is used in the equation to calculate value of PCE factor. Other variables are defined above.

Finite queue by passenger-car and infinite queue by truck:

$$PCE = \frac{Tlength_T}{Tlength_{PC}} = \frac{queue_T + headway_T}{queue_{PC} + headway_{PC}} = \frac{(\lambda_R - d_{2T}) \cdot \Delta t + headway_T}{queue_{PC} + headway_{PC}} \tag{39}$$

All variables are defined in the previous chapters.

Under certain condition, a truck will cause an infinite queue, but a passenger-car will not. In this condition, PCE factor value highly depends on LOS lasting time, because when time keeps increasing, queue caused by truck will keep accumulating, while queue caused by passenger-car will keep consistent. As shown in Equation (39), all parameters are fixed value except for Δt. Therefore, PCE value will increase as Δt increases.

CHAPTER 4. PARAMETERS ANALYSIS

4.1. Level of Service (LOS)

LOS is a quality measure describing operational conditions within a traffic stream, generally in terms of such service measures as speed, travel time, freedom to maneuver, traffic interruptions, and comfort and convenience (HCM, 2010). Six LOS are defined from letter A to F, with A representing the best operating condition and F the worst. In HCM (2010), it also presents criteria for each LOS of two-lane highway, shown in Table 6 and Table 7, using criteria Percent Time-Spent-Following (PTSF), Average Travel Speed (ATS), and Percent of Free-Flow Speed (PFFS). A segment of a two-lane highway must meet the criterion for all of these criteria depending on the type class of the two-lane highway. If LOS are different based on the two criteria for Class I highway, a lower LOS is supposed to be selected. For example, there is a Class I two-lane highway segment with a percent time-spent-following 40 percent, and an average travel speed equals to 47 mile per hour. It would be classified as LOS C other than LOS B. Table 6 and Table 7 only list criteria for LOS A to LOS E, because traffic under LOS F is so unstable that it is difficult to predict and collect data for LOS F.

Table 6. LOS Criteria for Two-Lane Highway

LOS	A	B	C	D	E
PTSF (Class I)	≤35%	35%-50%	50%-65%	65%-80%	>80%
ATS (mph) (Class I)	>55	50-55	45-50	40-45	≤40
PTSF (Class II)	≤40%	40%-55%	55%-70%	70%-85%	>85%
PFFS (Class III)	> 91.7	83.3-91.7	75-83.3	66.7-75	≤66.7

Table 7. Speed Limit under Different LOS

LOS	A	B	C	D	E
Average Speed (mph)	>55	50-55	45-50	40-45	≤40
Average Speed (m/s)	24	22-24	20-22	18-20	≤16

In passing process, speed of the vehicle that takes passing action must be faster than the vehicle being passed, and all vehicles that follow the slow vehicle are forced to keep the same speed as the slow vehicle. Thus, calculation in the model developed in this paper, passing speed is assumed as 65, 60, 55 and 50 miles per hour for LOS A, B, C and D, respectively. Accordingly, speed of the slow vehicle in the model is assumed to be 10 miles per hour for each group, which is the lower bound of each LOS. For example, in the model, under LOS C, speed of the slow vehicle is assumed to be 45 miles per hour, while speed of passing vehicles is 55 miles per hour. Under LOS E the possibility to allow a successful passing action is closed to zero. Therefore, no passing is assumed under LOS E.

4.2. Passing Sight Distance

In HCM (2010), passing sight distance is defined as: the visibility distance required for drivers to execute safe passing maneuvers in the opposing traffic lane of a two-lane, two-way highway. Passing sight distance can be calculated by four quantifiable portion d_1, d_2, d_3, d_4, shown in Figure 9 (Transportation Engineering Online Lab Manual, 2003).

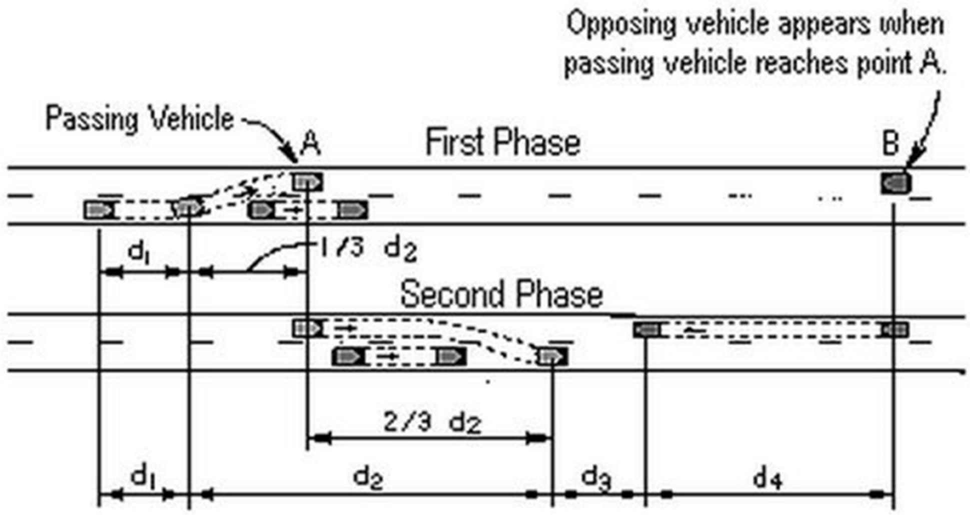

Figure 9. Diagram of Passing Sight Distance Components

Where

d_1 is perception-reaction-accelerate distance. In this distance, drives will contemplate passing maneuver and accelerate to the point of encroachment on the left lane.

d_2 is the length of highway that is traversed by the passing vehicle, while it occupies the opposite lane.

d_3 is the safety distance between passing vehicle and the vehicle from the opposite lane, when the passing vehicle returns back from the opposite lane.

d_4 is the distance that the vehicle from the opposite lane travels while the passing vehicle travels the 2/3 d_2.

Before calculating passing sight distance, there are six assumptions should be made:

(1) The vehicle being passing keeps a constant speed throughout the whole passing maneuver.

(2) The passing vehicle follows the slow vehicle into passing section.

(3) The passing vehicle travels 10 mph faster than the slow vehicle, when it travels on the opposite lane.

(4) Traffic from the opposite lane comes forward to the passing vehicle.

(5) There must be a safety distance between the passing vehicle and the opposing traffic, when the passing vehicle returns to right lane.

The difference between passing a passenger-car and a truck is the length of trucks. In this paper passenger cars assume to be 13.5 feet long, and trucks assume to be 85.5 feet long. Therefore, passing sight distance is 72 feet longer, when vehicles pass a truck than passing a passenger-car, with other conditions the same. Passing sight distance is completed by both of the passing vehicle and the opposing vehicle, so travel time of this distance equals to passing sight distance divided by sum of the speed of both vehicles.

According to method from NCHRP (2003), passing sight distance for each LOS is calculated and presented in Table 8. Average travel speed is criterion for determining LOS. Under each LOS, passing speed refers to average travel speed that the faster vehicle keeps during the passing process, and passed speed is average travel speed that the slower vehicle keeps when it is being passed. Both of these two factors are measured in miles per hour. Passing sight distance (PC) and (truck) refer to the minimal distance required when a passenger-car passing a passenger-car and a truck, respectively, which is $d_1 + d_2 + d_3 + d_4$, as shown in Figure 9.

Table 8. Passing Sight Distance

LOS	A	B	C	D
Average travel speed (mph)	>55	50-55	45-50	40-45
Passing speed (mph)	65	60	55	50
Passed speed (mph)	55	50	45	40
Passing sight distance (ft) (PC)	1985	1835	1625	1470
Passing sight distance (m) (PC)	605	559	495	448
Passing sight distance (ft) (truck)	2057	1907	1697	1542
Passing sight distance (m) (truck)	627	581	517	470

The time that a passenger-car spends on passing process is calculated by the sum of perception-reaction-accelerate distance and the length of highway that is traversed by the passing vehicle, which is $d_1 + d_2$, being divided by average travel speed of the faster vehicle. The result of this calculation is the required minimal time for a vehicle to complete passing action, which is denoted as α and t in Equation (13) and (19), respectively. The result is shown in Table 9.

Table 9. Time Spent on Passing Slow Vehicles

LOS	A	B	C	D
Passing Speed (ft/s)	96.8	79.2	74.8	64.5
Time to pass a PC (s)	26.65	28.85	26.54	28.43
Time to pass a truck (s)	27.26	29.59	27.32	29.35

4.3. Flow Rate

Defined by HCM (2000, p. 55), service flow rate is the “maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a given period under prevailing roadway, traffic, and control conditions while maintaining a designated level of service”. In R. Tapio (2001) research a relationship is developed between flow rate and average travel speed for two-lane highway. For no passing zone segment, his result is presented in Figure 10.

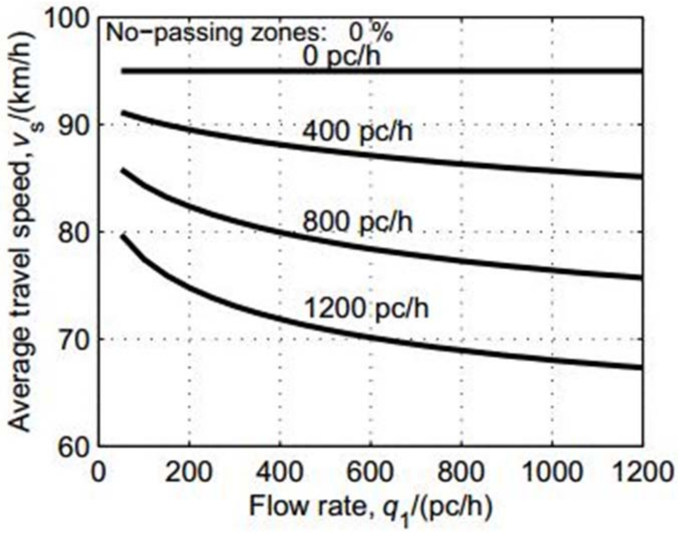

Figure 10. Relationship between Flow Rate and Average Travel Speed

Compared with research by Homburger, Kell and Perkins (1992), both of these two researches reach a same conclusion that under LOS A, B, C, and D that the maximum flow rate are 200veh/h, 375veh/h, 600veh/h, and 900 veh/h respectively. Under LOS E, in Homburger, Kell and Perkins (1992) research, maximum flow rate is 1400, while R. Tapio (2001) is 1200. In R. Tapio Luttinen’s research, passing opportunity is considered, and impact from heavy vehicles is also studied. The relationship between flow rate and average travel speed is concave when LOS getting worse. Because when traffic volume increases, opportunity to perform passing maneuver will decrease exponentially, which is theoretically proved by Jacobs (1974). Therefore, R. Tapio Luttinen’s result is more precise. In HCM (2000), LOS of two-lane highway is not determined by an intermittent value, but a range of speed criterion. Accordingly, flow rate under each LOS is presented in Table 10.

Table 10. Flow Rate under Various LOS

Level of service	A	B	C	D
Flow rate (veh/h)	<200	200-375	375-600	600-900

To calculate average queue length in model developed in this paper, a medium value of flow rate under each LOS is selected.

4.4. Stop Distance

Stop distance is the distance that the following vehicle travels from the time when the front vehicle starts to slow down, till the following vehicle stops. For passenger-cars and oil trucks, both of driver behavior and vehicle performance can affect the stop distance. According to NCHRP (2003), stop distance for trucks is calculated by Equation (40):

$$SD = 1.47Vt + 1.075\frac{V^2}{a} \tag{40}$$

Where

SD = stopping distance, ft;

t = brake reaction time in second;

V = initial speed before braking, mph;

a = deceleration rate in ft/s^2.

In North Dakota Strategic Freight Study on Motor Carrier Issues, the oil trucks in North Dakota is usually a straight truck (a tridem axle) plus a pup trailer (UGPTI, 2007). In NCHRP (2003, p. 64), ‘The brake reaction time is a driver characteristic and is assumed to be applicable to truck drivers as well as passenger car drivers. In fact, experienced professional truck drivers could reasonably be expected to have shorter brake reaction times than the driver population as a whole'. On the other hand, there is an approximately 0.5 second delay in brake application, because of the air braking systems used in tractor-trailer combination trucks. It is reasonable to assume that the factors offset one another and that both of passenger-car and truck drivers will have the same 2.5 seconds brake reaction time when operating vehicles. Table 11 lists total stop distance for an oil truck to stop under various travel speed. Deceleration rate of oil trucks varies with truck travel speed and listed in g force in Table 11, (1g=9.8m/s/s). Perception reaction distance is calculated by 1.47 multiplying product of reaction time and travel speed.

Table 11. Oil Trucks Stop Distance

Truck				
Truck speed (mph)	Deceleration rate (g)	Braking deceleration distance (Ft.)	Perception reaction distance (Ft.)	Total stop distance (Ft.)
15	0.37	44	81	125
20	0.36	77	108	185
25	0.35	117	132	249
30	0.34	175	162	336
35	0.32	237	189	426
40	0.31	311	216	527
45	0.31	393	243	636
50	0.31	485	269	754
55	0.32	588	297	884
60	0.32	699	323	1022
65	0.32	819	350	1170
70	0.32	952	377	1329

For passenger cars, stopping distance is calculated by:

$$SD = Vt + 0.5\frac{V^2}{a} \tag{41}$$

Where

SD = Stopping distance, Ft.;

t = Brake reaction time in second;

V = Initial speed before braking, mph;

a = Deceleration rate, 22.6 Ft./s^2.

