■ 論 文 ■

Development of BPR Functions with Truck Traffic Impacts for Network Assignment

노선배정시 트럭 교통량을 고려한 BPR 함수 개발

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요 약

도로교통량의 상당부분을 차지하는 트럭교통(truck traffic)은 교통혼잡, 주차, 교통안전 문제의 큰 요인이 되고 있다. 그러나 그 동안 교통수요예측 및 교통계획에서 트럭교통은 사람교통(passenger trip)에 비해 상대적으로 그 중요성이 간과되어 왔다. 트럭교통의 정확한 모형화가 선행되지 않으면 각종 교통수요예측 및 교통정책의 신뢰성은 낮아질 것이다. 본 연구의 목적은 교통수요예측 과정에서 트럭교통을 교통망(network)에 배정하는 기법을 개선하는 데 있다. 이를 위해 본 연구에서는 노선배정(network assignment)의 핵심적인 요소인 기존의 BPR(Bureau of Public Road) 함수에 트럭 교통량 변수를 포함하여, 수정된 새로운 BPR 함수를 개발하였다. 본 연구에서 제시된 방법은 교통수요예측시 트럭 교통량을 고려하여 보다 현실적이고 신뢰성 있는 도로교통수요 예측치를 담보할 수 있을 것으로 기대된다.

I. Introduction

Truck traffic accounts for a substantial fraction of the traffic stream in many regions and is often the source of localized traffic congestion and potential parking and safety problems. Ignoring truck traffic in transportation demand forecasting makes it impossible to plan for network improvements and causes inaccuracies in passenger transportation forecasting and planning. Modeling air quality and designing transportation projects to improve air quality requires effective treatment of trucks in travel demand forecasting.

Truck trips tend to be ignored or treated superficially in regional transportation planning models. This reduces the effectiveness and accuracy of travel demand forecasting and may result in misguided transportation policy and project decisions. Various approaches have been developed for incorporating truck trips in regional forecasting efforts. In the Seventies, there were a number of models constructed that loosely followed the four-step model paradigm to some degree or another. However, some researchers established that there were important differences in truck traffic determinants that should be taken into account in modeling.

One of the important differences is the fact that truck trips in urban areas are chained together in tours comprised of multiple delivery, pickup, and mixed pickup and delivery trips. The degree of trip chaining is so high compared to that encountered in urban passenger travel that it warrants special consideration in modeling. Second major difference was that trucks differ greatly in size and trip operating characteristics. In contrast to cars whose size differences are relatively unimportant for travel forecasting, the composition of truck traffic is of interest. A third difference is that the number of trucks and the number of truck trips vary considerably by location and by industry. Trucking and warehousing activities, not surprisingly, have the highest rates of truck trip generation.

It is commonsensical that the number of truck trips in a region is related to the number of trucks in a region, but bizarrely, most modeling efforts ignore this relationship. Moreover, none of the important differences noted above are appropriately reflected in recent work on freight models. Virtually most planning organizations need to address truck traffic in their modeling process; however, very few have done so. Moreover, where trucks are included they are usually treated like car traffic leading to problematic results. The need for appropriate methodologies for urban truck demand forecasting is nearly universal.

The purpose of this paper is to develop a truck trip assignment methodology for use in the urban travel demand forecasting process. The methodology should be capable of reasonably reflecting the volumes of trucks on major travel routes from available vehicle classification counts and produce reasonable and believable forecasts of truck volumes for the future. The CORSIM simulation results were used to develop the speed-flow relationships with the impact of truck traffic. The speed-flow relationships were developed for freeways and different categories of urban arterials. The simulated speed was first plotted against the simulated volume for a given truck percentage. General observations were made in regards to the underlying relationships among the relevant variables. Detailed statistical analyses were then performed to determine the best-of-fit functional forms and their associated coefficients. This paper presents in detail the general observations, proposed functional forms, and resulting properties of the speed-flow functions for each of the roadway categories.

II. Modeling Issues for Truck Traffic Assignment

In developing a new truck trip assignment methodology, the following issues need to be considered and addressed:

Route Choice Flexibility: In the past, it has been generally assumed that trucks have little flexibility in route choice. As a result, the typical procedure has been to execute a single "all-or-nothing pre-assignment" for trucks at the beginning of the traffic assignment process. The truck trip routes are then set after this first iteration. This means that trucks will not be able to respond to building congestion as auto trips are assigned to the network by seeking alternate, less congested routes in later iterations. We should consider whether this is still a valid assumption, or do trucks have more flexibility in route choice today? If there is greater flexibility in route choice, the model should determine the most appropriate method of reflecting this in the assignment process.

As part of this, it should be considered how truck route choices are affected by congestion. If there is flexibility in route choice, we should consider whether simultaneous assignment with autos (even on a limited basis) is the best method for dealing with this or whether there are alternate methods that better reflect truck behavior. If there is still limited flexibility in route choice, then we should consider whether the initial all-or-nothing assignment should be based on some pre-constrained travel times and speeds (rather than free flow speed), or if there are better alternative methods available for reflecting the response to congestion.

Impacts of Stops and Delays: The interviews with both trucking company officials and truck drivers revealed that one of the most important considerations for truck route choices is continuity of flow and avoidance of stops and delays. While this is true for all trucks, it is especially true for heavy trucks. This helps explain why trucks typically choose freeways over surface streets, even in relatively congested conditions. Conversely it explains why trucks tend to avoid streets with frequent traffic signals, at-grade rail crossings and other stops unless they have a specific destination along that route. It may also explain why trucks tend to avoid toll facilities with frequent stops at toll plaza, even when the facility appears to offer a substantial time savings.

Impacts on Available Capacity: A single truck will absorb much more of the available capacity on a roadway than an auto. In part this is simply because trucks are bigger - they physically take up more space. In addition, most drivers will maintain a greater spacing between their vehicle and a truck than they would with another auto. This is particularly true on higher speed roadways where drivers may have greater safety concerns about driving too close behind trucks.

In order to properly account for the absorption of available capacity, it may be necessary to convert trucks to auto equivalencies after the truck assignment. Alternative methods need to be considered for reflecting the impact of trucks on the absorption of available capacity, if other methods are available which may be easier to incorporate and provide more accurate or realistic results. In developing a new methodology, we should consider whether truck/auto equivalencies are the same on all facility types - that is, would trucks have a higher equivalency (command and use more space) or higher speed facilities such as freeways than on slower speed arterials and/or collectors? Also, we should consider whether separate auto equivalencies should be used for heavy and light trucks, and, if so, whether this would require separate pre-assignments for light and heavy trucks.

Impacts on Congested Speeds: A given volume of trucks on a roadway will offer result in a much greater deterioration of congested speeds than a similar volume of autos. This is because it generally takes a truck much longer to accelerate and decelerate than an auto. As a result, truck volume may have a significant impact on congested speeds of facilities with frequent interruptions of traffic flow, such as close signal spacing or high densities of driveways. Conversely, the impact of trucks on congested speeds may be almost imperceptible on freeways and other uninterrupted flow facilities.

