International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:8, No:11, 2014

Impact of Vehicle Travel Characteristics on Level of Service: A Comparative Analysis of Rural and Urban Freeways

Anwaar Ahmed, Muhammad Bilal Khurshid, Samuel Labi

***Abstract*—**The effect of trucks on the level of service is determined by considering passenger car equivalents (PCE) of trucks. The current version of Highway Capacity Manual (HCM) uses a single PCE value for all tucks combined. However, the composition of truck traffic varies from location to location; therefore, a single PCE value for all trucks may not correctly represent the impact of truck traffic at specific locations. Consequently, present study developed separate PCE values for single-unit and combination trucks to replace the single value provided in the HCM on different freeways. Site specific PCE values, were developed using concept of spatial lagging headways (that is the distance between rear bumpers of two vehicles in a traffic stream) measured from field traffic data. The study used data from four locations on a single urban freeway and three different rural freeways in Indiana. Three-stage-least-squares (3SLS) regression techniques were used to generate models that predicted lagging headways for passenger cars, single unit trucks (SUT), and combination trucks (CT). The estimated PCE values for single-unit and combination truck for basic urban freeways (level terrain) were: 1.35 and 1.60, respectively. For rural freeways the estimated PCE values for single-unit and combination truck were: 1.30 and 1.45, respectively. As expected, traffic variables such as vehicle flow rates and speed have significant impacts on vehicle headways. Study results revealed that the use of separate PCE values for different truck classes can have significant influence on the LOS estimation.

***Keywords*—**Level of Service, Capacity Analysis, Lagging Headway.

I. Introduction and Background

HIGHWAY agencies around the globe are striving to improve the traffic conditions so that the user can enjoy the best possible level of service (LOS). LOS is a qualitative measure, which describes the quality of travel under existing roadway and traffic conditions. A traffic stream is composed of mix of passenger cars, sport utility vehicles, recreational vehicles, single unit trucks (SUT), construction vehicles and combination trucks (CT). These vehicles have different physical (length, width etc.) and operational characteristics (acceleration/ deceleration abilities). In order to determine the operational quality of travel in a traffic stream, LOS is widely accepted measure. On basic freeway segments traffic density is considered as dominating factors and has been used widely as performance measure for establishing LOS. Traffic density is determined by converting all vehicles (other than passenger cars) in a traffic stream, to passenger cars using passenger car equivalencies (PCEs).

First time in 1965 Highway Capacity Manual (HCM), the term passenger car equivalent was used, as 1950 HCM arbitrarily assumed all trucks equivalent to two cars [1], [2]. In 1985 HCM, volume to capacity (v/c) was used as performance measure to estimate PCEs [3]. The 2000 version of highway capacity manual used thorough procedures to convert heavy vehicles into passenger car equivalent using PCEs. The 2000 HCM defined PCE as ''the number of passenger cars that are displaced by a single heavy vehicle of a particular type under prevailing roadway, traffic, and control conditions" [4].

In past, different studies have used different methodologies to calculate the PCEs for different types of highways/ vehicles. Headway, speed, delay, density, platoon formation, volume/capacity ratio and queue discharge have been used as popular performance measure [5]. Similarly for basic freeway segments different researchers in past have used different techniques. Werner and Morrall [6] were first to use the concept of lagging headway to estimate PCE for level terrain and developed following relationship:

$$PCE = \left[\frac{H_t}{Hp} - Ppc\right]/Ppt \quad (1)$$

where: H_t, H_P, P_{PC} and P_{PT} are the average traffic stream/ passenger car headway, and passenger cars and trucks proportion in the traffic stream, respectively. After Werner and Morrall, the concept of lagging headway was used by two other studies [7], [8] to describe the impact of heavy vehicles in a mix traffic stream. Elefteriadou et al. [9] formulated PCE assuming that headway depends on the following vehicle as follows:

$$PCE_{kj} = \left[\frac{H_{kj}}{H_{pcj}}\right] \quad (2)$$

where: H_{kj}, Hpc_j and PCE_{kj} are the lagging headway of following vehicle of class k, passenger car lagging headway and PCE value for vehicle class k under condition j,

Anwaar Ahmed, Associate Professor, is with the School of Civil and Environmental Engineering, National University of Science and Technology, Islamabad, Pakistan (Corresponding author: phone: +92-3468123478, e-mail: anwaar5148@gmail.com).