Table 12 lists distance for a passenger-car to stop under different travel speed. Column braking deceleration distance shows the distance a passenger-car would travel during braking process. Column perception reaction distance presents distance that a passenger-car moves during reaction time. Total stop distance is calculated as the summation of braking deceleration distance and perception reaction distance.

Table 12. Passenger-Cars Stop Distance

PC				
reaction time=2.5s	deceleration rate=11.2ft/s/s			
PC speed (MPH)	PC speed (Ft./S^2)	Braking deceleration distance (Ft.)	perception reaction distance (Ft.)	total stop distance (Ft.)
15	22	22	55	77
20	29.3	38	73	112
25	36	58	90	148
30	44	86	110	196
35	51.3	117	128	246
40	58.7	154	147	301
45	66	194	165	359
50	73.3	240	183	423
55	80.7	291	202	492
60	88	346	220	566
65	95.3	405	238	644
70	102.7	471	256	728
75	110	540	275	815
80	117.3	614	293	908

4.5. Safety Distance

Safety distance is the minimal safety distance that two consecutive vehicles keep when driving on highway. Based on headway model, safety distance is calculated under three scenarios: one passenger-car following one passenger-car, one passenger-car following one oil truck, and one oil truck following one passenger-car. Based on these three scenarios, result of headway model is shown in Table 13. Space taken by three consecutive vehicles is presented under various LOS. The combination of three consecutive vehicles are shown in Figure 5, which are three consecutive passenger-cars, and one passenger-car followed by one oil truck that followed by one passenger-car.

Table 13. Result of Headway Model

LOS	A	B	C	D	E
Average travel speed (mph)	55	50	45	40	35
PC following PC (ft)	222	203	185	167	148
PC following truck (ft)	293	275	257	238	220
Truck following PC (ft)	685	606	533	465	400
Space of PC-PC-PC (ft)	443	407	370	333	297
Space of PC-Truck-PC (ft)	979	881	790	703	620

CHAPTER 5. RESULT AND ANALYSIS

Based on model described in Chapter 3 and all parameters analyzed in Chapter 4, results are discussed in this section. The PCEs are calculated and summarized in this chapter for various combinations of LOS for analysis direction and opposite direction. In all figures in this section, label LOS x with y denotes as the situation that LOS of traveling lane is x, while LOS of the opposite lane is y.

5.1. Travel Direction under LOS A

Table 14 presents model calculation result when condition of traveling lane is under LOS A. Time spent on following slow vehicle depends on LOS of both the analysis direction lane and the opposite lane. Therefore, to indicate relationship between PCE factor and LOS of opposite lane, PCE factor value is listed under various LOS of opposite lane. As mentioned in methodology section, when queue birth rate is less than queue death rate, a finite queue will be generated. Otherwise, queue will be growing with a rate that equals to vehicle arrival rate from upstream, until traffic volume of upstream decreases. In Table 14, row 3 refers to the number of passenger-cars that affected by the slow passenger-car in the model, if queue birth rate is less than queue death rate. Otherwise, growth rate of queue by the slow passenger-car is shown in row 4, measured in vehicle per hour. The same rule works for truck throughout section 5.1. As calculated in headway model, 443 and 979 are length of highway taken by three consecutive vehicles for all passenger-cars combination and one truck involved combination, respectively.

Table 14. Model Result under LOS A

LOS of traveling lane	A				
LOS of opposite lane	A	B	C	D	E
Number of PC affected by the slow PC (veh/h)	0.012	0.02	0.14	1.5	--
Queue growth rate by the slow PC (veh/h)	--	--	--	--	19
Space affected by the slow PC (ft)	443	443	443	775	4650
Number of PC affected by the truck (veh/h)	0.023	0.05	0.9	--	--
Queue growth rate by truck (veh/h)	--	--	--	7	19
Space affected by the truck (ft)	979	979	979	2577	5187
PCE	2.2	2.2	2.2	3.3	1.1

In Table 14, it indicates that when the slow passenger-car travels under LOS A, it has little impact on upstream traffic. As indicated in row 3 of Table 14, when LOS of opposite lane is A, B, C, the slow passenger-car only affects less than one passenger-car. Thus, it is reasonable to draw the conclusion that the effect of this passenger-car on following traffic is almost zero. Therefore, length of highway affected by this passenger-car is only determined by headway model. The same pattern is for slow truck as shown in row 6 of Table 14; however, when opposite lane LOS drop to C, the affected vehicle is almost 1 for one slow large truck operated on LOS A condition. When LOS of opposite lane gets worse to D, the slow passenger-car causes a queue with 1.5 passenger-cars. Then, the length of highway affected by this passenger-car needs to add up the length of highway taken by the 1.5

passenger-cars. Under LOS E for opposite lane, there is hardly any possibility to allow a successful passing maneuver. Therefore, all coming vehicles are blocked by the slow vehicle. A sudden increase of queue length can be observed in row 5 and 8 of Table 14, when LOS of opposite lane changes from D to E. In fact, it is only possible to happen in tidal traffic in real life. In this situation, slow vehicles cause an infinite queue that queue length is related with time. Therefore, value of PCE factor for LOS A with E (Analysis direction of LOS A and opposite direction of LOS E) is a function with time, which is shown in Figure 11. In this paper, we simulate the congestion lasting time up to two and half hours, because we believe that in most cases, within two and half the LOS condition will change. However, it is easy to extend the simulation time over two and half hours.

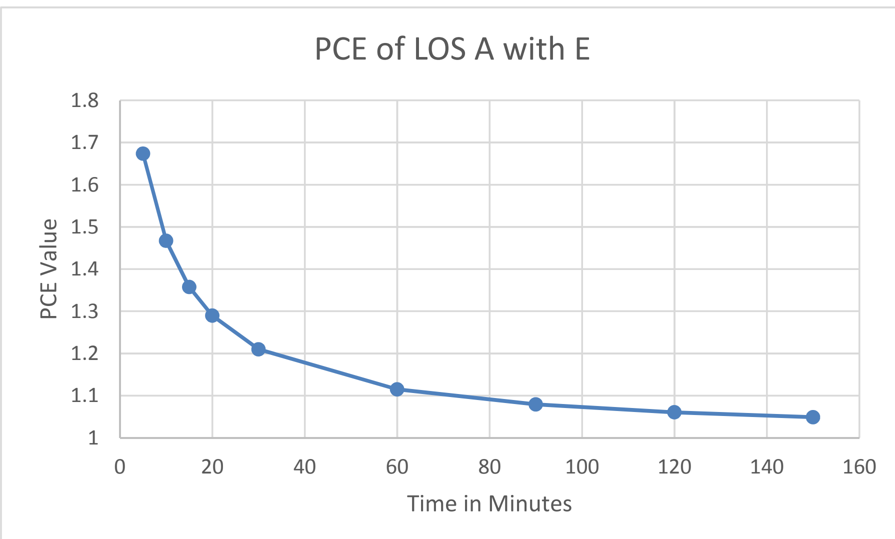

Figure 11. Relationship between PCE Factor and Time under LOS A with E

In Figure 11, horizontal axle denotes time incremental, and vertical axle shows value of PCE factor under LOS A with E. The trend showing in the graph is that when LOS E starts in the opposite direction, the PCE is less than 2, as congestion lasting time increases, PCE value drops exponentially to 1.2 around when LOS E is lasting for about half hour and then it slowly gets closed to 1 as congestion lasting time increases. PCE equals to 1 means no difference between large truck and passenger car. The reason that causes this trend is that the difference between total length that affected by truck and the slow passenger-car is depended on both headway and delay. When the opposite direction get to LOS E which means almost no chance for passing, and at the beginning of congestion, both affected headway and delay queues has impact on PCE, however, the delay affected queues start to dominant headway distances in a nonlinear way quickly as congestion time lasting. As congestion lasting over a certain time, in an hour in this case, the effect of headway on PCE factor gets fading away and PCEs almost purely depend on delay caused queue which shows less and less depending on type of slow vehicles.

Showing in Table 14 row 6, the truck almost has finite effect on the following traffic when LOS of the opposite lane is better than D. Queue length does not increase with LOS lasting time. When LOS of the opposite lane reaches D, an infinite queue is generated with a growth rate of seven passenger-cars per hour however, for slow passenger car there are still chances for passing behavior happen. Therefore, in this case, PCE factor is still a function of time, as shown in Figure 12.

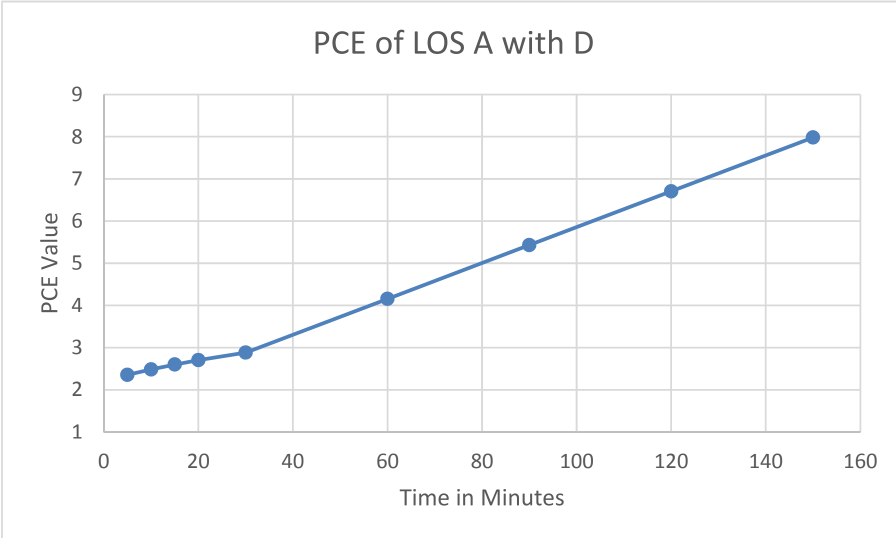

Figure 12. Relationship between PCE Factor and Time under LOS A with D

Figure 12 denotes the trend of PCE value when time increases in horizontal axle. It is showing that with road condition and LOS holding constant for both direction, PCE value of LOS A with D and time are linearly related with two time ranges with half hour as bench mark. With congestion time in opposite lane increasing and before it reaches to half hour, PCE value goes up with relative lower increasing rate from around 2 to 3 and from half hour and up, PCE value increases with relative higher increasing rate to 4 at congestion lasting about one hour.

5.2. Travel Direction under LOS B

Table 15 shows values of PCE factor when LOS of travel direction is B, while opposite lane is under various LOS. When LOS of traveling lane reaches to B, there is more traffic coming in analysis direction, average travel speed also decreases, compared with that under LOS A. Thus, more traffic will come during unit time and queue caused by slow vehicles is longer than that under LOS A. With LOS of opposite lane getting worse, it is getting less possible to act a successful passing maneuver. So the same pattern as under LOS A is observed however, at better opposite lane LOS condition queue starts to build infinitely for both passenger car and truck. Moreover, the higher number impacted vehicles observed shown in row 3 and 6 in both Table 14 and 15. It is worth to note that before the queue start to build infinitely the impacted number of vehicles is 4 (Cell 3x4 in Table 15) compared with 1.5 (Cell 3x5 in Table 14) for passenger cars. The trend meets the expectations that with the analysis direction LOS getting worse, we expect to see more affected vehicles before there is no chance for passing happens. Observed from this set of PCE value, under LOS B with C, the difference effect of trucks and slow passenger-cars on following traffic reaches the maximum value. When LOS of opposite lane keeps getting worse, it is all less possible to pass a truck or a passenger-car. Thus, the difference between a truck and a passenger-car get smaller gradually.

Table 15. Model Result under LOS B

LOS of traveling lane	B				
LOS of opposite lane	A	B	C	D	E
Number of PC affected by the slow PC (veh/h)	0.1	0.2	4	--	--
Queue growth rate by the slow PC (veh/h)	--	--	--	24	51
Space affected by the slow PC (ft)	407	407	1221	5315	10785
Number of PC affected by the truck (veh/h)	0.2	0.7	--	--	--
Queue growth rate by truck (veh/h)	--	--	19	39	51
Space affected by the truck (ft)	881	881	4910	8939	11259
PCE	2.2	2.2	4.0	1.7	1.04

Figure 13 shows the relationship between PCE factor and time under LOS B with C. The two-step trend again is observed, however, with analysis direction LOS at B, the benchmark happens at congestion lasting time around one hour instead of half hour. Before reach to one hour, the increasing rate is much slower compare to after one hour. Comparing with the Figure 12, the increasing rate before reaching benchmark value for LOS at B is higher. It means the PCE starts increase in a faster speed with lasting time increase when analysis direction LOS of B compared to analysis direction LOS of A when the opposite analysis direction's condition start to limit passing truck but not for passing passenger cars.