We should consider whether this is a significant issue for the accuracy of model results. That is, does the failure to account for the impact of trucks on congested speeds have a significant impact on the accuracy of route choice and assignment volumes, reported speeds and other model results, particularly on major truck routes? If so, we should determine the most effective and efficient method for improving the model to account for this impact. One possible method is through the use of Truck/Auto equivalencies in calculating congested speeds. That is, the pre-assigned truck volumes would be converted to a volume of autos, which would have the same impact on congested speeds. This auto equivalency would then be added to the assigned auto volumes in each iteration of trip assignment before calculating the new congested speeds.

Ⅲ. Speed-Flow Functions with Truck Impacts for Freeways

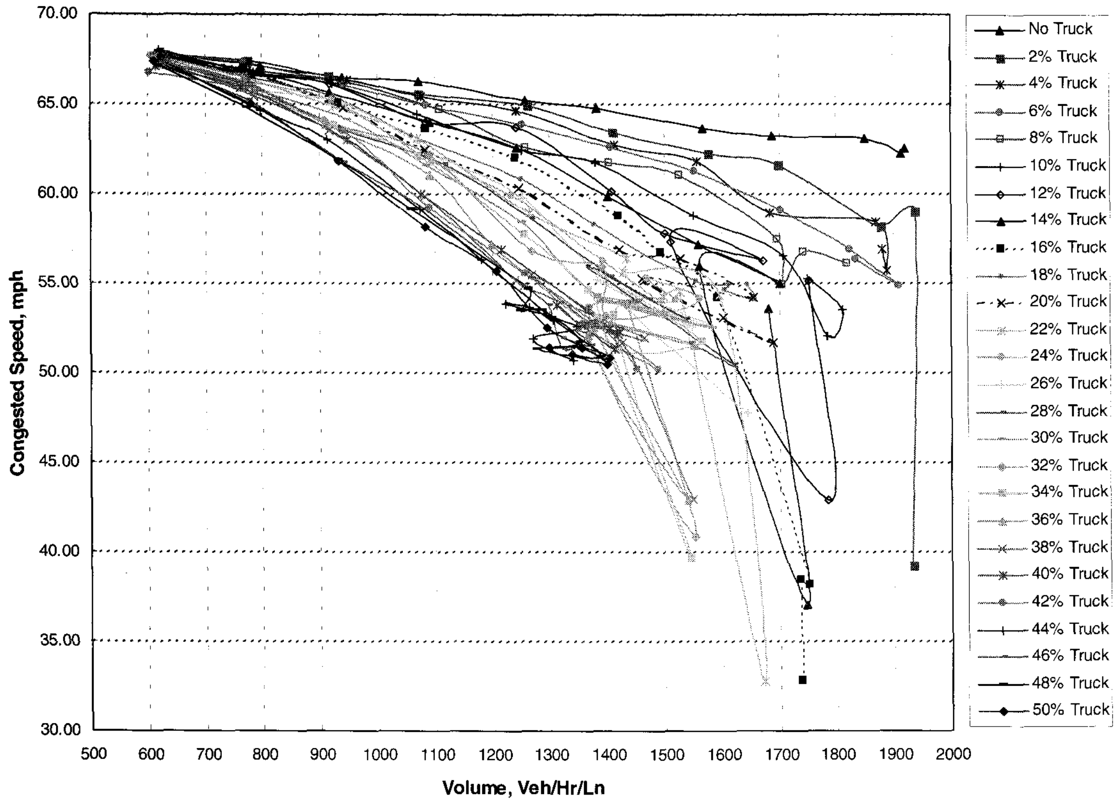
Freeways are multilane, divided highways having at least two (2) lanes for exclusive use of traffic in each direction and full control of access and egress. They can be located in rural areas, at or near urban fringes, in urbanized areas, or near downtown areas. The posted speeds for freeways normally range from 55 mph to 70 mph. The freeway is the only highway facility that provides completely "uninterrupted" flow. The traffic is not interrupted by at-grade intersections, signals or other fixed causes of periodic delay.

For the purpose of this study, the hypothetical freeway segment for the CORSIM simulation has three (3) lanes in each direction. The free flow speed is assumed to be 70 mph. A total of 26 simulation runs was performed for the freeway segment with each run representing a different truck percentage. The truck percentages range from 0% to 50% with a 2% increment.

General Observation of CORSIM Simulation Results for Freeways

Figure 1 illustrates the CORSIM simulation results for the freeway segment. The *x*-axis represents the simulated volumes in terms of vehicles per hour per lane (vphpl); the *y*-axis represents the resulting congested speeds in unit of miles per hour (mph). A number of general observations can be made of the charted CORSIM simulation results. First of all, the travel speed decreases as the total volume of the freeway increases. For instance, Figure 1 shows a general downward turn from over 65 mph to below 55 mph as the volume increases. Secondly, the driving speed decreases as the percentage of trucks increases.

As shown in Figure 1, at a volume of 1,400 vphpl, when there are no trucks on the road the speed is approximately 64 mph, however when the total traffic includes 50 percent trucks, the speed is approximately 51 mph. Finally, and perhaps more importantly, the truck impact to the travel speed tends to be much greater when the traffic volume is higher. For example, at a volume of approximately 600 vphpl, the travel speed for a traffic stream having no trucks is approximately 68 mph; the travel speed for a traffic stream consisting of 50 percent of trucks is slightly over 67 mph. The difference in speed between the two traffic streams is less than one (1) mph. However, when the traffic volume increases to 1,200 vphpl, the travel speeds of the two traffic streams decrease to 65 mph and 56 mph,



〈Figure 1〉 Simulated Speeds vs. Volumes with Different Truck Percentages for Freeways

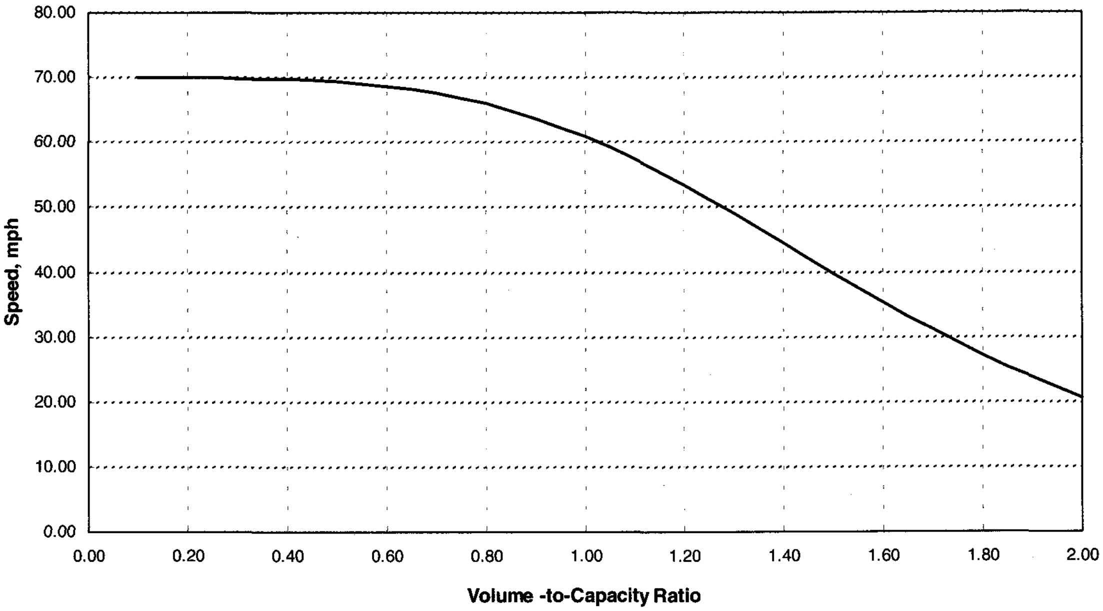
respectively. The difference in speed increases to 9 mph.