Muhammad Bilal Khurshid, Associate Professor, is with the School of Civil and Environmental Engineering, National University of Science and Technology, Islamabad, Pakistan (e-mail: baliarj111@yahoo.com).

Samuel Labi, Associate Professor, is with the Purdue University, 550 Stadium Mall Drive, West Lafayette IN, 47907 (e-mail: labi@purdue.edu).

respectively. More recently [10] used the concept of spatial lagging headways to estimate PCEs.

This paper is an extension of a recent work that used the concept of spatial lagging headway to estimate PCEs for urban freeway segments [12]. Spatial lagging headway is the "distance from the rear bumper of a leading vehicle to the rear bumper of the following vehicle" [10]. Spatial lagging headway is the actual space a vehicle consumes when it is in a traffic stream [5]. This study used lagging headways concept to compare separate PCE values for SUT and CT on urban and rural freeways. Present study used data from four different locations on an urban freeway and three different rural highways for state of Indiana. This study used three-stage-least-squares (3SLS) regression techniques to estimate models that predict lagging headways for passenger cars, single unit trucks, and combination trucks to estimate PCEs. Finally present study presents a comparison between PCE values estimated for rural and urban highways and their impact on LOS.

II. Data Collection and Collation

The field data for this study were collection using a mobile traffic laboratory. For urban freeway, a total of 90 hours of video was recorded (this is equivalent to 540 lane-hours of video recorded traffic data, with three traffic lanes in each direction) from four sites along Interstate-465 in Indianapolis. Of the 540 lane-hours, only the peak 15-minutes of data were considered for final model building. Thus, the processing of urban data yielded a total of 540 observations. Of these 540, 452 observations with at least one PC, one SUT and one CT were used for model building. In the case of rural interstates, the data collection effort yielded 31 lane-hours of video recorded traffic data at three different rural interstate locations (I-65, I-70 and I-74). The processing of rural interstate video data yielded 94 observations which had at least one PC, one SUT and one CT. Thus a total of 94 observations were available for building the headway model for rural interstates. The 15-minute video clips were analyzed using computer software traffic tracker to extract speed, lagging headway, and percentage and number of different vehicles in traffic stream. The lagging headways were bounded between vehicle length and stopping sight distance as two extremes.

III. Study Methodology and Results

For three vehicle classes-following combinations (PC, SUT or CT following any other vehicle) statistical approach was adopted to estimate the spatial lagging headways. The dependent variables are the lagging headway values, for PC, SUT, and CT. The dependent variables are considered endogenous and three-stage-least-squares (3SLS) regression was used to model three equations simultaneously in order to ensure that results are not biased due to error terms correlation [11], [12]. Mathematically, the system of regression models can be written as follows:

$$Ln(\text{LHpc}) = \propto_1 + \beta_1 Xpc + \partial \ln(LHsut) + \emptyset \ln(LHct) + \epsilon_1 \quad (3)$$

$$\text{Ln(LHsut)} = \propto_2 + \beta_2 \text{Xsut} + \mu \ln(\text{LHpc}) + £ \ln(\text{LHct}) + \epsilon_2 \quad (4)$$

$$\text{Ln(LHct)} = \propto_3 + \beta_3 Xct + \pi \ln(LHpc) + € \ln(LHsut) + \epsilon_3 \quad (5)$$

where: ln(LHpc), ln(LHsut), ln(LHct) are the natural logarithm of average lagging headway of PC, SUT and CT, Xpc, Xsut and Xct are independent variable such as speed of individual vehicles, total vehicle flow, and percentage of PCs and SUT and CT, π, $\emptyset$, ∂, μ £, € and β_i are model parameters, and ε_i are the disturbance terms. The results of 3SLS models estimates for urban and rural freeways are presented in Table I and a discussion on results is presented as follows:

A. Urban Freeway 3SLS Model

The details of 3SLS model for urban freeway are provided in [12]; however it is discussed here briefly to provide a comparison with rural freeway 3SLS model.