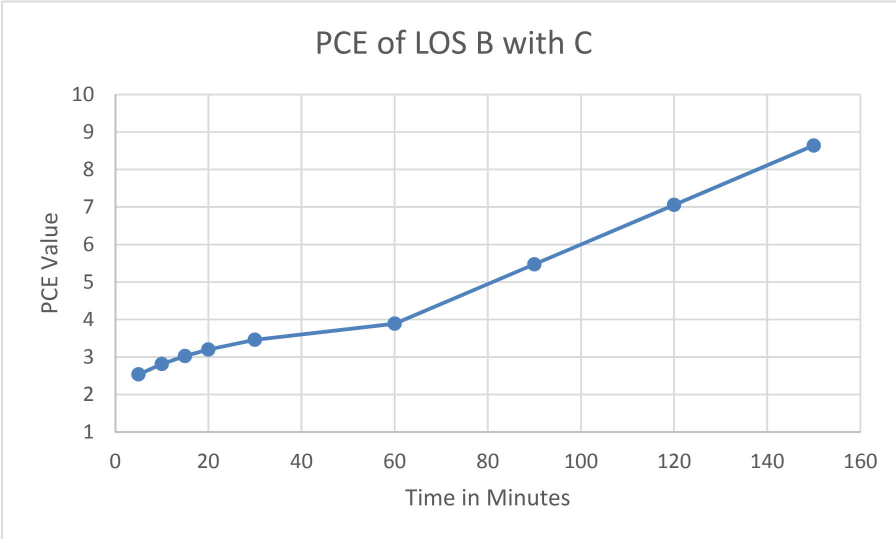

Figure 13. Relationship between PCE Factor and Time under LOS B with C

Different with the trend under LOS B with C, PCE values under LOS B with D and E decrease with time increasing however, with decreasing changing speed. Note, for LOS B with D, the PCE value is approaching to 1.6 as congestion time is approaching to two and half hours and for LOS B with E, the PCE value is approaching to 1 as congestion time is approaching to one and half hours. It indicates that when the opposite analysis lane get really congested, the difference between large trucks and passenger cars is quickly approaching to zero. Under traffic condition that both of the slow passenger-car and the truck cause infinite queue, PCE factor can be calculated as Equation 42, which is derived from Equation 18 and Equation 12:

$$PCE = \frac{Headway_T + q_T * \Delta t}{Headway_{PC} + q_{PC} * \Delta t} \tag{42}$$

Where

$Headway_T$ is space occupied by the first three vehicles: passenger-car, truck and passenger-car.

$Headway_{PC}$ is space occupied by the first three passenger-cars.

q_T is queue length growth rate caused by the truck.

q_{PC} is queue length growth rate caused by the slow passenger-car.

Δt is time incremental.

Both of $Headway_T$ and $Headway_{PC}$ keep roughly constant when time increases under LOS B with D and E,. When Δt is approaching to infinity, value of PCE is the ratio of q_T to q_{PC}, which explain the trends shown in Figure 14 and Figure 15.

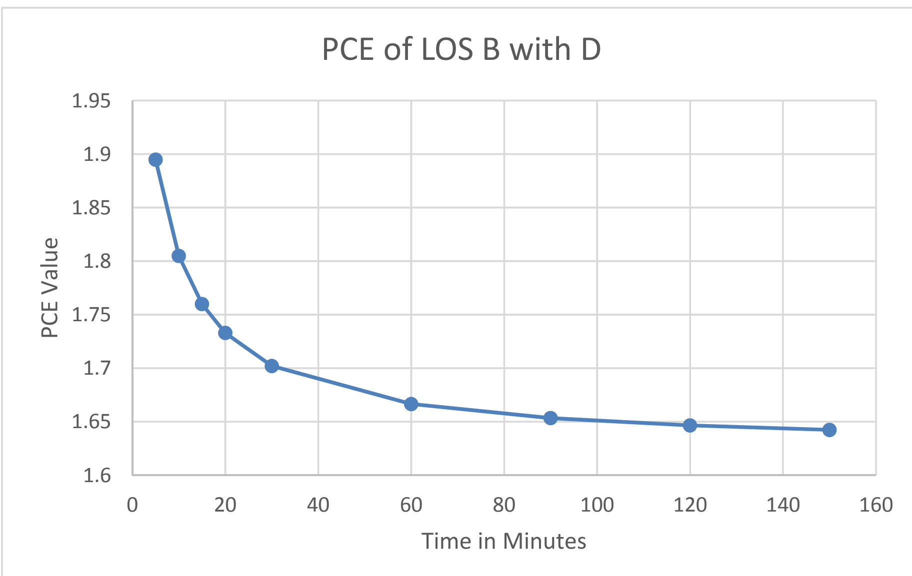

Figure 14. Relationship between PCE Factor and Time under LOS B with D

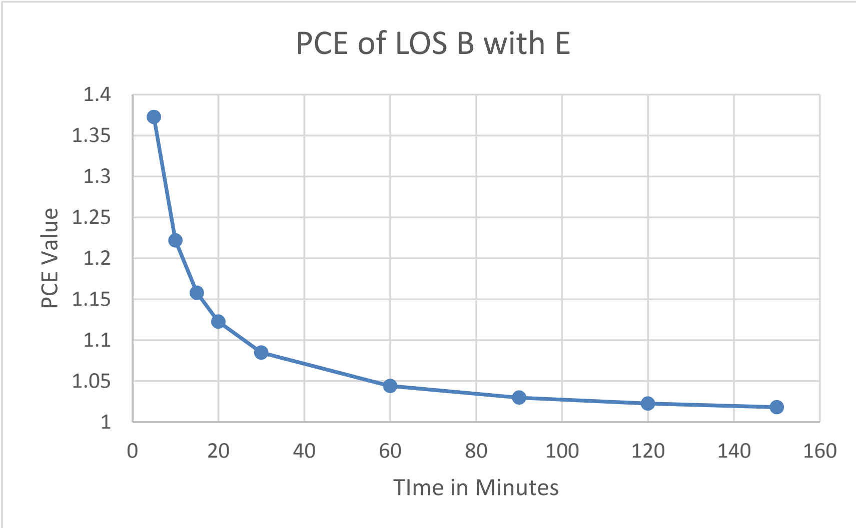

Figure 15. Relationship between PCE Factor and Time under LOS B with E

5.3. Travel Direction under LOS C

Table 16 shows calculation of PCE factor under LOS C. When LOS of opposite lane is A and B, slow vehicles only cause finite queues with queue birth rate lower than queue death rate. In these conditions, PCE factor is non-related with time. However, compared with traveling direction of LOS A and B, the number of blocked vehicles increases by times under LOS C, but the number is still low. This trend is expectable, because when traffic condition is good, such as under LOS A and B, few vehicles can be blocked by slow vehicles, because long distance shows up frequently in opposite traffic to allow a safe passing action. When opposite traffic volume increases, more passenger-cars are blocked by slow vehicles, and the impact of headway model on PCE value start to fade away, which is discussed in section 5.1.2. When LOS of opposite lane is worse than C, PCE factor is related with length of time that certain LOS lasts, and approaching to the ratio of queue growth rate by the truck to that by the slow passenger-car. To sum up, with analyzed direction of LOS C, when LOS of opposite lane is worse than B, PCE factor value is related with LOS lasting time. Instead, before LOS of opposite lane gets worse than B, PCE factor value does not vary with time. Compared with LOS A and B, this benchmark shows up earlier again.

Table 16. Model Result under LOS C

LOS of traveling lane	C				
LOS of opposite lane	A	B	C	D	E
Number of PC affected by the slow PC (veh/h)	0.4	1	--	--	--
Queue growth rate by the slow PC (veh/h)	--	--	28	61	86
Space affected by the slow PC (ft)	370	555	5565	11692	16354
Number of PC affected by the truck (veh/h)	1	5	--	--	--
Queue growth rate by truck (veh/h)	--	--	57	79	86
Space affected by the truck (ft)	790	1715	11446	15442	16774
PCE	2.6	3.1	2.1	1.3	1.03

Under LOS C with C, D, and E, relationship between PCE factor values and duration of LOS are shown in Figure 16, 17, and 18, respectively. Compared with these three graphics, when LOS of opposite lane lasts more than 0.5 hour, PCE factor value tends to approach to a fixed value, and decreasing rate in each graphics slows down and approaches to zero. Therefore, when LOS of opposite lane lasts more than 0.5 hour, it is demonstrated that value of PCE factor does not vary with time incremental, even though it is a function of time. Before duration of LOS reaches 0.5 hours, PCE factor value decreases exponentially.

However, in the relatively noticeable reducing process, PCE factor values do not vary distinctively. Therefore, PCE factor values keep roughly consistent under LOS C with C, D and E, varying between (2.04, 2.09), (1.3, 1.55), and (1.01, 1.25), respectively. The difference among these three graphics is the value of PCE factor. As shown above, when opposite lane under LOS C, PCE factor value is roughly 2.0, which means that there is still difference between trucks and passenger-cars. However, when opposite lane under LOS D and E, PCE factor is around 1.0 to 1.5, so difference between trucks and passenger-cars is not noticeable, especially when opposite lane is under LOS E.

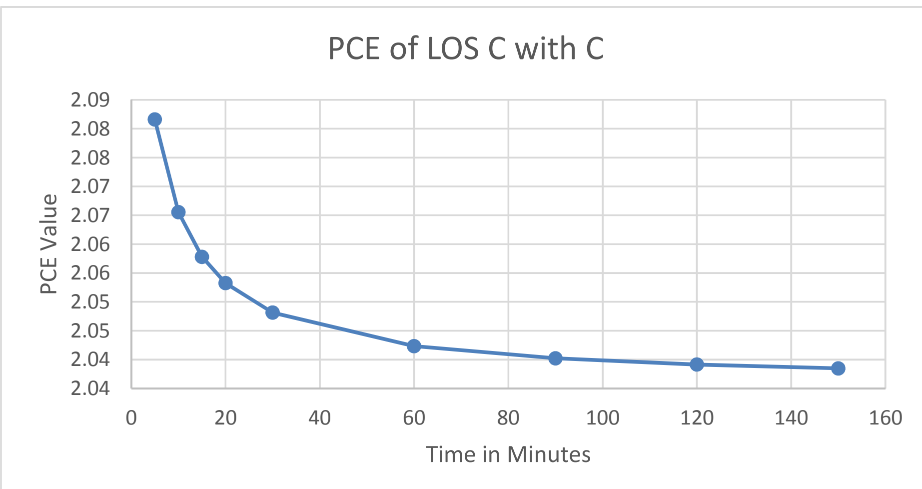

Figure 16. Relationship between PCE Factor and Time under LOS C with C

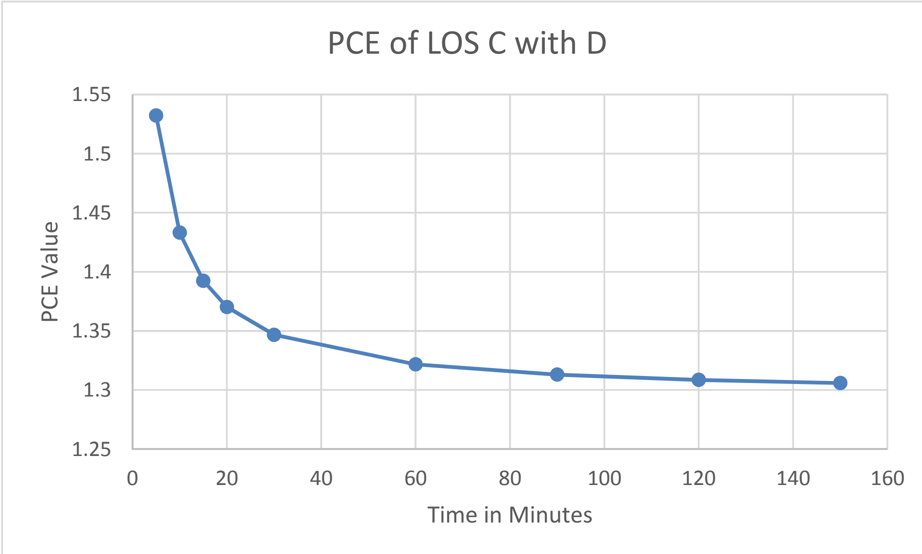

Figure 17. Relationship between PCE Factor and Time under LOS C with D

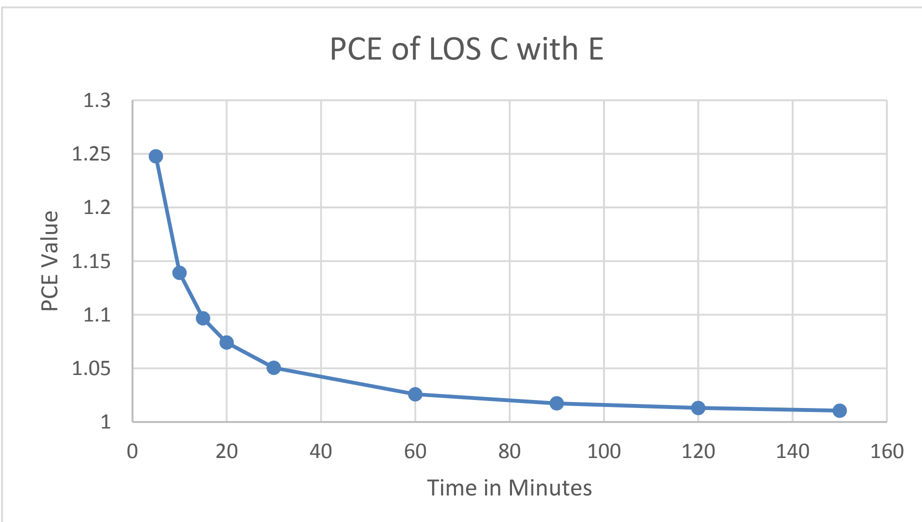

Figure 18. Relationship between PCE Factor and Time under LOS C with E

5.4. Travel Direction under LOS D

When LOS of travel direction is LOS D, more traffic arrives in unit time period and average travel speed decreases. Thus, queue caused by slow vehicles is longer than that under LOS A, B, and C. Table 17 shows queue length caused by slow vehicles and value of PCE factor under various LOS of opposite lane. Analysis of queue caused by a slow passenger-car is shown in row 1 to row 5 in Table 17. When opposite lane traffic condition is under LOS A, there is still a queue caused by the slow passenger-car, although traffic is mostly allowed to make a passing action, which is shown in cell (3*2 in Table 17). When LOS of opposite lane gets worse than A, an infinite queue is generated, and queue growth rate increases by times. Different with LOS A, B, and C, for LOS D, the inflection point for passenger-car shows up at LOS A, which means that under opposite lane of LOS A, queue length by passenger-car does not related with time, but when LOS of opposite gets worse than A, queue length by passenger-car is a function of time. The fix number of blocked vehicles is larger than under all LOSs discussed above. Analysis of queue caused by a truck is presented in row 6 to 8 in Table 17. From the table, it is evident that a truck blocks more traffic and cause a longer queue than a passenger-car. Nonetheless, the difference between queue caused by trucks and passenger-cars declines when LOS of opposite lane getting worse.