It may be worth noting that the simulated congested speed shows a somewhat erratic pattern when traffic volume is high. There are cases where the congested speed is significantly lower than what the trend would otherwise indicate. There are other cases where slower speed is observed where traffic volume is low. This is because the CORSIM simulation attempts to replicate the real-world traffic operating conditions. In reality, when traffic volume approaches to capacity, there is a sudden drop in operating speed. The traffic flow becomes very unstable under these circumstances. Under over-saturated conditions, only a small number of vehicles can pass a certain point or road segment at a very low speed during certain period of time, resulting low traffic volume at low speed.

The unstable pattern shown in Figure 1 when volumes approach to capacity makes perfect sense from traffic engineering point of view. However, the volumes observed under these conditions do not represent the true demand for the roadway facility. The simulated speeds and volumes for these cases will be excluded from the analysis.

Proposed Functional Form for Freeways

The speed-flow relationship has been traditionally represented by the BPR (Bureau of Public Road) function in transportation planning models. This curve was developed based on the 1965 Highway Capacity Manual (HCM). The BPR curve is graphically illustrated in 〈Figure 2〉, and its functional form is described as follows:



〈Figure 2〉 Standard BPR Curve for Freeways

$$S=\frac{S_0}{1+\alpha(V/C)^{\gamma}} \quad (1)$$

Where

S : Congested Speed in miles per hour,
S_0 : Free Flow Speed in miles per hour,
V : Volume in vehicles per hour,
C : Capacity in vehicles per hour, and
α, γ : Coefficients. For freeways, α = 0.15, γ = 4.00.

As shown in 〈Figure 2〉, the BPR curve is parabolic in shape, and speed is fairly sensitive to increasing flows. The simulated curves shown in Figure 1 bare much resemblance with the standard BPR curve. In other words, for a given truck percentage, the relationship between congested speed and volume should be similar to the BPR function. To reflect the impact of truck traffic on the speed-flow relationship, a second term related to the truck percentage needs to be introduced into the equation. If this term is denoted by $f(T)$, meaning a function of truck percentage (T), then the speed-flow relationship with truck impact will have the following functional form:

$$S=\frac{S_0}{1+\alpha f(T)(V/C)^{\gamma}} \quad (2)$$

Where

S : Congested Speed in miles per hour,
S_0 : Free Flow Speed in miles per hour,
V : Volume in vehicles per hour,
C : Capacity in vehicles per hour,
α, γ : Coefficients to be determined,
T : Proportion of trucks in the traffic mix in decimal point, and
$f(T)$: Function of T to be specified.

Function $f(T)$ should possess the following two properties:

1) $f(T)$ = 1 when T = 0.

This ensures that when there are no trucks in the vehicle mix, i.e., when T = 0, the proposed functional form remains consistent with the standard BPR functional form.

2) $f(T)$ increases when T increases.

This ensures that the proposed functional form reflects the CORSIM simulation results shown in Figure 1. As discussed earlier, travel speed decreases as truck percentage increases at a given volume. Since $f(T)$ is inversely related to the congested speed S in the proposed function, an increase in $f(T)$ will cause a decrease in speed.

A number of different functional forms for $f(T)$ were tested and a "Curve Estimation" analysis was performed using the SPSS software package. It was determined from the analysis that a power function in the form of $(1+T)^{\beta}$ satisfies both conditions mentioned above. In addition, the simple functional form allows for easy calibration and easy modification of the standard BPR function if it is implemented in the traditional travel demand estimation models. To summarize, the proposed functional form to represent the speed-flow relationship for freeways is as follows:

$$S = \frac{S_0}{1+\alpha(1+T)^{\beta}(V/C)^{\gamma}} \tag{3}$$

Where

S : Congested Speed in miles per hour,

S_0 : Free Flow Speed in miles per hour,

V : Volume in vehicles per hour,

C : Capacity in vehicles per hour,

T : Proportion of trucks in the traffic mix in decimal point, and

α, β, γ : Coefficients to be determined.

Determination of Coefficients

To determine the coefficients α, β, and γ, the proposed functional form was first transformed as following:

$$\log_{10}\left(\frac{S_0}{S}-1\right) = \log_{10}\alpha + \beta\log_{10}(1+T) + \gamma\log_{10}(V/C) \tag{4}$$

If we let

Y : $\log_{10}\left(\frac{S_0}{S}-1\right)$,

A : $\log_{10}\alpha$,

X_1 : $\log_{10}(1+T)$, and

X_2 : $\log_{10}(V/C)$

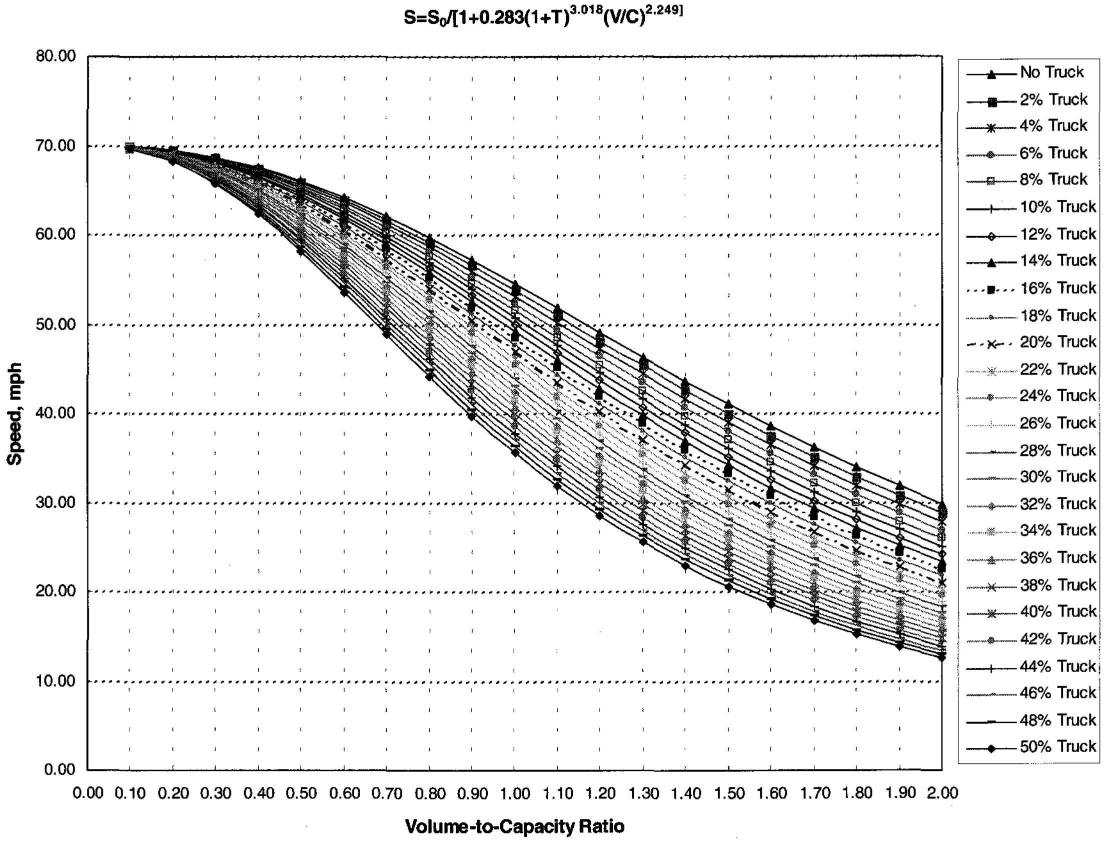
Then equation (4) becomes the standard two-dimensional linear equation shown as follows:

$$Y = A + \beta\ X_1 + \gamma\ X_2 \tag{5}$$

A multiple linear regression analysis was performed, with $\log_{10}\left(\frac{S_0}{S}-1\right)$ being the dependent variable, $\log_{10}(1+T)$ and $\log_{10}(V/C)$ being the independent variables. The freeway lane capacity C used in the analysis was determined from the *1998 Level of Service Handbook* published by the Florida Department of Transportation. According to the Handbook, the generalized peak hour directional volume for a 6-lane Group 1 (within urbanized area over 500,000 and leading to or passing within 5 miles of city central business district) freeway is 6,270 vehicles per hour when the Level of Service is E. Therefore, the capacity for each lane for a 3-lane freeway segment is one third of the directional hour volume, or 2,090 vphpl. The three coefficients determined from the regression analysis are -0.548 for constant, 3.018 for β and 2.249 for γ, respectively. Since the value -0.548 is the logarithm of α, α can be calculated as follows:

$$\alpha = 10^{-0.548} = 0.283 \tag{6}$$

With the coefficients determined, the speed-flow



〈Figure 3〉 Freeway Speed-Flow Relationships with Different Truck Percentages

relationships with tuck traffic for freeways can be represented by the following equation:

$$S = \frac{S_0}{1+0.283(1+T)^{3.018}(V/C)^{2.249}} \tag{7}$$

Properties of Freeway Speed-Flow Curves

Even with the new term T (proportion of trucks in the traffic mix) introduced, the newly developed speed-flow equation is still considered a variation of the standard BPR function. The most appealing feature of this type of equations is its simplicity. Traffic forecasting models must be able to analyze thousands of links in each model run. Using a simple equation rather than a complex procedure to estimate link speed can reduce processing time. Also, the simple data requirements of the speed-flow curve will facilitate the data entry for modelers and planners.

The traffic forecasting models generally require that travel time be a monotonically increasing function of volume to ensure that a single user equilibrium solution can be found for the traffic assignment problem. Given that travel speed is the inverse of travel time, this means that the travel speed needs to be a monotonically decreasing function of volume. As discussed earlier, the functional form of the freeway speed-flow curve satisfies this condition. This is even more evident when the congested speed is plotted against flow as shown in 〈Figure 3〉.

Some interesting properties of the speed-flow curves may be explored by looking at some special values of truck percentage (T) and volume-to-capacity ratio (V/C). Firstly, the functional form performs reasonably under certain extreme conditions. For example, when V is close to zero (0), or $V \rightarrow 0$, indicating a near free flow condition, the "congested" speed estimated from the equation is close to the free-flow speed, or $S \rightarrow S_0$. Also, when $T = 0.00$, meaning there are no trucks in traffic mix, the functional forms becomes the standard BPR function, even though the values of coefficients are different.

Secondly, as compared with the standard BPR function, the congested speed estimated from the freeway speed-flow curve is much lower when volume is at capacity, i.e., $V/C \rightarrow 1$, and the difference increases as the truck percentage increases. This is because the multiplier of the term $(V/C)^{\gamma}$ in Equations (1) and (7) actually represents the percent drop in speed from the free-flow speed. For the standard BPR function represented by Equation (1), the multiplier is 0.15, indicating there is a 15% drop in speed when the volume approaches to capacity. For the newly developed speed-flow curve represented by Equation (7), this multiplier is $0.283(1+T)^{3.018}$, a monotonically increasing function of T, which means the estimated speed will drop at least 28.3% when the volume-to-capacity ratio is close to one (1).

Finally, a smaller value of exponent of (V/C) ($\gamma = 2.249$) in the speed-flow equation indicates that the speed is sensitive to changes in traffic flow. However, the speed drop when V/C gets close to 1.0 is not as abrupt as the standard BPR function, where the exponent of (V/C) is 4.0.

Ⅳ. Speed-Flow Functions with Truck Impacts for Urban Arterials

Urban arterials are signalized roadways that serve primarily through traffic and provide access to abutting properties as a secondary function. The spacing between the signalized intersections normally does not exceed 2 miles, and turning movements at intersections are usually less than 20 percent of total traffic. Based on signal density, urban arterials can be divided into following four classes:

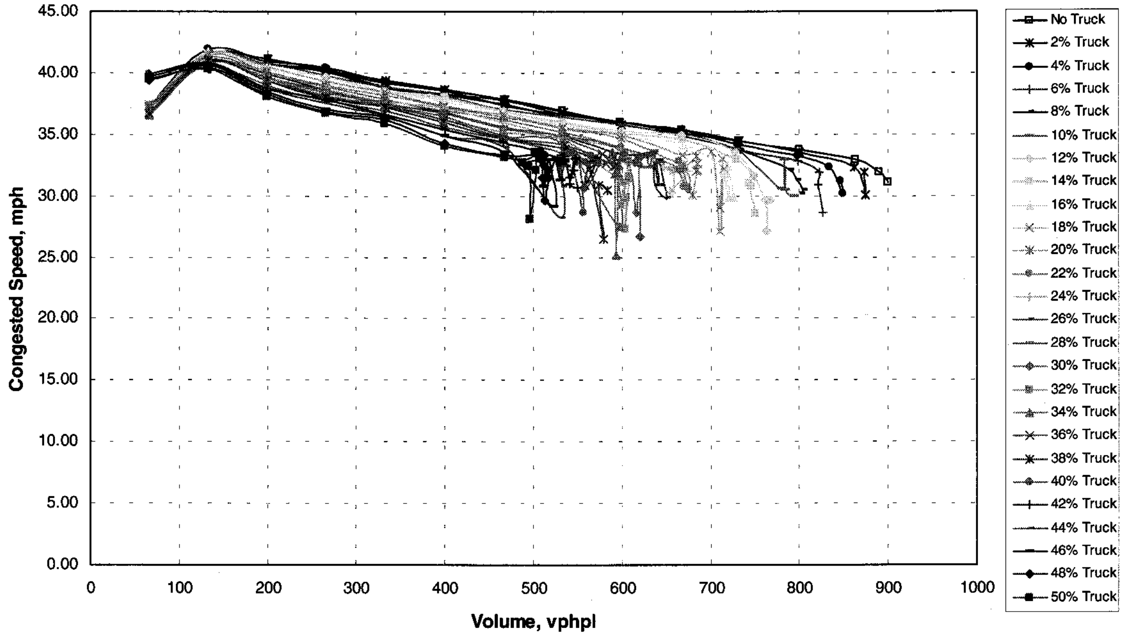
- Class Ⅰ - Arterials in non-rural areas with speed limits of at least 45 mph and a signal density of less than 2 signals per mile.
- Class Ⅱ - Arterials with speed limits of 35 to 45 mph and a signal density from 2 to 4.5 signals per mile.
- Class Ⅲ - Arterials with speed limits of 30 to 40 mph and a signal density of at least 4.5 signals per mile.
- Class Ⅳ - Arterials in the downtown core of cities in urbanized areas of population over 750,000 with speed limits from 25 to 30 mph and a signal density of more than 6 signals per mile.