PC flow and SUT flow have intuitive signs, as adding more vehicles will reduce the maneuverability space thus resulting in decrease in average PC lagging headway. The negative sign for these variables shows that PC lagging headway decreases with an increase in PC or SUT flow rate. Average PC speed, another significant variable, has intuitive sign as at higher speeds larger stopping distance is required, thus a following vehicle may keep larger distance from leading vehicle. However, the average SUT speed has negative correlation with PC lagging headway indicating that at higher speeds SUT and PC start behaving in a similar fashion. Both endogenous variables (lagging headway of SUT and CT) have significant positive relationship with PC lagging headways [5], [12].

PC and SUT speeds have significant association with the SUT lagging headway. However, SUT lagging headway increases with an increase in the SUT speed, while SUT lagging headway decreases with an increase in the PC speed. This indicates that at higher speed SUT exercise caution and opt for defensive driving, thus keep longer distance from vehicle in front (leading vehicle), while an increase in PC speed actually makes the SUT comfortable thus resulting into reduced SUT headway. Both endogenous variables PC and CT lagging headways have significant positive relationship with PC lagging headways [5], [12].

SUT flow has significant positive correlation with CT lagging headway as adding more vehicles will reduce the maneuverability space thus resulting in decrease in average SUT lagging headway. Speed of the CT has significant correlation with the CT lagging headway suggesting that at higher speed CT vehicles keep more safety distance from leading vehicles. Both endogenous variables SUT and PC lagging headways have significant positive relationship with CT lagging headways [5], [12].

TABLE I
MODEL ESTIMATION RESULTS

Variable	Urban Freeway			Rural Freeway		
	Coefficient	t-stat	Mean	Coefficient	t-stat	Mean
ln(Average PC Lagging Headway) (ft.)						
Constant	3.259	20.231	-	3.354	0.154	
PC Flow (PC/15min)	-0.007	-9.464	218.646	-0.003	-5.694	85.265
SUT Flow (SUT/15 min)	-0.003	-4.319	13.067	0.002	2.357	35.904
Average PC Speed (mph)	0.017	14.877	61.240	0.015	6.938	68.435
Average SUT Speed (mph)	-0.002	-2.403	60.598	-	-	-
ln(Average SUT lagging headway (ft.))	0.142	6.748	5.650	0.073	1.961	5.944
ln(Average CT lagging headway (ft.))	0.956	3.386	5.819	0.18	2.157	6.068
Adjusted R^2		0.6543			0.7284	
Durbin-Watson		2.0647			1.7459	
ln(Average SUT Lagging Headway) (ft.)						
Constant	-1.696	-3.725		2.5411	2.503	
Average PC Speed (mph)	-0.015	-4.720	61.240	-	-	-
Average SUT Speed (mph)	0.009	4.434	60.598	0.012	2.957	67.238
ln(Average PC lagging headway (ft.))	0.733	7.750	5.341	0.459	2.230	5.694
ln(Average CT lagging headway (ft.))	0.644	10.340	5.819	-	-	-
Adjusted R^2		0.2605			0.2892	
Durbin-Watson		1.7968			1.9786	
ln(Average CT Lagging Headway) (ft.)						
Constant	2.254	8.056		3.645	8.399	
SUT Flow (SUT/15 min)	0.003	2.033	13.066	-	-	-
Average PC Speed (mph)	-	-	-	-0.009	-2.119	68.435
Average CT Speed (mph)	0.004	2.653	59.938	0.019	6.497	64.982
ln(Average PC lagging headway (ft.))	0.248	4.153	5.341	0.314	3.183	5.695
ln(Average SUT lagging headway(ft.))	0.352	10.465	5.650	-	-	-
Adjusted R^2		0.2435			0.6400	
Durbin-Watson		1.9911			2.1480	
Number of Observations		452			94	

The PC equation has best fit with an adjusted R^2 of 0.6543 while SUT and CT equations have a reasonable fit having an adjusted R^2 of 0.2605 and 0.2435 respectively. Mean Absolute Percent Error (MAPE) values were estimated to evaluate the predictive accuracy of the 3SLS models. MAPE value of 0.087, 0.210, and 0.046 was obtained for PC, SUT and CT.