In Table 17, PCE of LOS D with B is extremely higher than the average, which is resulted from several reasons:

1. In the table, queue length is calculated as a cumulative value. That is the total queue length generated in an hour. In this way, effect of headway model on PCE value is weakened. It is demonstrated in Figure 15 that for a time incremental that is less than one hour, PCE value is lower than 4.5.
2. Under LOS D, traffic volume is much higher than LOS A, and traffic condition is closed to unstable. Therefore, a slight change in traffic flow may result in huge impact on traffic performance.

3. LOS of opposite lane is B, which is better than C but worse than A. Under LOS A, because of less traffic volume, mostly it is possible to pass slow vehicles. Therefore, the difference of passing a truck and passing a passenger-car is not prominent as to result in a huge difference in queue length. On the contrary, under LOS C, it is both less likely to pass a truck or pass a passenger-car. Thus, most traffic are blocked by slow vehicles, and the queue length by the slow passenger-car is slightly shorter than that by the truck. However, during the transition of LOS A and C, various headways are showing in traffic flow. The difference of required passing distance between the truck and the slow passenger-car attributes to discrepancy in probability to allow the passing action, which results in the high PCE value.

Table 17. Model Result under LOS D

LOS of traveling lane	D				
LOS of opposite lane	A	B	C	D	E
Number of PC affected by the slow PC (veh/h)	2	--	--	--	--
Queue growth rate by the slow PC (veh/h)	--	11	86	119	144
Space affected by the slow PC (ft)	666	2164	14652	20146	24309
Number of PC affected by the truck (veh/h)	--	--	--	--	--
Queue growth rate by truck (veh/h)	4	55	109	134	144
Space affected by the truck (ft)	1369	9860	18851	23014	24679
PCE	2.1	4.5	1.3	1.1	1.02

Figure 19 to Figure 23 present the relationship between PCE factor and length of time that according LOS lasts. As it shown in Figure 19, PCE factor value under traveling lane of LOS D and LOS opposite lane of LOS A has a unique trend. It decreases linearly first with a low decreasing slope, roughly zero, until LOS lasting time reaches to one hour. Then it increases linearly from 2.1 to 3.6 when LOS lasting time increases from one hour to 2.5 hours. Before PCE factor value reaches the inflection point at one hour, it shows a decreasing trend, because PCE factor is calculated by two parts: length of first three vehicles and length of queue caused by the slow vehicles, as shown in Equation 42. Ratio of $Headway_T$ to $Headway_{PC}$ is higher than ratio of $q_T * \Delta t$ to $q_{PC} * \Delta t$. Therefore, when time increases, PCE factor value is dragged down by ratio of $q_T * \Delta t$ to $q_{PC} * \Delta t$. When lasting time passes the inflection point, queue caused by the passenger-car will not increase, however, queue caused by the truck will keep growing with LOS lasting time. Therefore, these two different progresses result in the unique trend of PCE factor.

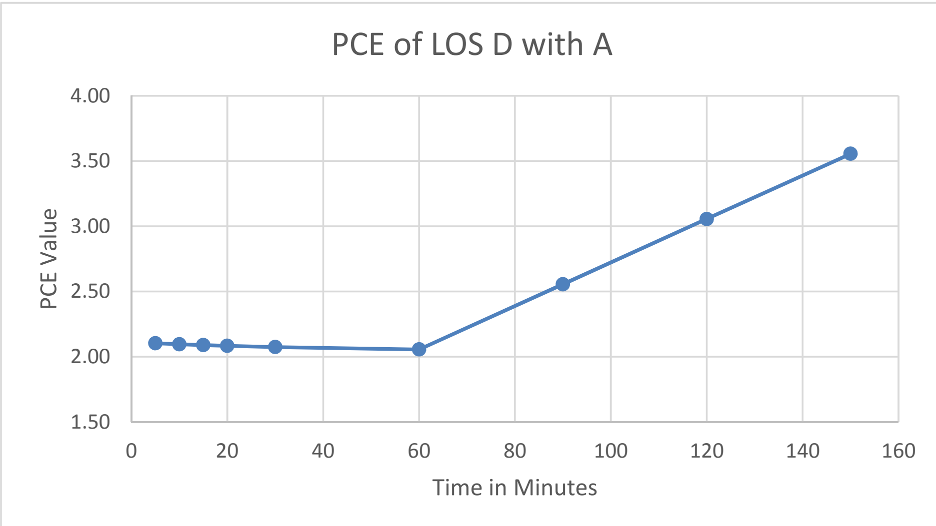

Figure 19. Relationship between PCE Factor and Time under LOS D with A

As it shown in Figure 20, PCE values of LOS D with B have a relatively evident fluctuation that increasing from 3.0 to 4.8. Under this condition, PCE factor value increases logarithmically. Before LOS lasting time reaches to one hour, a noticeable increasing trend can be observed, which is from 3.0 to 4.6. After duration of LOS reaches 60 minutes, PCE factors under LOS D with B tend to stabilize and approach to 5.0 infinitely. Under LOS D with C, D, and E, PCE factor values show an exponentially decreasing trend, however, there are no significantly overall fluctuations, which is roughly from 1.0 to 1.4. In addition, they all start to stabilize at lasting time of one hour. Therefore, under LOS D with C, D, and E, PCE factor values can be represented by mean value of each group.

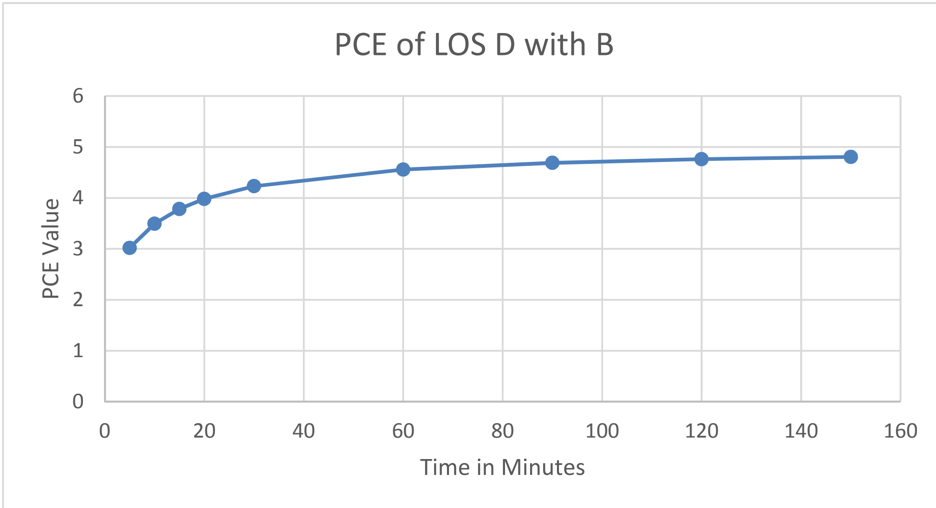

Figure 20. Relationship between PCE Factor and Time under LOS D with B

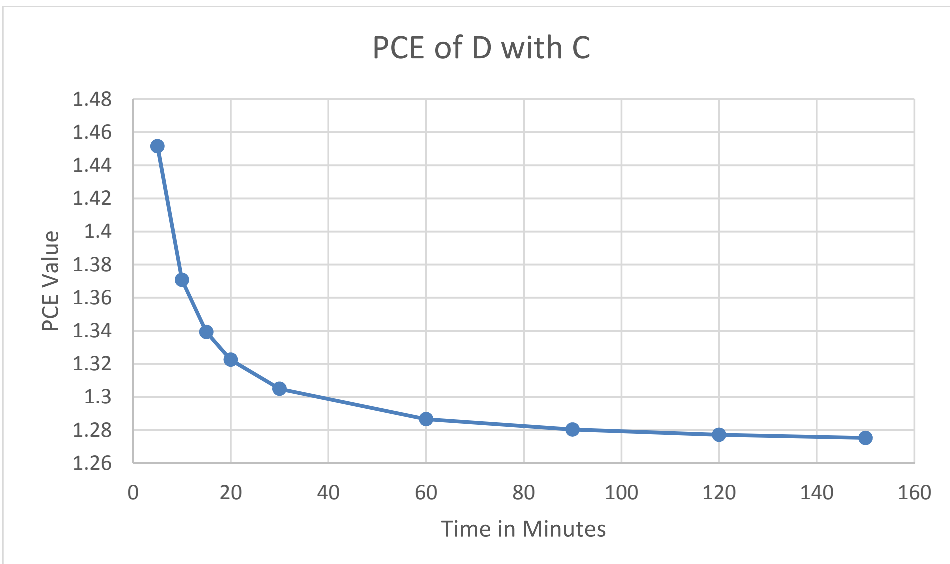

Figure 21. Relationship between PCE Factor and Time under LOS D with C

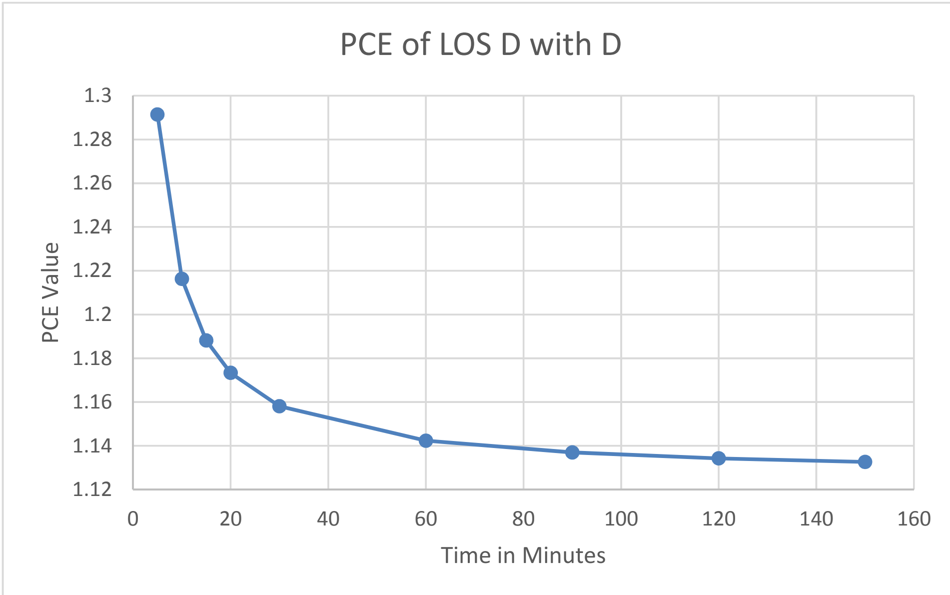

Figure 22. Relationship between PCE Factor and Time under LOS D with D

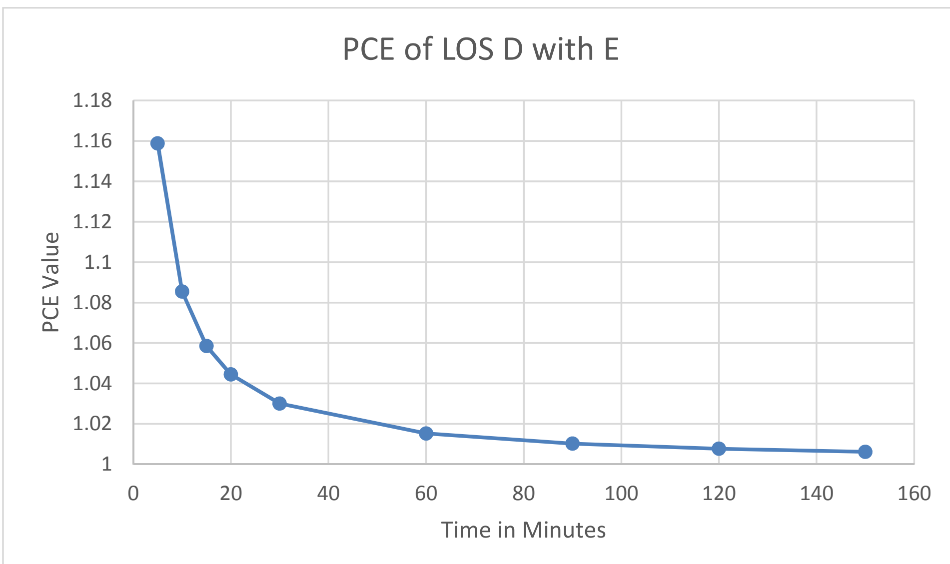

Figure 23. Relationship between PCE Factor and Time under LOS D with E

5.5. Travel Direction under LOS E

When LOS of traveling lane gets to E, traffic volume approaches to facility capacity, and average travel speed decreases. With a high arrival rate, queue length growth rate is much higher than under other conditions. As it shown in Table 18, there is an infinite queue generated, even though LOS of opposite lane is A. Also, queue length growth rate increases with LOS of opposite lane getting worse. When LOS of both of lanes reaches to E, there is no difference between queue growth rate by the truck and the slow passenger-car. The only difference between the effect of a truck and a slow passenger-car comes from headway model. However, compared with the huge queue length caused by the slow vehicles, the impact of headway model on PCE factor value is not significant in this situation.