The development of speed-flow relationships for urban arterials follows the same procedure as freeways. A hypothetical roadway segment is set up for each of the four classes of arterials. Each roadway segment has three (3) lanes in each direction. All of the intersections are assumed to be controlled by pre-timed signals. The signal cycle length, phasing and splits are fixed in all cases. Similar to freeways, CORSIM simulation runs were performed for different truck percentages ranging from zero (0) percent to 50 percent with a 2 percent increment.

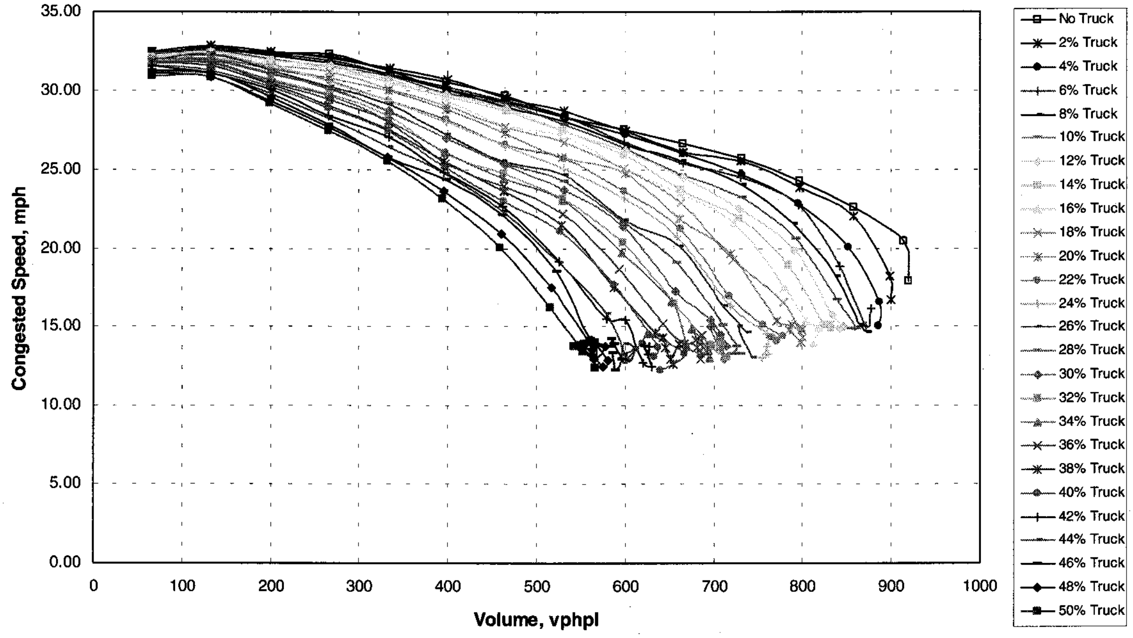
This section presents the development of speed-flow relationships with truck traffic impacts for urban arterials based on the CORSIM simulation results. It will focus on areas where travel characteristics differ from those of freeways.

CORSIM Simulation Results for Urban Arterials

The CORSIM simulation results for Class Ⅰ,

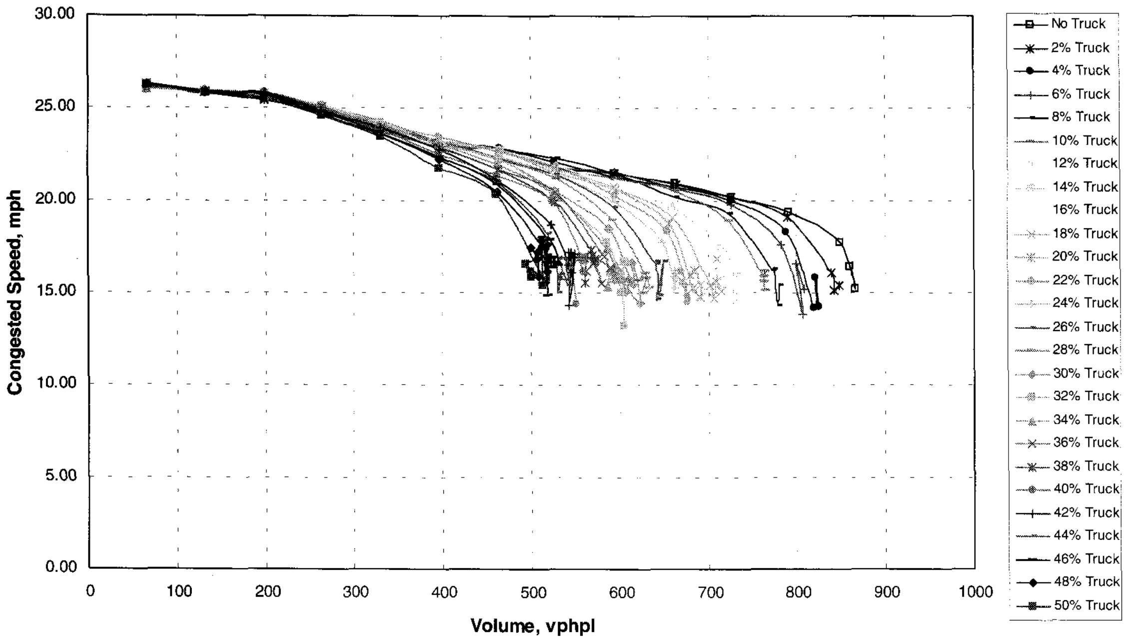


〈Figure 4〉. Simulated Speeds vs. Volumes with Different Truck Percentages for Class I Urban Arterial
Free Flow Speed = 50 mph, Signal Density = 1 signal/mi