B. Rural Freeway 3SLS Model

The sign of the variables PC flow indicates that, all else being equal, an increase in flow rate of PC decreases PC predicted lagging headway. The finding is intuitive; as addition of more PCs in traffic stream, will result in smaller headways. The sign of the variable CT flow indicates that, all else being equal, an increase in the flow rate of CT increases the predicted lagging headway of PCs. This might be because when more CTs are added into the traffic stream PCs exercise caution by keeping more safety distance from combination trucks. The average PC speed was found to be a significant variable that increases headway, which might be attributed to requirement of larger stopping distance at higher speeds. Both endogenous variables have a significant positive relationship that is intuitive as explained in previous model.

The speed of SUT has significant correlation with the SUT lagging headway. This reveals that at higher speed SUTs, exercise caution and opt for more spacing from vehicle in front. The average PC lagging headway is significantly correlated with SUT lagging headway. The finding is intuitive and consistent with past research [12].

The speed of PCs and CTs are significantly correlated with the CT lagging headway. However, a higher PC speed decreases the lagging headway of CT, while an increase in speed of CT increases the CT lagging headway. This might be attributed to the fact that fast moving CT opt for defensive driving and prefer more safety distance from vehicle in front (leading vehicle). In a stream with fast moving PC, CT feel comfortable and prefer lesser distance from vehicle in front. The endogenous variable (PC lagging headway) is similar to single-unit trucks. An increase in PC lagging headway is associated with an increase in CT lagging headway, which indicated that as PCs increase their headway CT also behave similarly. The PC and CT equations have good fit with an adjusted R^2 of 0.7284 and 0.6400 respectively. The SUT equations have a reasonable fit having an adjusted R^2 of 0.2892. MAPE value of 0.130, 0.402, and 0.13 were obtained for PC, SUT and CT equations (of 3SLS models). Overall the findings are consistent with [12].

From Table I it is clear that models are similar, however despite lower number of observation used for estimation of rural 3SLS models it has comparatively better fit. Also, signs of almost all the coefficients in both models are intuitive. The comparison of average lagging headways estimated using two different models for urban and rural freeways are provided in Table II. It can be observed that generally the predicted values

of lagging headways are reliable. The predicted values of headways differ from observed values ranging from 2.06% to 6.01% for urban freeways and 4.39% to 12.88% for rural freeways. For rural freeways both measured and predicted headways are larger compared to urban freeways. The ratio of SUT or CT lagging headway to that of PC lagging headway can be used to estimate PCE for each truck class. Table III presents PCE values for urban and rural freeways and their comparison with HCM values.

TABLE II
COMPARISON OF OBSERVED VS. PREDICTED HEADWAYS

Variable	Urban Interstate		Rural Interstate	
	Measured	Predicted (% Deviation from measured)	Measured	Predicted (% Deviation from measured)
Average Passenger Car Lagging Headway (ft.)	213.063	208.671 (-2.062%)	311.295	297.254 (4.51%)
Average Single Unit Truck Lagging Headway (ft.)	302.55	284.362 (-6.011%)	438.002	381.59 (12.88%)
Average Combination Truck Lagging Headway (ft.)	347.672	336.875 (-3.105%)	451.979	432.144 (4.39%)

TABLE III
COMPARISON OF PREDICTED PCE WITH HCM VALUES

Variable	Urban Interstate (% Deviation from HCM)	Rural Interstate (% Deviation from HCM)	HCM Methodology
SUT Passenger Car Equivalent	*1.35* (-9.58%)	*1.30* *(-13.33%)*	*1.5*
CT Passenger Car Equivalent	*1.60* (+9.35%)	*1.45* *(-3.33%)*	*1.5*

The SUT and CT, PCE values estimated using the 3-equation 3SLS model for urban interstates are: 1.35 and 1.60 respectively. For the rural interstate estimated SUT and CT, PCE values are: 1.30 and 1.45 respectively. Headway based PCE values estimated for urban and rural interstate are different from the single PCE value of 1.5 provided by the HCM. This difference can be more prominent at locations having higher traffic volumes and larger numbers of SUT or CT, as a greater disparity may exist between the LOS using estimated PCEs (developed using field traffic data) and the LOS estimated using HCM's single PCE value. The PCE values for SUT are both less than HCM values while PCE value for CT on urban freeways is greater than 1.5 and less than HCM values for rural freeways.