This set of PCE value does not fluctuate as PCE value under other LOS. It is more stable that decreasing with LOS of opposite lane getting worse. The reason is that queue birth rate is much higher than queue death rate for both queue caused by trucks and passenger-cars. In addition, headway model provide little influence on PCE value. However, headway model does not relate with time incremental, which means that it has more impact on PCE value when a short time incremental is studied.

Table 18. Model Result under LOS E

LOS of traveling lane	E				
LOS of opposite lane	A	B	C	D	E
Number of PC affected by the slow PC (veh/h)	--	--	--	--	--
Queue growth rate by the slow PC (veh/h)	46	104	190	219	248
Space affected by the slow PC (ft)	7128	15741	28512	32818	37125
Number of PC affected by the truck (veh/h)	--	--	--	--	--
Queue growth rate by truck (veh/h)	108	162	219	241	248
Space affected by the truck (ft)	16658	24677	33141	36408	37448
PCE	2.3	1.2	1.2	1.1	1.01

Figure 24 to Figure 28 show PCE factor value under various LOS of opposite lane. Comparing these five figures, trend of PCE factor values under LOS E with A is distinctive from others, which forms a logarithmical trend, while the other four are decreasingly exponential trend. Under LOS E with A, PCE factor value increases with a decreasing increase rate. It is observed that PCE factor values tend to stabilize and approach to a fixed value in all these five groups. In addition, the fixed value that each group approaching to decreases when LOS of opposite lane changes from A to E. Under LOS E with A, the value PCE factor approaches to is 2.35, and that is 1.56, 1.15, 1.1, and 1.0 under LOS E with B, C, D, and E, respectively. Furthermore, PCE factor values under LOS E present little fluctuation, which means that the overall variance is less than one unit. Under LOS E with A, B, C, D, and E, PCE factor value increases from 2.26 to 2.35, 1.66 to 1.56, 1.26 to 1.15, 1.2 to 1.1, and 1.1 to 1.0.

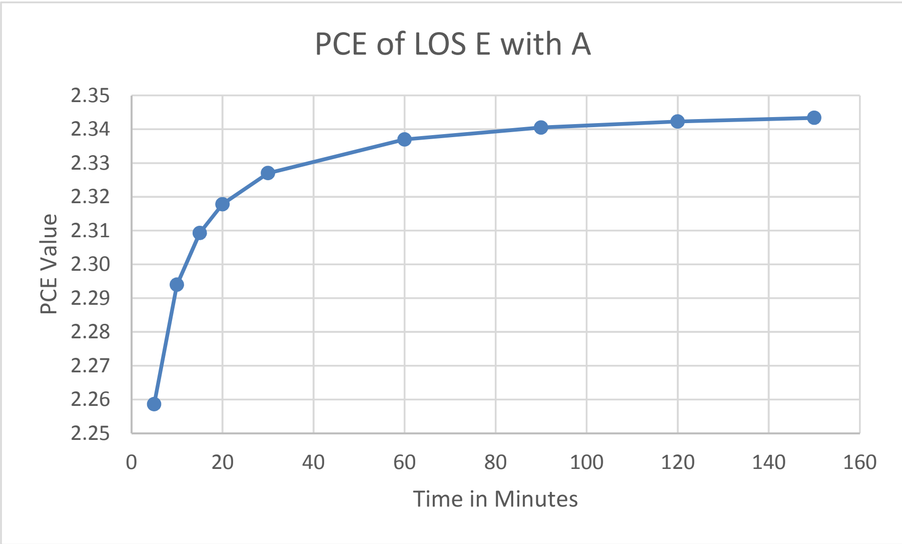

Figure 24. Relationship between PCE Factor and Time under LOS E with A

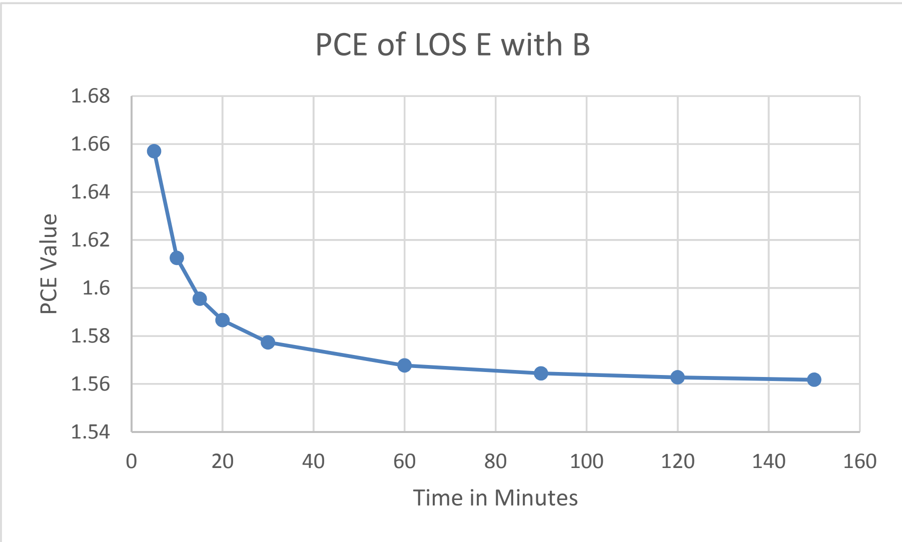

Figure 25. Relationship between PCE Factor and Time under LOS E with B

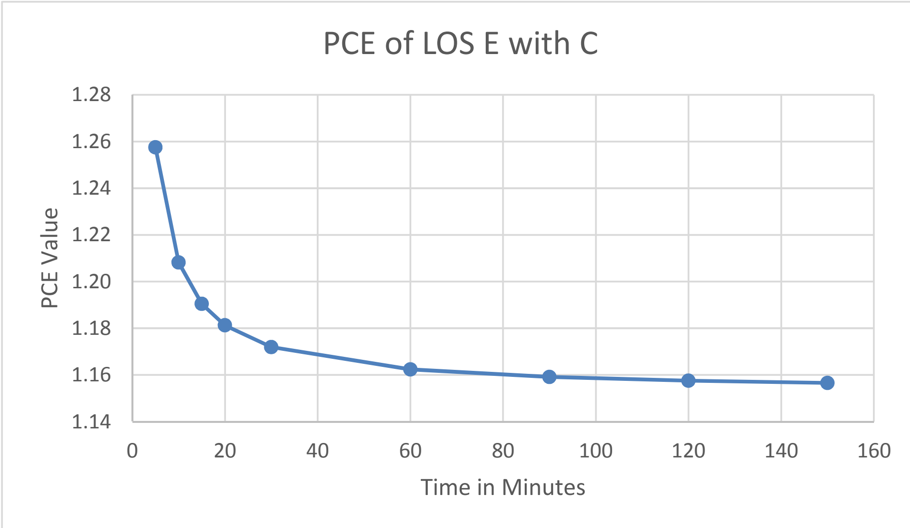

Figure 26. Relationship between PCE Factor and Time under LOS E with C

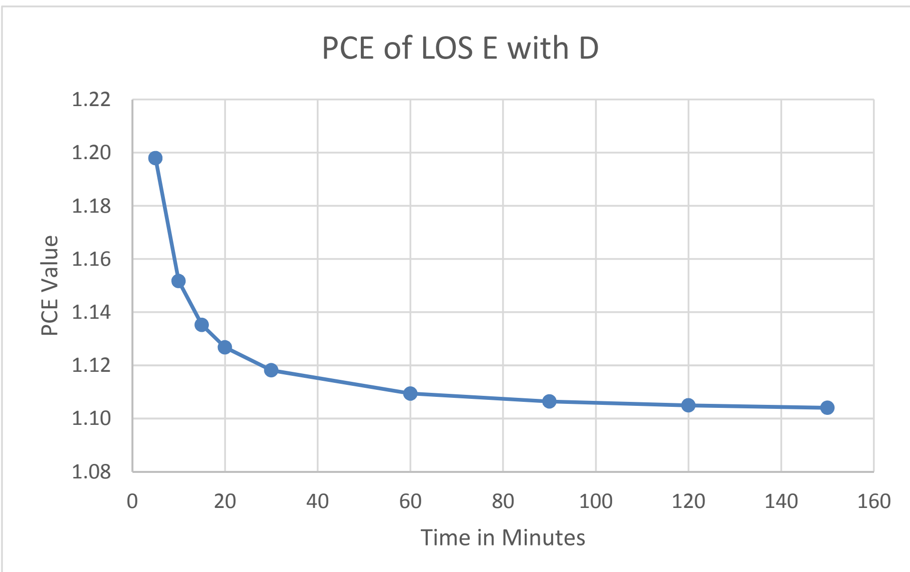

Figure 27. Relationship between PCE Factor and Time under LOS E with D

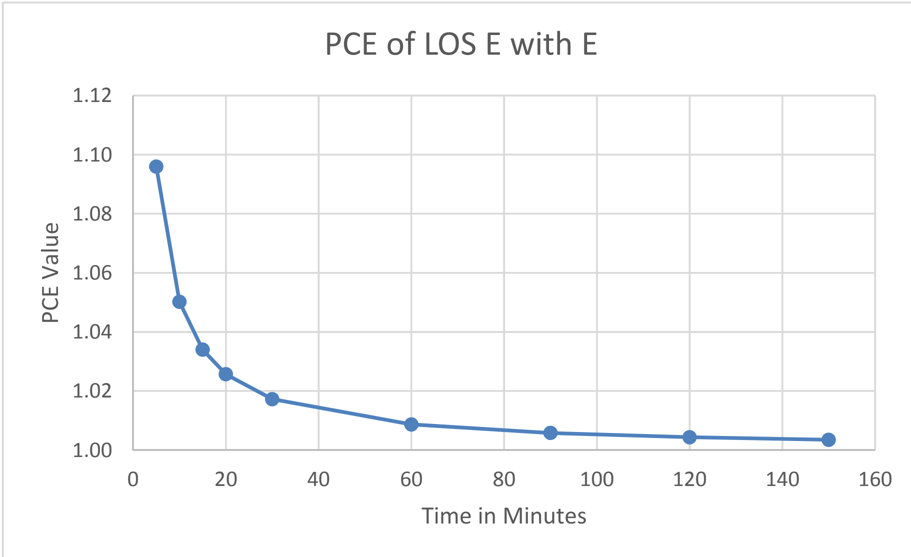

Figure 28. Relationship between PCE Factor and Time under LOS E with E

5.6. Overall Comparison

In this section, PCE factor values are shown in graphic to visualize fluctuation of PCE values with LOS of traveling lane keeping constant, while LOS of opposite lane varying from A to E. Additionally, when queue birth rate exceeds queue death rate, PCE values change with the lasting time of the prevailing LOS. Therefore, based on lasting time of the prevailing LOS, PCE factor values are divided into six groups: 5 minutes, 15 minutes, 30 minutes, 60 minutes, 90 minutes, and 120 minutes.

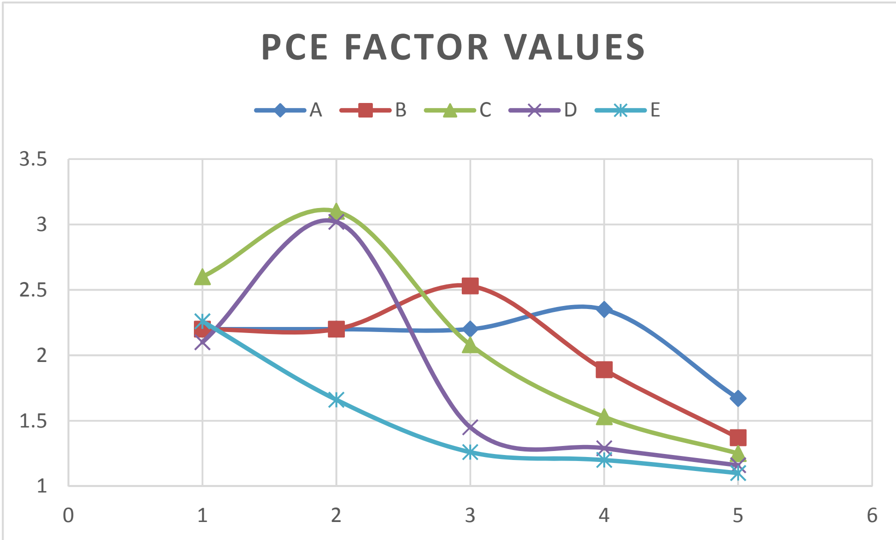

Figure 29. PCE Values under Various LOS with Duration of 5 Minutes

Figure 29 shows the relationship between PCE values and LOS of opposite lane. Each line denotes as PCE factor under according LOS. Horizontal axle is LOS of opposite lane: numbers 1 to 5 represent LOS A to E. As shown in this graphic, when traveling lane is under LOS A, PCE factor does not vary with opposite lane condition, until LOS of opposite lane gets worse than C. This results from the low traffic volume of both lanes. Therefore, only a short and stable queue can be generated. Under these conditions, PCE factor mostly depends on headway model. At LOS D of opposite lane, this set of PCE factor reaches peak value because more traffic arrive within unit time from opposite direction. Crowded traffic from the opposite direction limits the number of passing, which attributes to a longer queue in traveling lane, though a limited number of passings can still be allowed. Thus, under LOS A with D, it presents the most noticeable difference of impact on following traffic between trucks and passenger-cars. Comparing all the five trend lines, PCE factor value under each LOS reaches its peak value under different LOS of opposite lane, which are LOS D, C, B, B, and A, respectively. Moreover, each peak value is different. The highest PCE factor value is 3.1, which is observed from LOS C with B. However, the lowest peak value is from LOS E with A.