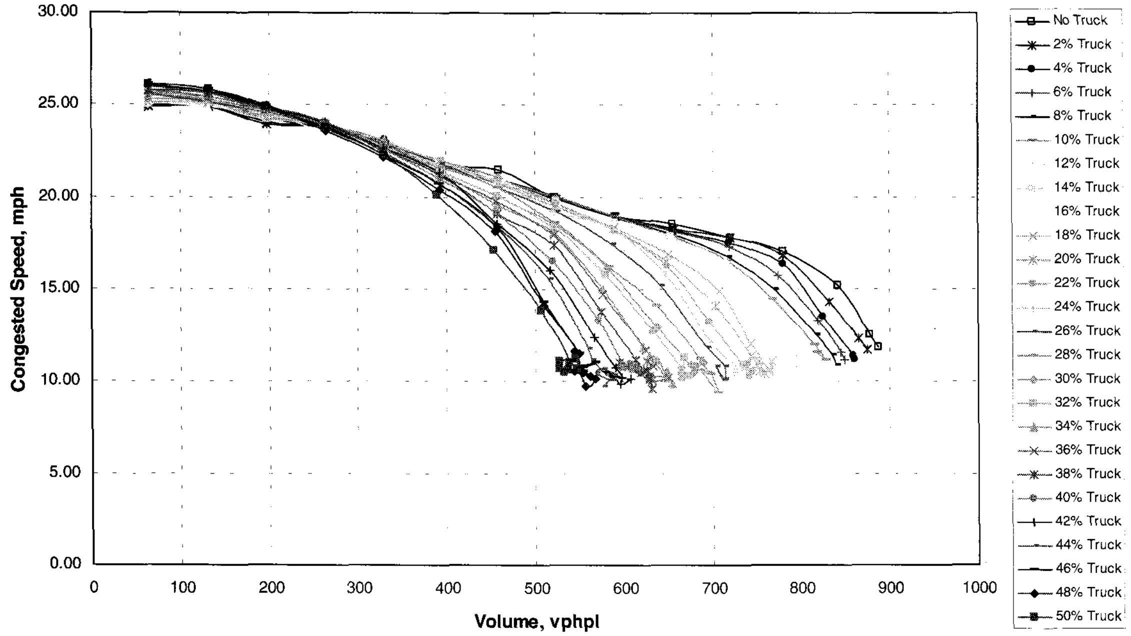


〈Figure 5〉. Simulated Speeds vs. Volumes with Different Truck Percentages for Class II Urban Arterial
Free Flow Speed =40 mph, Signal Density = 3 signals/mi

Class II, Class III, and Class IV urban arterials are illustrated in 〈Figure 4〉, 〈Figure 5〉, 〈Figure 6〉, and 〈Figure 7〉, respectively. In general, the speed changes for urban arterials with respect to changes in traffic volume and truck percentage show a similar pattern to freeways. Like the



〈Figure 6〉 Simulated Speeds vs. Volumes with Different Truck Percentages for Class III Urban Arterial Free Flow Speed =35 mph, Signal Density = 4 signals/mi



〈Figure 7〉 Simulated Speeds vs. Volumes with Different Truck Percentages for Class IV Urban Arterial Free Flow Speed =30 mph, Signal Density = 5 signals/mi

freeway CORSIM simulation results, an increase in traffic volume or truck percentage will cause the travel speed to decrease. However, the impact of trucks on travel speed for arterials is not as significant as that for freeways. This is particularly true for Class III and IV urban arterials as demonstrated in ⟨Figure 6⟩ and ⟨Figure 7⟩. The overlapping curves for different truck percentage at low volumes as shown in these figures suggest that the truck impact on travel speed tend to be minimal.

When developing speed-flow curves for urban arterials, it is important to note that unlike freeways, traffic flows on urban arterials are "interrupted" flows caused by traffic signals and other traffic control devices. Among many other factors, traffic signal phasing and timing have as much impact, if not more, on the average speed of the traffic flow, as does the traffic volume or the percentage of trucks in the traffic mix.

Proposed Functional Form for Urban Arterials

A number of possible functional forms to represent the speed-flow relationships for arterials were explored. The same functional form for freeways based on the original BPR function seemed appealing at first. However, a closer examination of the properties of the equation revealed a potential flaw of the functional form. In particular, when traffic volume is close to "free" flow conditions, or $V/C = 0$, the estimated speed from the equation is equal to free flow speed, or $S = S_0$. This is true for freeways, but may not be the case for arterials simply because of the delays caused by traffic signals.

In order to remedy the problem, it is necessary to introduce a different term with respect to V/C into the equation. The "best" possible relationship between the speed and the V/C ratio is determined by a "Curve Estimation" analysis using the SPSS software package. Figure 8 includes the analysis results for urban arterials. The average travel speed (S) is first transformed to (S_0/S-1), denoted by SSMINUS1. The Curve Estimation analysis is then performed using SSMINUS1 as dependent variable and V/C (denoted by VC) as independent variable. Four possible functional forms including linear, logarithm, inverse and exponential functions are tested, and the final results show that the exponential function provides the "best" fit of the observed data as indicated by the highest R-square value of 0.744.

Based on the curve estimation analysis results, the functional form representing the speed-flow relationships for urban arterials are proposed as follows:

$$S = \frac{S_0}{1+\alpha(1+T)^{\beta}\gamma^{(V/C)}} \tag{8}$$

Where

S : Congested Speed in miles per hour,
S_0 : Free Flow Speed in miles per hour,
V : Volume in vehicles per hour,
C : Capacity in vehicles per hour,
T : Proportion of trucks in the traffic mix in decimal point, and
α, β, γ : Coefficients to be determined.

Determination of Coefficients

In order to determine the coefficients in Equation (8), the functional form needs to be first transformed as following:

$$\log_{10}\left(\frac{S_0}{S}-1\right) = \log_{10}\alpha + \beta\log_{10}(1+T) + (V/C)\log_{10}\gamma \tag{9}$$

Let Y : $\log_{10}\left(\frac{S_0}{S}-1\right)$,
A : $\log_{10}\alpha$,
X_1 : $\log_{10}(1+T)$,
B : $\log_{10}\gamma$, and
X_2 : V/C

Then Equation (9) becomes the standard two-dimensional linear equation shown as follows:

$$Y = A + \beta\, X_1 + B\, X_2 \tag{10}$$

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Curve Fit

MODEL:  MOD_4.

Independent:  VC

 Dependent Mth   Rsq  d.f.      F  Sigf      b0      b1

  SSMINUS1 LIN  .654   362  682.80  .000   .1386   .5813
  SSMINUS1 LOG  .644   362  653.78  .000   .6246   .2407
  SSMINUS1 INV  .544   362  431.17  .000   .6191  -.0713
  SSMINUS1 EXP  .744   362 1052.50  .000   .1934  1.4652
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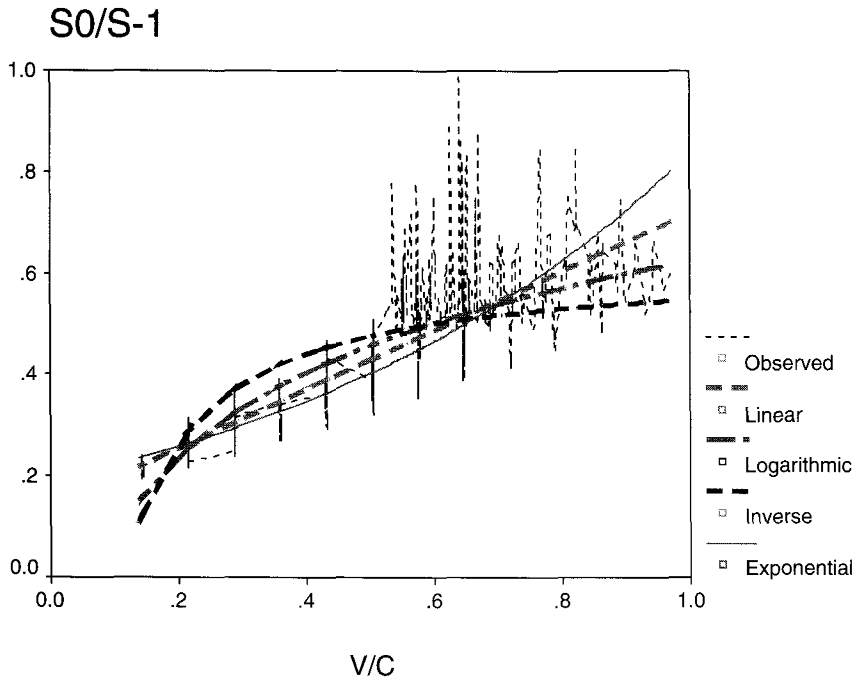


⟨Figure 8⟩ Curve Estimation Analysis Results for Urban Arterials

The value of A, β, and B are determined by performing multiple linear regression analysis using $\log_{10}\left(\frac{S_0}{S}-1\right)$ (or Y) as dependent variable, and $\log_{10}(1+T)$ (or X_1) and V/C (or X_2) as dependent variables. Similar to freeways, the lane capacities for different classes of arterials are determined from the 1998 *Level of Service Handbook*. These values, together with the coefficients determined from regression analyses, are provided in ⟨Table 1⟩.