This disparity indicates that truck travel characteristics (average space consumed by trucks) differ for different traffic composition/ freeway type. The methodology used in present study can be used to estimate separate PCE values for different truck classes. The separation of the PCE values for truck classes can influence the LOS estimation. To illustrate the implications of the study results, a number of hypothetical scenarios were examined. Table IV presents three scenarios for an urban freeway. For all three scenarios, the percentage of SUTs is maintained constant at 5% while the percentage of CT is varied from 20% to 5%. The values of different traffic parameters used for comparison purposes are within the range of actual observed traffic.

TABLE IV
HYPOTHETICAL LOS COMPARISON: EFFECT OF VARYING PERCENTAGE OF CT

Variable	Scenario -1		Scenario -2		Scenario -3	
	Headway Approach	HCM	Headway Approach	HCM	Headway Approach	HCM
PC Flow (PC/hr)	713	713	1335	1335	585	585
ST Flow (SU/ hr)	48	48	79	79	33	33
CT Flow (CT/hr)	190	190	157	157	33	33
Percent PC	75%	75%	85%	85%	90%	90%
Percent ST	5%	5%	5%	5%	5%	5%
Percent CT	20%	20%	10%	10%	5%	5%
Average PC Speed (mph)	60	60	65	65	60	60
PCE (ST)	1.35	1.5	1.35	1.5	1.35	1.5
PCE (CT)	1.60	1.5	1.60	1.5	1.60	1.5
Vp (PC/hr)	1081	1069	1692	1688	681	683
Density	18.01	17.81	26.03	25.97	11.35	11.38
LOS	**C**	**B**	**D**	**C**	**B**	**B**
Remarks	Different		Different		Similar	

Scenario 1: (5% Single-unit and 20% Combination Trucks): Consider a traffic stream composed of 713 PCs, 48 SUTs and 190 CTs (Table IV). Using the PCE value of 1.6 for CT and 1.35 for SUT estimated using headway models, and following an otherwise standard HCM procedure for a flat freeway section, a LOS C is obtained. However, under same traffic characteristics but with a single PCE value of 1.5 for all trucks yields LOS B.

Scenario 2: (5% Single-unit and 10% Combination Trucks): Consider a traffic stream composed of 1335 PCs, 79 SUTs and 157 CTs (Table IV). Using separate PCE values of 1.6 for CT and 1.35 for SUT, for the same flat freeway section, a LOS D is obtained. However, the single PCE value of 1.5 yields LOS C.

Scenario 3: (5% Single-unit and Combination Trucks): Consider a traffic stream composed of 585 PCs, 33 SUTs and 33 CTs (Table IV). Using PCE values of 1.6 for CT and 1.35 for SUT, for the same freeway section a LOS B is obtained. The single PCE value of 1.5 also yields LOS B.

As the percentage of CTs increases, difference in traffic densities increases with different assignments of PCE values, resulting in differences in LOS. When the percentage of CTs in a traffic stream is small (5%), the gap between the resulting LOS values from the two methodologies decreases with converging results. A similar effect was observed for SUTs.

IV. Conclusions & Recommendations

Using lagging headways estimated from separate 3SLS models for rural and urban interstates PCE values were estimated and compared with single HCM value. Models were calibrated using field data (video recorded field traffic data) at three locations on three different rural interstates and four locations on a single urban freeway in Indiana. The study results revealed that reliable estimates of PCE values for different truck classes can be obtained using spatial lagging headways and estimated values of PCE for single-unit and combination trucks can be used for converting a mixed traffic stream to an equivalent passenger car stream.

The average observed lagging headways for passenger cars, single-unit trucks, and combination trucks across all study locations, both for rural and urban interstate, differed only marginally from predicted headways. The single-unit and combination truck PCE values estimated using the 3-equation 3SLS model for urban interstates are: 1.35 and 1.60 respectively. For rural interstates the corresponding PCE values are: 1.30 and 1.45 respectively. Depending upon traffic composition, the separate PCE values for combination trucks and single unit trucks, may lead to different LOS indices compared to single HCM PCE value of 1.5 for all truck types. Separation of PCE values by truck type is supported when a traffic stream has high percentage of trucks of either or both types. The use of separate PCE values by truck types may result in a different characterization of LOS, thus having significant impact on roadway design or operational studies. In addition, the proposed model allows for the prediction of site-specific PCE values. Highway agencies can use the adopted methodology for estimation of site specific PCE values for multiple truck classes.