Observing from the above figure, when LOS of opposite lane is A and E, there is no huge variance among all PCE values, compared with under LOS B, C, and D of opposite lane. It is demonstrated that impact of trucks does not highly depend on LOS of traveling lane, when opposite lane is at its best and worst condition.

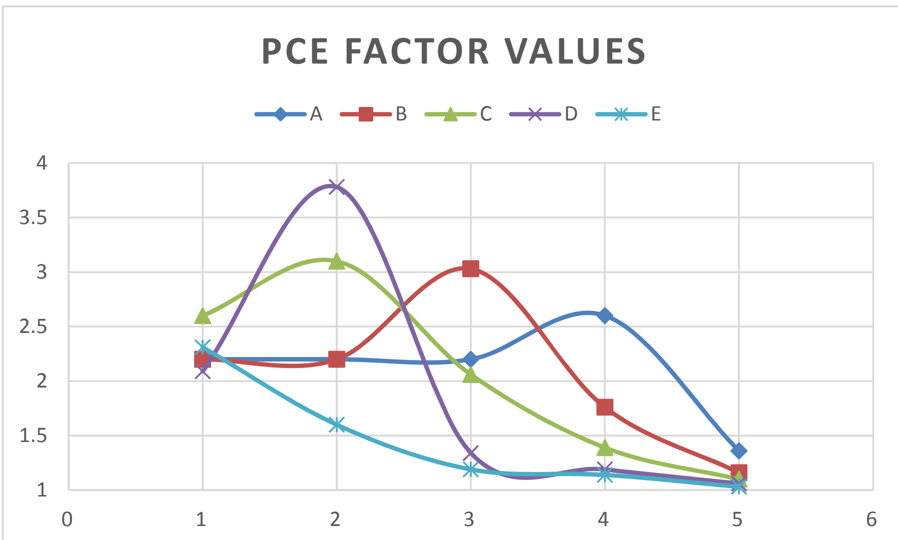

Figure 30. PCE Values under Various LOS with Duration of 15 Minutes

Figure 30 presents relationship between PCE factor value and LOS, when duration of LOS of according lane is 15 minutes. Compared with Figure 18, the most distinct change is PCE factor of LOS D with B, which is higher than all other values and also higher than that in Figure 18. In addition, peak value of LOS A and C all increase slightly. This is predictable by analyzing the queue length model. Under condition LOS D with B, LOS C with C, and LOS A with D, queue caused by the truck is a function of time. As the duration of this condition keeps increasing, queue will keep accumulating. However, queue length caused by a slow passenger-car does not related with time incremental. Instead, it keeps constant within unit time. Therefore, as the duration of current condition increases, the difference between queue caused by a truck and a passenger-car becomes more noticeable. This trend can also be observed from Figure 31 to Figure 34.

Based on Figure 30, the highest PCE factor value is 3.8, when LOS of traveling lane is D, and LOS of opposite lane is B. It indicates that difference of impact between trucks and passenger-cars is the most prominent under this condition.

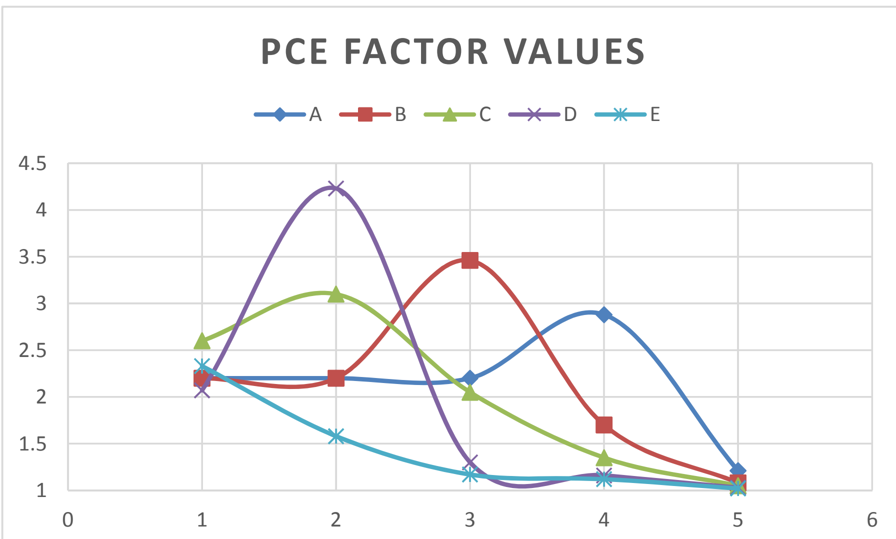

Figure 31. PCEs Value under Various LOS with Duration of 30 Minutes

Figure 31 indicates the fluctuation of PCE factor value when duration of certain road condition lasts 30 minutes. As it explained above, under condition LOS D with B, LOS C with C, and LOS A with D, queue length caused by a truck is a function of time, while queue length caused by a passenger-car is not. Thus, queue length caused by a truck will increase exponentially, while queue length caused by a passenger-car is held consistent. Therefore, these PCE values are increasing with time incremental accumulating.

Figure 32 is presented below to visualize the fluctuation of PCE factor under various LOS. All PCE values shown in Figure 32 are computed with duration of LOS 60 minutes.

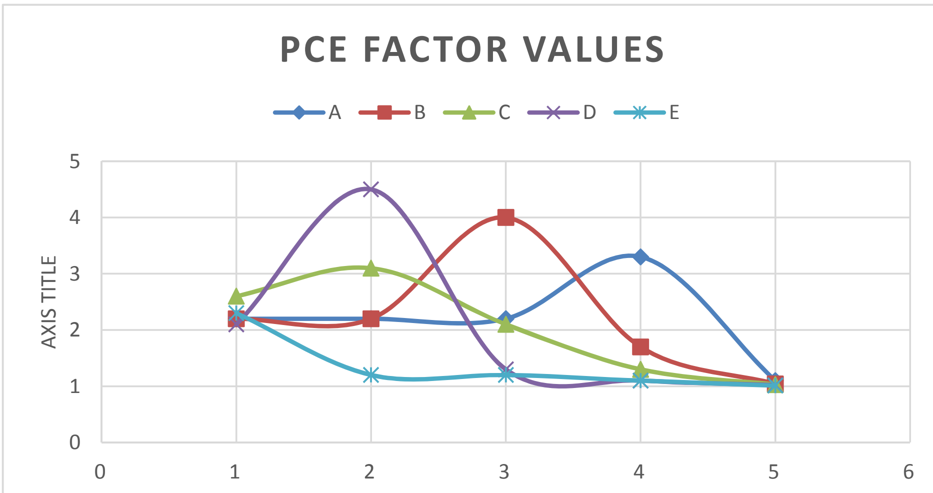

Figure 32. PCE Values under Various LOS with Duration of 60 Minutes

As discussed above, PCE values are more stable when traveling lane under LOS E than under other LOSs. PCE value reaches its peak value at LOS D with B, with the second and third highest value at LOS B with C and LOS A with D. The highest value of summations of PCE value under each LOS is 11.14 under LOS B, and the lowest value is 6.81 under LOS E. Based on this information, it is demonstrated that trucks have more impact on following traffic under LOS B, and less effect under LOS E. It is obvious that all the trend lines starts and ends at the similar values, which indicates that when traffic condition of opposite lane is under LOS A or E, PCE factor does not vary with LOS of traveling lane. It reveals that regardless of LOS of traveling lane, trucks have the same impact on following traffic, as long as opposite traffic is under the ideal or the worst condition.

The average PCE value is roughly 2.0. However, the average value is not recommended. PCE factor depends on time incremental, traffic volume and LOS of both lanes. A fixed value of PCE factor cannot be applicable for all conditions.

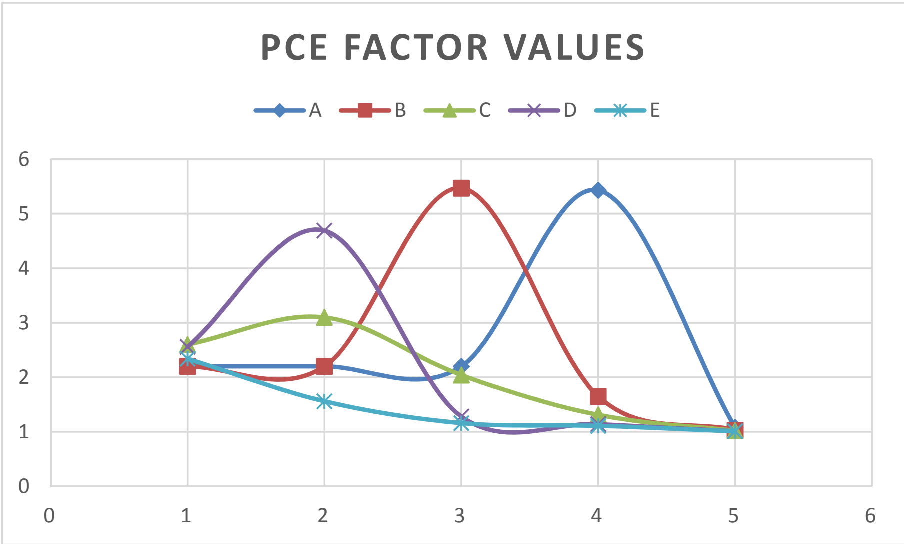

Figure 33. PCE Values under Various LOS with Duration of 90 Minutes

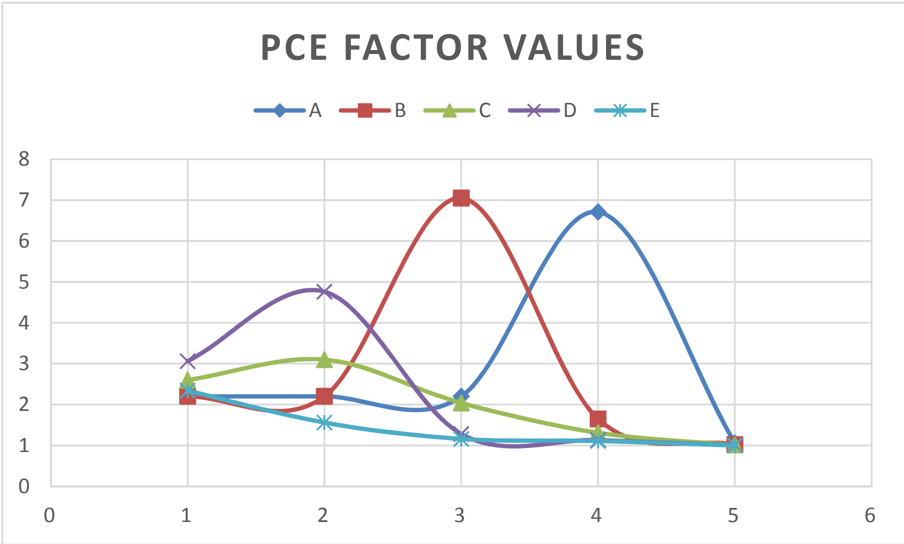

Figure 34. PCE Values under Various LOS with Duration of 120 Minutes

Figure 33 and Figure 34 present PCE values under various LOS of opposite lane with duration of each condition 90 minutes and 120 minutes, respectively. As shown in these two figures, PCE values under LOS A with D and LOS B with C are higher than 5.5, which are much higher than all values shown in above figures. Compared with the values provided by HCM, these values are much higher. However, it results from a long and consistent duration of traffic condition. For example, under LOS B with C, when both lanes keep the corresponding LOS for 90 minutes, PCE value under this condition is 5.5. It is explainable by using analytical model; however this situation is rare in practical. In real life, traffic characteristics can be affected by any traffic fluctuation from upstream and downstream, such as a large number of traffic coming from upstream, or a bottleneck appears in downstream. These issues have an effect on LOS of study road segment. Thus, in most cases, it is less possible that a certain road condition keep consistent for such a long time.

Compared with all the trends shown in Figure 29 to Figure 34, it reveals that, under each LOS, PCE value will decrease sharply, after it reaches its peak value. It is attributed by the condition where PCE factor reaches its peak value. Peak value of PCE factor under certain LOS means that trucks have the most impact on coming flow compared with passenger-cars under the current LOS. As observed, these peak values happen when queue length caused by trucks is related with time incremental, while queue length caused by passenger-cars is not. When LOS of opposite lane getting worse, queue length caused by passenger-cars is also a function of time. Therefore, peak values are observed at critical points, and PCE values are relatively low when LOS of opposite lane is better or worse than the critical point. Furthermore, peak value of each LOS is distinctive with each other under various duration of current LOS. Each peak value is decided by traffic flow characteristics and LOS of both lanes. Queue length and queue growth rate is depended on the queue birth rate and queue death rate, which are related with traffic arrival rate, headway distribution of opposite lane and more factors. Therefore, under different LOS, the peak values are distinct.

In all these 6 figures, there are only slight changes in trends line of LOS E.

CHAPTER 6. SUMMARY AND CONCLUSION

6.1. Summary

As analyzed in Chapter 5, there are four types of relationship between PCE factor values and LOS lasting time:

Constant with time relationship: under LOS A with A, A with B, A with C, B with A, B with B, B with C, and C with A, PCE values do not vary with LOS lasting time. In this category it can be observed that PCE values are stable, concentrating around 2.2 with little variance. Also, it is clear that LOS of at least one of both lanes is under good condition: either A or B. The low traffic volume will result in high possibility to allow a passing action and a low queue generation rate. Thus, queues caused by a passenger-car and a truck are finite. In fact, number of vehicles blocked by slow vehicles is expected to be less than one measured in one hour. In this case, queue length model has little effect on PCE values. Thus, PCE value is mostly decided by headway model. Headway model is only affected by vehicle average travel speed, so PCE values hold constant when LOS lasting time increases.