⟨Table 1⟩ Coefficients Determined from Regression Analyses

Arterial	Capacity, vphpl	A	β	B	$\alpha=10^A$	$\gamma=10^B$
Class Ⅰ	930	-0.865	1.234	0.704	0.136	5.058
Class Ⅱ	910	-1.139	3.140	1.231	0.073	17.022
Class Ⅲ	880	-0.711	1.105	0.845	0.195	6.998
Class Ⅳ	850	-1.132	1.989	1.328	0.074	21.281

Based on 〈Table 1〉, the speed-flow curves for urban arterials can be summarized as follows:

Class Ⅰ: $$S=\frac{S_0}{1+0.136(1+T)^{1.234}5.058^{(V/C)}} \quad (11)$$

Class Ⅱ: $$S=\frac{S_0}{1+0.073(1+T)^{3.140}17.022^{(V/C)}} \quad (12)$$

Class Ⅲ: $$S=\frac{S_0}{1+0.195(1+T)^{1.105}6.998^{(V/C)}} \quad (13)$$

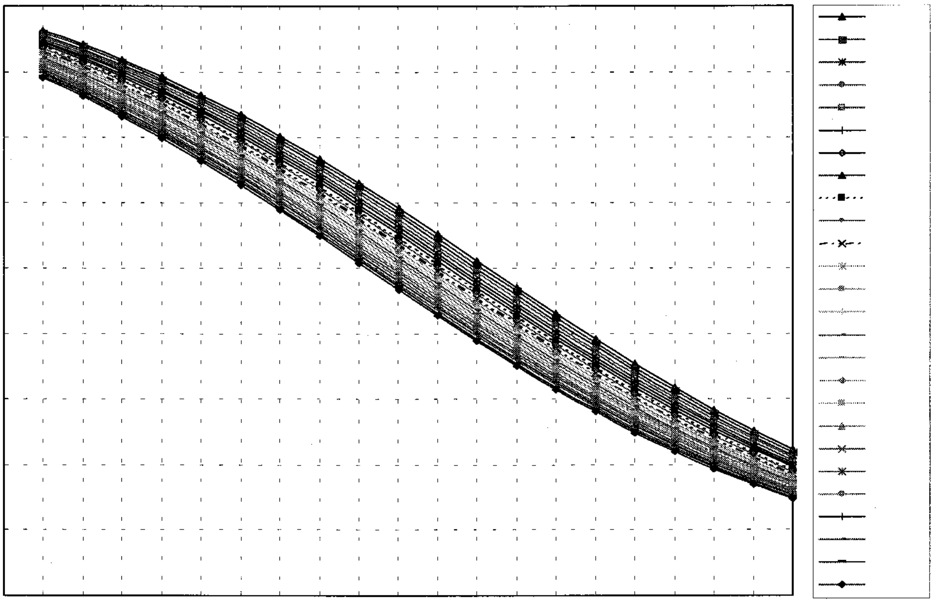
Class Ⅳ: $$S=\frac{S_0}{1+0.074(1+T)^{1.989}21.281^{(V/C)}} \quad (14)$$

Properties of the Urban Arterial Speed-Flow Curves

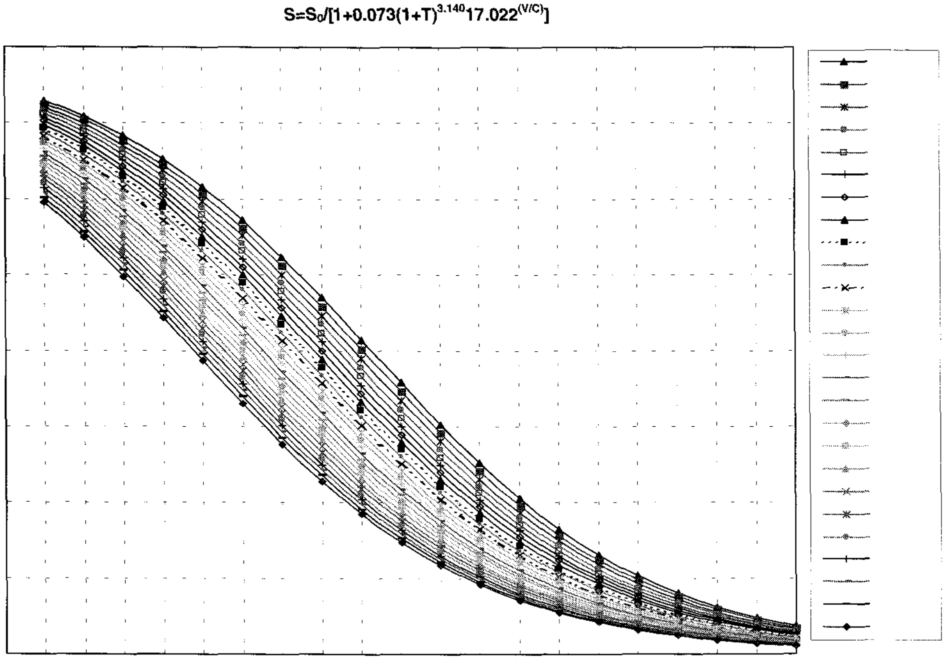
The speed-flows curves for urban arterials share some common characteristics with those of freeways. For any given truck percentage, these curves maintain the simplicity of a single differentiable, monotonically decreasing function, which makes it easier to implement the equations in the transportation planning models. The speed flow curves for urban arterials are shown in 〈Figures 9〉 to 〈Figures 12〉.

The coefficient α in the generalized speed-flow function in Equation (8) represents the drop in speed from the free-flow speed when traffic is light and when there are no trucks present. As mentioned earlier, the speed drop is mainly due to the delays caused by traffic signals. For example, in the case of Class I urban arterial α is equal to 0.136, which means the average speed will drop by 13.6 percent from free-flow speed even if the traffic volume is very low. Even though α is a facility specific parameter, its value is influenced more by traffic timings at individual intersections and how well the signals are coordinated along the corridor.