References

[1] Highway Research Board "Highway Capacity Manual: Practical Applications for Research, Department of Traffic and Operations, Committee on Highway Capacity, United States Government Printing Office, Washington, DC., 1950.

[2] Highway Research Board, "Special Report 87, Highway Capacity Manual", National Research Council, Department of Traffic and Operations, Committee on Highway Capacity, Washington, D.C., 1965.

[3] E. Linzer, R. Roess, and W. McShane, "Effect of Trucks, Buses, and Recreational Vehicles on Freeway Capacity and Service Volume" Transportation Research Record No. 699, National Research Council, Washington, DC., pp. 17-24, 1979.

[4] Transportation Research Board "Highway Capacity Manual 2000". TRB, National Research Council, Washington, DC. 2000.

[5] A. Ahmed, M. Volovski, D. VanBoxel, S. Labi, and K. C. Sinha, "Truck Travel Characteristics as an Indicator of System Condition and Performance", Final Report, Purdue University, West Lafayette, Indiana, USA, 2011.

[6] A. Werner, J. and Morrall "Passenger Car Equivalencies of Trucks, Buses, and Recreational Vehicles for Two-Lane Rural Highways" Transportation Research Record No. 615. National Research Council, Washington, D. C., pp. 10-17, 1976.

[7] E. Seguin, K. Crowley, and W. Zweig. "Passenger Car Equivalents on Urban Freeways." Report DTFH61-80-C-00106. State College, PA: Institute for Research, 1982.

[8] W. D. Cunagin, and C. J. Messer, "Passenger Car Equivalents for Rural Highways" Transportation Research Record No., 905, pp. 61–68, 1983.

[9] L. Elefteriadou, D. Torbic, and N. Webster, "Development of Passenger Car Equivalents for Freeways, Two-Lane Highways, and Arterials" Transportation Research Record No. 1572(1), pp. 51–58, 1997.

[10] D. V. Van Boxel, K. C. Sinha, M. B. Darcy and F. L. Mannering "An Exploratory Study of Vehicle Class Headway Ratios as Passenger Car Equivalence Values Using Three Stage Least Squares Estimation", in Proc. 89thAnnual Meeting of Transportation Research Board, Washington, D.C., 2009.

[11] S. Washington, M. Karlaftis, and F. Mannering. "Statistical and Econometric Methods for Transportation Data Analysis". CRC Press, 2000.

[12] A. Ahmed, D. VanBoxel, M. Volovski, P. Ch. Anastasopoulos, S. Labi, and and K. C. Sinha. "Using Lagging Headways to Estimate Passenger Car Equivalents on Basic Freeway Sections" Journal of Transportation of the Institute of Transportation Engineers vol. 2 (1), Oct. 2011, pp. 1-17.

Dr. Anwaar Ahmed is an associate professor of Civil Engineering at National University of Sciences and Technology, Islamabad, Pakistan. He received his MSCE in Transportation and Infrastructure Systems Engineering and PhD from Purdue University in 2009and 2012 respectively. His research interests are infrastructure systems management and traffic safety. He is a member of the American Society of Civil Engineers (ASCE) and a Fellow of International Road Federation (IRF).

Dr. Muhammad Bilal Khurshid is an associate professor of Civil Engineering at National University of Sciences and Technology, Islamabad, Pakistan. He received his PhD Civil Engineering from Purdue University in 2010. His research interests are highway asset management, statistical and econometric modeling and transportation system evaluation.

Dr. Samuel Labi is an associate professor at Purdue University, carries out teaching and research in the impact evaluation of transportation systems and highway infrastructure management systems. He is a member of ITE, the American Society of Civil Engineers (ASCE), and the American Association for the Advancement of Sciences (AAAS). He is a co-author of Transportation Decision-Making: Principles of Project Evaluation and Programming.