Two-step linear relationship: Figure 12, 13, and 19 belong to this type. Figure 29 shows combination of these three figures. There are several interweaves between PCE factor values under LOS A with D and LOS B with C. From 0 to 50 minutes and 90 to 150 minutes, PCE value under LOS B with C is higher, but PCE value under LOS A with D is higher from 50 to 90 minutes. In general, PCE values of these two groups are closed, and both of the two groups start and end at similar point. However, PCE values under LOS D with A are much lower than the other two groups. In addition, before the inflection point, only group LOS D with A shows a decreasing trend. Moreover, PCE value under LOS A with D has a unique inflection point, which is at 30 minutes.

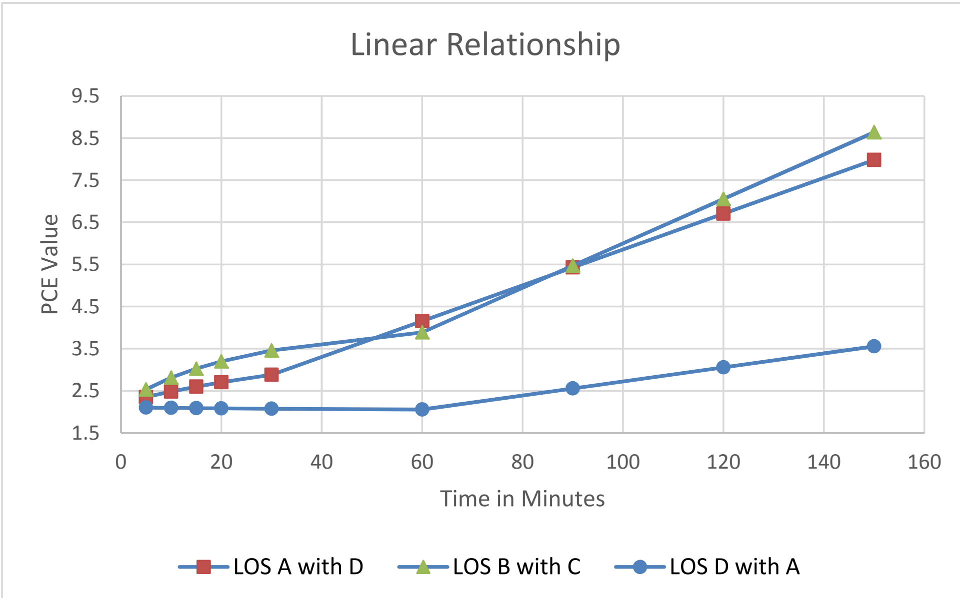

Figure 35. Linear Relationship

The difference between queues caused by the passenger-car and truck attributes the pattern of this relationship. Queue caused by the slow passenger-car is finite, because when opposite lane under such a good traffic condition, such as A, B or even C, slow passenger-car only blocks a small amount of vehicles. Thus, queue death rate is higher than queue birth rate. On the contrary, queue caused by the truck is infinite under the accordingly same condition. Before LOS lasting time reaches the inflection point, the ratio of PCE value depends on queue birth rate caused by the passenger-car and the truck. When LOS lasting time passes the inflection point, queue caused by the passenger-car stops increasing, while queue caused by the truck still keeps growing. The difference between the two queue lengths gets to be outstanding. Thus, a two-step linear relationship is generated, and PCE values start to increase much faster after the inflection point.

Exponential relationship: Figure 11, 14, 15, 16, 17, 18, 21, 22, 23, 25, 26, 27, and 28 all present the same exponential trend. The overall variance in each group is really low, and the most significant change is only less than 1 unit, which is labeled with value in each point. Most of these groups vary between 1.0 and 1.4, which means under these conditions, only slight difference existing between trucks and passenger-cars. Mostly, PCE values decease before LOS lasting time reaches to one hour, and decreasing rate starts with a high value, but reduces in a short time. After LOS lasts for more than one hour, all groups tend to stabilize and approach to a fixed value.

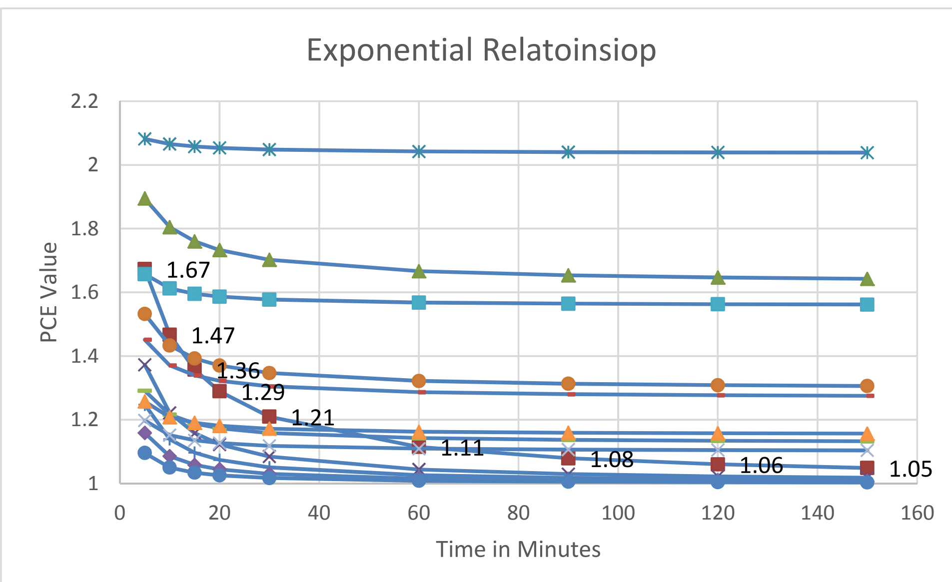

Figure 36. Exponential Relationship

As it shown, in this category, driving condition of either lane is poor, mostly under LOS D or E. When LOS of opposite lane is under D or E, passing is nearly impossible.

Therefore, even though analyzed lane is under good driving condition, queues caused by passenger-cars and trucks are infinite, such as under LOS A with E. When LOS of analyzed lane is very low, queue birth rate gets so high, that an infinite queue can still be generated, even though there is little traffic in opposite lane, such as under LOS E with B.

In this category, both of queues caused by the passenger-car and the truck are infinite, because queue birth rate is higher than queue death rate. Exponential relationship results from both of queue length model and headway model. In this category, queue length ratio of queue caused by the truck and queue caused by the passenger-car is lower than headway ratio of truck headway and passenger-car headway. Therefore, before LOS gets to last a long time, headway model determines most of PCE values. However, when LOS lasting time goes on, weight of queue length model gets much higher than headway model. Therefore, PCE values in this category get approach to a low fixed value.

Logarithmic relationship: Figures 20 and 24 show up a logarithmic trend. Under LOS D with B, the PCE value changes significantly, until LOS lasting time reaches one hour. The increasing rate starts with a high value, but it decreases with time going on. Also, under LOS D with B, the PCE value is much higher than the average. The lowest value in this group is 3.0, which is already higher than exponential category, and the highest value reaches to almost 5.0. On the contrary, under LOS E with A, PCE value can be taken as keeping roughly consistent and it keeps at a relatively low range compared with under LOS D with B.

Under these two conditions showing in Figure 20 and 24, queues caused by the passenger-car and the truck are infinite. But different with exponential category, the ratio of queue length caused by the truck and queue length caused by the passenger-car is higher than the ratio of truck headway and passenger-car headway. Therefore, in this category, PCE values start with a higher value than in exponential category. Also, different with exponential category, the ratio of queue lengths by the two kinds of vehicles enhances the PCE values with time going on, instead of diminishing PCE values. Therefore, PCE values get approach to a high value when time goes on.

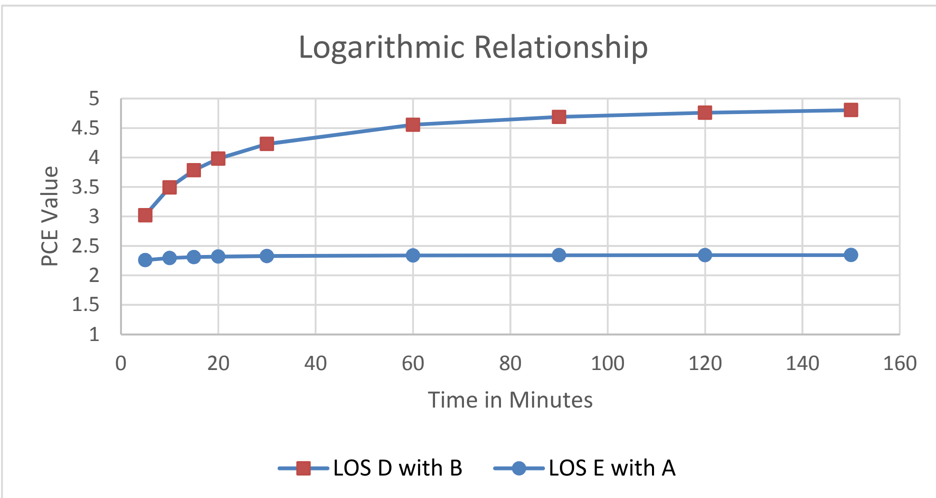

Figure 37. Logarithmic Relationship

As shown in Table 19, PCE factor value is presented under all LOS combinations.

Table 19. PCE Factor Value

PCE Factor Value							
	Analyzed Lane LOS	LOS Lasting time					
Opposite Lane LOS	A	5min	15min	30min	60min	90min	120min
A		2.2	2.2	2.2	2.2	2.2	2.2
B		2.2	2.2	2.2	2.2	2.2	2.2
C		2.2	2.2	2.2	2.2	2.2	2.2
D		2.35	2.60	2.88	4.16	5.43	6.71
E		1.67	1.36	1.21	1.11	1.08	1.06
	B						
A		2.2	2.2	2.2	2.2	2.2	2.2
B		2.2	2.2	2.2	2.2	2.2	2.2
C		2.53	3.03	3.46	3.89	5.47	7.05
D		1.89	1.76	1.70	1.67	1.65	1.65
E		1.37	1.16	1.08	1.04	1.03	1.02
	C						
A		2.6	2.6	2.6	2.6	2.6	2.6
B		3.1	3.1	3.1	3.1	3.1	3.1
C		2.08	2.06	2.05	2.04	2.04	2.04
D		1.53	1.39	1.35	1.32	1.31	1.31
E		1.25	1.10	1.05	1.03	1.02	1.01
	D						
A		2.10	2.09	2.07	2.06	2.56	3.06
B		3.02	3.78	4.23	4.56	4.69	4.76
C		1.45	1.34	1.30	1.29	1.28	1.28
D		1.29	1.19	1.16	1.14	1.14	1.13
E		1.16	1.06	1.03	1.02	1.01	1.01
	E						
A		2.26	2.31	2.33	2.34	2.34	2.34
B		1.66	1.60	1.58	1.57	1.56	1.56
C		1.26	1.19	1.17	1.16	1.16	1.16
D		1.20	1.14	1.12	1.11	1.11	1.10
E		1.10	1.03	1.02	1.01	1.01	1.00

Compared data in Table 19 and PCE values given by HCM (Table 5), the new developed PCE values are slightly higher than the ones in HCM, when LOS of analyzed lane is lower than LOS of opposite lane by one level. This result meets the expectation, because physical length of an oil truck is longer than the average, which reduces passing possibility by times. In HCM 2010, it does not provide PCE values related with various LOS of each lane. To analyze PCE values under imbalanced flow, Table 20 is generated, and PCE values in Table 20 are measured when LOS lasting time is one hour.

Table 20. PCE Values under Imbalanced Flow

LOS of Analyzed Lane	LOS of Opposite Lane	PCE Value	LOS of Analyzed Lane	LOS of Opposite Lane	PCE Value
A	D	3.3	A	E	1.1
B	D	1.7	B	E	1.1
C	D	1.3	C	A	2.6
C	B	3.1	C	E	1.1
D	B	4.5	D	A	2.1
E	B	1.2	E	A	2.3

Column 3 in Table 20 shows PCE values under second extremely imbalanced flow, and Column 6 in Table 20 presents PCE values under extremely imbalanced flow. Comparing these two columns, it implies that when analyzed lane is under LOS A, B, C, and D, PCE factor gets a lower value with extremely imbalanced traffic flow. With less extremely imbalance traffic flow, PCE values are much higher. It indicates that when driving condition of opposite lane is perfect or the worst, there is less difference between trucks and passenger-cars. When opposite lane is under perfect condition, possibility to pass a passenger-car is almost the same as passing a truck. Thus, queue length caused by these two kinds of vehicles is the same. On the other hand, when opposite lane is over-saturated, it is impossible neither to pass a passenger-car or a truck. Thus, in this case, little difference can be observed in queue length caused by trucks and passenger-cars. However, when traffic condition is between these two extreme conditions, length of vehicle has huge impact on possibility to pass a slow vehicle. Therefore, under these situations, queue caused by trucks is longer than queue caused by passenger-cars, and PCE factor has a higher value.

It is necessary to point that directional distribution measure is not the same, because slow vehicles are assumed to be on analyzed lane. For example, under LOS D with B, PCE value is 4.5, while it is 1.7 under LOS B with D. LOS of analyzed lane decides queue birth rate, and LOS of opposite lane decides queue death rate.