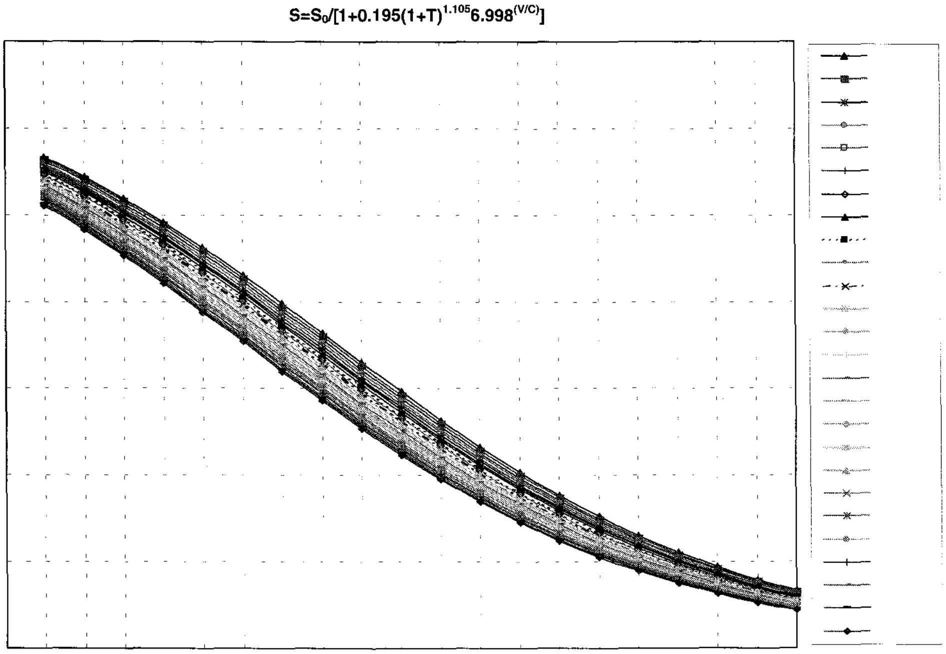
The coefficient β in Equation (8) is an indication of how sensitive the travel speed is to the presence of trucks in the traffic mix. The



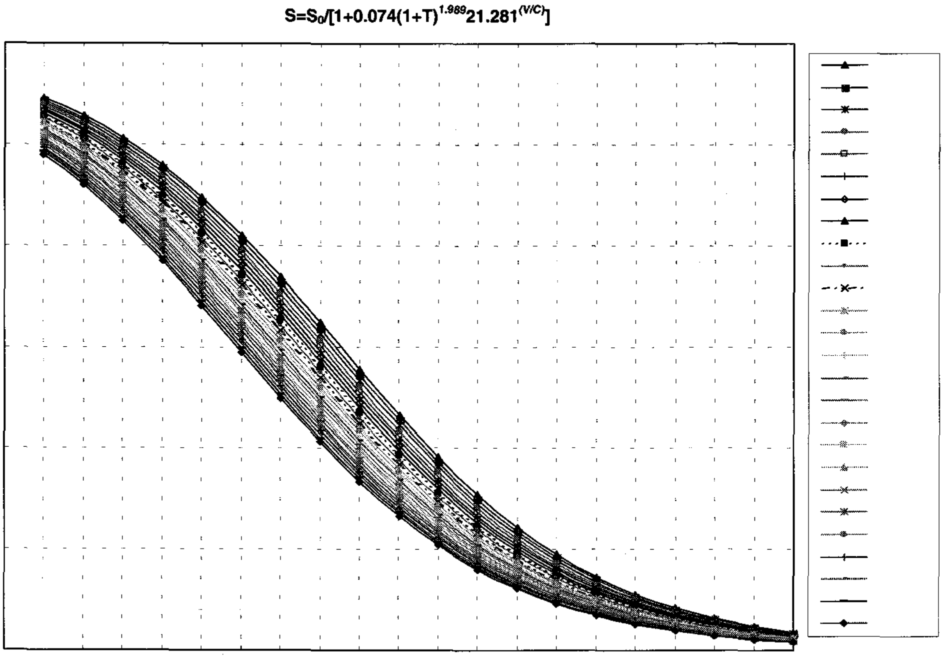
〈Figure 9〉 Class Ⅰ Urban Arterial Speed-Flow Relationships with Different Truck Percentages
Free Flow Speed = 50 mph, Signal Density = 1 signal/mi



〈Figure 10〉 Class II Urban Arterial Speed-Flow Relationships with Different Truck Percentages
Free Flow Speed =40 mph, Signal Density = 3 signals/mi



〈Figure 11〉 Class III Urban Arterial Speed-Flow Relationships with Different Truck Percentages
Free Flow Speed =35 mph, Signal Density = 4 signals/mi



〈Figure 12〉 Class IV Urban Arterial Speed-Flow Relationships with Different Truck Percentages
Free Flow Speed =30 mph, Signal Density = 5 signals/mi

higher the value of β is, the more impact the trucks will have on the average travel speed. In addition, it may be interesting to note that the value of β is inversely related to that of α. As shown in 〈Table 1〉, the values of β equal to 1.234 and 1.105 for Class I and Class III urban arterials, respectively. These numbers are lower compared to those of Class II and Class IV urban arterials, which are 3.140 and 1.989, respectively. However, the respective α values for Class I and Class Ⅲ urban arterials are 0.136 and 0.195, which are much higher than the respective α values of 0.073 and 0.074 for Class II and IV urban arterials. This phenomenon may not be surprising given that α represents the delays caused by traffic signals. When α is low, meaning the speed drops caused by signals are low, the impact of trucks on the speed becomes more significant.

Finally, the coefficient γ in Equation (8) indicates how quickly the average speed will drop when traffic volume increases. A higher value of γ indicates a "steeper" drop in speed when volume gets higher.

Ⅴ. Summary and Conclusions

In this paper, a new truck trip assignment methodology was developed for use in the urban travel demand forecasting process. This paper has presented the development of speed-flow relationships with truck impact based on CORSIM simulation results for freeways and four types of urban arterials. The traditional BPR (Bureau of Public Road) function representing the speed-flow relationships for roadway facilities is modified to specifically include the impacts of truck traffics. A number of new speed-flow curves have been developed based on CORSIM simulation results for freeways and urban arterials. The basic process involves the following steps:

- Observing the general characteristics of the simulation results,
- Proposing the functional forms representing the speed-flow relationships,
- Performing regression analysis to determine the coefficients,
- Evaluating the quality of the resulting regression equations, and
- Discussing the properties of the newly developed speed-flow curves.

The resulting speed-flow relationships for the roadway facilities are listed as follows:

Freeways:

$$S = \frac{S_0}{1 + 0.283(1+T)^{3.018}(V/C)^{2.249}}$$

Urban Arterials:

Class Ⅰ: $$S = \frac{S_0}{1 + 0.136(1+T)^{1.234}5.058^{(V/C)}}$$

Class Ⅱ: $$S = \frac{S_0}{1 + 0.073(1+T)^{3.140}17.022^{(V/C)}}$$

Class Ⅲ: $$S = \frac{S_0}{1 + 0.195(1+T)^{1.105}6.998^{(V/C)}}$$

Class Ⅳ: $$S = \frac{S_0}{1 + 0.074(1+T)^{1.989}21.281^{(V/C)}}$$

It must be emphasized that even though the above equations are based on sound theory and statistically significant with respect to the specific simulation results, they must be considered preliminary given the limited data sets and many underlying assumptions. The validity of the equations need to be evaluated by comparing them with the real-world data, and by implementing them in the travel demand estimation models to compare the traffic assignment results against the traffic counts.

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