6.2. Conclusion

In this paper, a new model is developed to calculate value of PCE factor of oil trucks on two-lane rural highway. Two criteria are selected to calculate PCE values: headway and queue length. Compared with PCE values in HCM 2010, the new set of PCE values is a little higher. Also, it is found that PCE factor is affected by LOS of both lanes and LOS lasting time. Between LOS lasting time and PCE values, four relationships are observed: consistent with time, two-step linear, exponential, and logarithmic. Furthermore, PCE values reach to peak values when two-lane traffic flows are imbalanced, but not under extremely imbalanced conditions.

In above section, it is noted that the new set of PCE values are slightly higher than PCE values in HCM 2010, considering the length of oil trucks. With the new set of PCE values, it can help to improve the calculation in highway capacity design (showing in Equation 43 and 44).

$$C = 3200 * PHF * f_G * f_{HV} - V_{NP} \tag{43}$$

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} \tag{44}$$

Where

C is two-way highway capacity;

PHF is peak hour factor, which is 0.88;

f_G is adjustment factor for heavy vehicles;

f_{HV} is adjustment factor for heavy vehicles;

V_{NP} is volume adjustment for no passing zone;

P_T is truck percentage;

E_T is passenger-car equivalent factor.

Compared with applying the new set of PCE values in oil area highway capacity design, HCM 2010 overestimates highway capacity in some cases. For example, under LOS B with B HCM suggests a PCE value of 1.4, while the new value is 2.2. In this case, two-lane highway capacity will not reach to the design value, if HCM value is applied, because oil trucks have more impact on capacity than HCM estimated under such traffic condition. On the other hand, HCM underestimates highway capacity in some cases, such as under LOS A with E, where PCE value in HCM is 1.9, and the new value is 1.1. In this case, a two-lane highway can handle more traffic than HCM expected.

There are four relationships between PCE values and LOS lasting time. The four relationships and the PCE values reveal the change of impact that oil trucks will have on highway capacity with time going on. For example, tide traffic is common at recreational roads. Because of one way demand traffic, during certain time period, one of lanes will get extremely congested, while the other lane is under perfect driving condition. Such as LOS A with E, or LOS E with A, one can observe such situations on Interstate 70 West bound in Colorado, every Friday later afternoon till midnight and I-70 East bound every Sunday later afternoon till midnight will get really congested while the other side of road is under perfect driving condition because of the needs to get into the mountain on Friday and needs to come back to city on Sunday. If similar creational road segments are shared with oil truck routes, then agencies will know that trucks on the congested side of the road (LOS E with A) will have relative higher PCE (around to 2.0) compared to trucks on non-congested side of the road (LOS A with E) (around to1.0). Moreover, they both are not sensitive to LOS lasting time. Even with the higher PCE, the values are all around 2 which is close to the PCE when LOS A with A (the situation might be when recreational traffic is gone), so agencies can decide that no need to restrict truck access to those road segments during those time periods, since it won’t reduce truck impact on capacity.

In oil area, because of high traffic volume and balanced inbound-outbound traffic demands, it is common that both of lanes are congested but not over-saturated and often time the conditions of both lanes stay or last for longer periods, such as under LOS C with C or LOS D with D which display an exponential relationship, where the PCEs are higher when traffic condition just start to enter the LOS combination and start to drop to either close 1 or close 2 with condition lasting time increasing. From Figure 16 and Figure 21, One can tell in these situations, PCE is not sensitive to condition lasting time however, trucks has lower impact on traffic under LOS D with D (with approaching PCE equals 1) comparing with under LOS C with C (with approaching PCE equals to 2). If highway planers want to limit truck impact on capacity consumption, improving LOS condition will not help. Basically, the research results reveal that in oil field, having balanced LOS for both directions of a two-lane highway, trucks consume twice capacity as cars when the condition is no worse than LOS of C, which is originated from the physical differences. One can tell that no truck impact reduction will happen even if LOS condition is improved, because the PCEs would be always around 2.

When it is two-step linear or logarithmic relationship, trucks impact will equal to at least three passenger-cars, and PCEs are very sensitive to LOS condition lasting time. It can get as high as over 5 in one and half hour. If in oil field, agencies observed the not-so-extreme unbalanced LOS during certain time period, for example, during rush hours, oil traffic combined with the commuter traffic generates condition like LOS B with C and that condition only lasts for short period, such as from 7am to 8am and 4pm to 5pm. In that case, limiting truck entrance to certain segment during that certain time period can significantly reduce truck impact on capacity.

It can be observed from Table 19 that PCE value is also related with LOS of the lane used by trucks. In most cases, PCE will be different, if LOS of analyzed lane exchanges with LOS of opposite lane. For example, under LOS A with D, PCE value changes from 2.5 to more than 6.0 with lasting time going on, while under LOS D with A, PCE value only reaches to 3.0 at most. This kind of tide traffic can be observed when commuters travel from suburban to central city, where one lane is congested but not over-saturated with the other lane under perfect condition. If trucks share the lane with congested traffic, they will have less impact on capacity than they use the uncongested lane. In this case, planners can limit trucks entrance to the uncongested lane until condition of the other lane gets better, where PCE has a value of 2.2 under LOS A with C. On the contrary, in some cases, trucks are restricted to access to the congested lane. For example, under LOS D with B, PCE varies from 3.0 to 4.7, while it has a value below 2.0 under LOS B with D. In these imbalanced situations, trucks have more impact on capacity when they share lane with congested traffic, instead of with uncongested traffic. For highway planners, it is demonstrated that trucks will have less impact on capacity, if truck access gets limited to such a lane until traffic condition getting better to LOS C, where PCE value is around 3.0 at LOS C with B. In other cases, there is no need restricting truck access to certain road segments. As mentioned above, when it is under LOS A with E or LOS E with A, capacity will not fluctuate too much with trucks in traffic flow or not.

6.3. Further Study

The process to estimate PCE factor is complicated. Model developed in this paper is an analytical model. All criteria in the model can be described and calculated by mathematical methodology. Several factors are ignored or considered as an average value as default when building the model, such as lane width, passing lane percentage, and shoulder width. Also, studied type of terrain is only considered as level terrain and no curvature is considered. However, all these factors can be reflected in traffic performance. Thus, to calculate condition that is not included in this paper, traffic performance can be changed to the values to conform certain condition. For example, to study a highway segment with a narrower lane width, average travel speed can be set up with a lower value. Or under rolling terrain, deceleration of trucks is greater than that under level terrain, but acceleration rate is lower than that under level terrain.

As mentioned above, this set of PCE value is not applicable for all situations. A further study is needed to complete this set of PCE value, such as under combination of various type of large vehicles, under curve or rolling terrain, at intersection location, and under traffic accidents. Most factors can be explained by mathematical model, but human factor and behavior are hard to predict or described as a mathematical model. To predict people’s reaction under certain situation, an applicable method is to collect data from large amount of surveys, and observe the trend existing in the data.

REFERENCES

Al-Kaisy, A., Jung, Y., and Rakha, H. (2005). Developing Passenger Car Equivalency Factors for Heavy Vehicles during Congestion. *J. Transp. Eng., 131(7), 514–523*. Retrieved from http://ascelibrary.org/doi/abs/10.1061/(ASCE)0733-947X(2005)131%3A7(514)

Andrew, K., & Kimberly, V. (2012). Oil County Traffic Safety Survey, 2012. *Upper Great Plains Transportation Institute.* Retrieved from http://www.visionwestnd.com/documents/OilCountyTrafficSafetySurvey.pdf

Commercial Transport Act. (2011). [Graph illustration the Oil Truck Configuration]. *Commercial Transport Regulation.* Retrieved from http://www.bclaws.ca/Recon/document/ID/freeside/30_78

Craus, J., Abishai, P., & Itzhak, G. (1980). A Revised Method for the Determination of Passenger Car Equivalencies. *Transportation Research Part A: General, 14, 241-246.*

Douglas, W., Harwood, D., May, I. B., Anderson, L. L., & A. Ricardo, A. (1999). Capacity and Quality of Service of Two-lane Highway. Retrieved from http://www.sierrafoot.org/civics/traffic/nchrp%203-55(3)%20report_2-lane_road_capacity_LOS.pdf

Greenshilds, B. D., & Weida, F. M. (1952). Statistics with Applications to Highway Traffic Analyses. *The ENO Foundation for Highway Traffic Control Saugatuck Connecticut.* Retrieved from ntl.bts.gov/lib/26000/26700/26797/STATISTICS_WITH_APPLICATIONS_TO_HWY_TRAFFIC_ANALYSES.pdf

Hansen, B. (2012). North Dakota's Oil/Gas Boom to Get Even Bigger, Official Says. *McGraw Hill Financial.* Retrieved from www.platts.com/latest-news/oil/Washington/North-Dakotas-oilgas-boom-to-get-even-bigger-3246174

Hend, J., & Francesco, V. Queues at Signalized Intersections: the Old Theory Revised. Retrieved from https://www.mech.kuleuven.be/cib/verkeer/dwn/pub/P2006F.pdf

Homburger, Kell & Perkins, Fundamentals of Traffic Engineering, 13th Edition, Institute of Transportation Studies, UBC (Berkeley; www.its.berkeley.edu), 1992, p. 4-4.

Jacobs, F. (1974). Queues and Overtakings on Two-lane Roads. In D. J. Burckley (ed.), Transportation and Traffic Theory. (Proceedings of the Sixth International Symposium on Transportation and Traffic Theory). New York: Elsevier, p. 181-202

Krammes, R A., & Crowley, K W. (2008). Passenger Car Equivalents for Trucks on Level Freeway Segments. *Transportation Research Record, 1091, 10-17.*

Krumins, I. (1991). Two-Lane Highway Capacity and Level of Service Research Project: Phase III Final Report. *Transportation Association of Canada.*

Limpert, R., & Gamero, Franco. (2008). Air Brake Design and Safety Part One Straight \ Trucks. *PC-Brake, Inc.* Retrieved from www.pcbrakeinc.com/epub/PCB_2_2007.pdf

Nathan, W., & Elefteriadou, L. (1997). A Simulation Study of Truck Passenger Car Equivalents (PCE) on Basic Freeway Sections. *Transportation Research Part B: Methodological, 33, 323-336.*

National Cooperative Highway Research Program. (2003). Review of Truck Characteristics as Factors in Roadway Design. *Transportation Research Board. Retrieved from* onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_505.pdf

National Safety Council. Driving Defensively. Retrieved from the-security-institute.org/userfiles/file/Driving%20Defensively.pdf

ND Monthly Oil Production Statistics. Retrieved from https://www.dmr.nd.gov/oilgas/stats/historicaloilprodstats.pdf

Official Portal for North Dakota State Government. (2013). *North Dakota Drilling and Production Statistics*. Retrieved from www.dmr.nd.gov/oilgas/stats/statisticsvw.asp

R. Tapio Luttinen. (2001). Traffic Flow on Two-lane Highways. *TL Consulting Engineers, Ltd.* Retrieved from http://www.phnet.fi/public/luttinen/tlrr01_01.pdf

Reinhart, K., and Panos, M. Continuum Flow Models. Retrieved from http://fhwainter.fhwa.dot.gov/publications/research/operations/tft/chap5.pdf

Sun, D., Lv, J., & Paul, L. (2008). Calibrating Passenger Car Equivalent (PCE) for Highway Work Zones Using Speed and Percentage of Trucks. *Transportation Research Record 1115.*

Tolliver, D., & Dybing, A. (2010). Additional Road Investments Needed to Support Oil and Gas Production and Distribution in North Dakota. *Upper Great Plains Transportation Institute.* Retrieved from www.ugpti.org/resources/downloads/2010-12_AddRoadInvToSupportOil.pdf

Transportation Engineering Online Lab Manual. (2003). [Graph illustration the Passing Sight Distance]. *Geometric Design Theory and Concepts.* Retrieved from www.webpages.uidaho.edu/niatt_labmanual/Chapters/geometricdesign/theoryandconcepts/PassingSightDistance.htm

Transportation Research Board. (1965). *Highway Capacity Manual 1965*. TRB National Research Council, Washington, DC.

Transportation Research Board. (1985). *Highway Capacity Manual 1985*. TRB National Research Council, Washington, DC.

Transportation Research Board. (2000). *Highway Capacity Manual 2000*. TRB National Research Council, Washington, DC.

Transportation Research Board. (2010). *Highway Capacity Manual 2010*. TRB National Research Council, Washington, DC.

Upper Great Plains Transportation Institute. (2007). North Dakota Strategic Freight Analysis Truck Size and Weight Issues in North Dakota. *Upper Great Plains Transportation Institute.* Retrieved from www.ugpti.org/pubs/pdf/DP185.pdf

U.S. Energy Information Administration. (2013). [Graph illustration the Oil Production]. *Monthly Energy Review.* Retrieved from http://www.eia.gov/totalenergy/data/monthly/index.cfm#petroleum

Vasconcelos, L., Silva, A. B., Seco, Alvaro., & Silva, J. (2012). Estimating the Parameters of Cowan's M3 Headway Distribution for Roundabout Capacity Analyses. *The Baltic Journal of Road and Bridge Engineering,* 7(4), 261-268. Retrieved from repositorio.ipv.pt/bitstream/10400.19/1285/1/Estimating%20the%20Parameters%20of%20Cowan%E2%80%99s%20M3%20Headway%20Distribution%20for%20Roundabout%20Capacity%20Analyses.pdf

Wolfgang, S. H., Louis, E. K., & William, R. M. (1982). *Transportation and Traffic Engineering Handbook.* Prentice-Hall, Inc., New Jersey, 1982.