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A Free-Flow Speed Model for Indiana Arterial Roads

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Abstract

As a basic characteristic of traffic flow, vehicular travel speed is indispensable in many research and management tasks. In travel speed estimation, vehicular free-flow speed is a crucial determining factor, particularly when the traffic is in light or moderate conditions. This paper explores the current state of the art of modeling free-flow speeds. It describes the development of free-flow speed models for Indiana arterial roads that may be also suitable for other Midwest states. The paper presents separate free-flow speed models for cars and trucks for day and night hours. Aggregate models could be easily available if follow the methods provided. The presentation includes the research background, data collection, data processing, model development, and analysis and refinement.

Keyword: speed prediction, free-flow speed, arterial roads

1. Introduction

Vehicular travel speed is an important characteristic of traffic flow. Therefore, speed is essential information in many research and management tasks. Vehicular speed is an important parameter in the estimation of pollution and safety factors and it is also a measure of congestion. Urban planners and transportation engineers need speed data for planning, design, and operation. Transportation management tools, such as congestion and safety management systems, also require speed data.

Highway management may require speed estimates or predictions for large networks with many road sections. From this point of view, it is neither practical nor economical to collect field speed data on every highway section in the network. Moreover, if the

speed information is needed for future conditions, field measurements that reveal the present conditions may produce biased results. In such cases, predictive models are more suitable than measurements. A prediction method uses the relationships between speed and other traffic data to derive speed information. To be practical, prediction methods should require only data that is available in the management process such as traffic volumes and basic parameter of road geometry (number of lanes, sections length) and should be computationally efficient.

A literature review (1,2,3) conducted as a part of this research indicated that most of the speed estimation methods require free-flow speed as an input. Free-flow speed is observed for extended periods on many arterial roads. It persists for entire days on many rural freeway sections. This makes accurate free-flow speed prediction an important component of speed modeling. Basically, free-flow speed is the mean speed of vehicles under actual road and weather conditions but without interference between vehicles. Inter-vehicle interference is commonly considered negligible under low and moderate traffic volumes (3).

An example of free-flow speed model is provided in the 1997 Highway Capacity Manual (3), where 75 mph is recommended for ideal rural freeways and 70 mph for ideal urban and suburban freeways. A set of adjustments to improve the estimation of free-flow speeds is also provided. The adjustments incorporate the effects of freeway physical characteristics including lane width, right-shoulder lateral clearance, number of lanes, and interchange density. The free-flow speed adjustments can be obtained from tables given by it. Equation 1 is used to estimate the free-flow speed of a basic freeway section:

$$FFS = FFS_i - f_{LW} - f_{LC} - f_N - f_{ID}, \quad (1)$$

where

FFS = estimated free-flow speed (mph);

FFS_i = estimated ideal free-flow speed, 70 or 75 mph;

f_{LW} = adjustment for lane width;

f_{LC} = adjustment for right-shoulder lateral clearance;

f_N = adjustment for number of lanes;

f_{ID} = adjustment for interchange density.

Although Equation 1 incorporates a number of free-flow speed factors, there are several potential free-flow speed variables that are not included in the existing method. These include speed limit, season, time of the day, and proportion of heavy vehicles. Further, the 1997 Highway Capacity Manual method represents average national conditions, while regional differences in drivers' behavior are possible.

The practical objective of the present research is to give planners and engineers a tool for obtaining free-flow speed information so that free-flow speed can be easily computed from available data and used for planning and management purpose. The research objective is to investigate the effect of type of vehicle and day/night conditions on the free-flow speed. In addition, the frequent assumption of the lack of interaction between vehicles in heterogeneous streams (cars and trucks) when volumes are low will be examined.

Section 2 proposes a general form of model and a method of its calibration. Section 3 describes the data collection technique and the pre-processing phase to obtain a sample of observations. Section 4 provides the regression analysis, while Section 5 discusses the results. The last section gives conclusions.

2. Model Form

Among many characteristic that can be associated with free-flow speed, the following are believed to be the most significant: speed limit, number of lanes, road classification, land use, truck percentage, weather, visibility, time of day and driver characteristics. Data on some of these items, such as those driver or weather related, are difficult to obtain and they cannot be incorporated in the prediction model if the model is to be practical. Consequently, the following four factors were considered in the present study:

1. Speed limit (65 and 55 mile/h)
2. Number of lanes (four/six)
3. Road classification (freeway/non-freeway)
4. Land use (rural/urban)

The impact of construction zones is not included since the model describes typical freeway conditions. The impact of freeway curves is negligible in many cases. Besides, typically, curvature data is not easily available for all sections of the analyzed network. Therefore, this impact is not included. Trucks and cars are expected to behave quite differently and they will be modeled separately. The same conjuncture can be made about driving in daytime and nighttime conditions. Consequently, four vehicle-type and time-of-day specific models were developed:

1. Daytime cars
2. Daytime trucks
3. Nighttime cars
4. Nighttime trucks

Free-flow speeds at a given location follow normal distribution (4). In addition, the variability of mean free-flow speeds across similar locations is small compared to the

sample mean. These two conditions allow us to propose a linear model with a normal error. An ordinary least-square technique for calibrating the models should suffice. Models for all the four cases have the same form:

$$v_{ij} = v_{0ij} + a_{tij} \cdot t_j + a_{vij} \cdot V_i + a_{rij} \cdot r + a_{fij} \cdot f + a_{nij} \cdot n + \varepsilon_{ij} \quad (2)$$

where

i = vehicle type, (t for trucks, c for cars);

j = time of day, (d for daytime, n for nighttime);

$v_{..}$ = free-flow speed;

$v_{0..}$ = intercept;

$a_{...}$ = regression coefficients;

t = truck percentage;

V = speed limit, (1 for 65 mi/h and 0 for 55 mi/h);

r = land use, (1 for rural, 0 for urban);

f = road class, (1 for freeway or 0 for non-freeway);

n = number of lanes, (1 for six lanes, 0 for four lanes);

$\varepsilon_{..}$ = error term.

The $a_{tij} \cdot t_j$ is used to test the impact of flow heterogeneity (vehicles and trucks mix) in low volumes. If the assumption of none or weak interactions between vehicles is true, then this term should be insignificant.

Using four separate models helps reveal differences between behaviors of the two types of vehicles during day and night that may be useful for traffic management and for evaluating the Indian speed limit policy. If the average free-flow speed of the entire flow is needed, then two joint models by combining the truck and car models under daytime and nighttime conditions respectively can be used, as shown below:

$$v_j = t_j \cdot v_{ij} + (1 - t_j) \cdot v_{cj} \quad (3)$$

To calculate average speed for the entire day, the average speeds for daytime and nighttime can be aggregated using equation similar to Equation 3. The percents of daily traffic during day and night should be used.

3. Data Collection and Pre-processing

The data required for calibration of the model (Equation 2) was obtained from the long-term traffic speed monitoring study conducted in Indiana by the Joint Transportation Research Program. All sites selected for speed monitoring were representative of Indiana arterial roads. Most of the speed stations were located at existing INDOT weigh-in-motion or telemetry permanent count locations (Figure 1). Some sites were temporary installations of pneumatic tubes and electromagnetic loops taped to the pavement (Figure 2). Locations were selected so that they were free from impacts of work zones, sharp curves, or intersections. The main sensors used in the collection of data were Peek traffic classifiers set to count vehicles in three classes determined by vehicle length: 1-20 ft, 21-45 ft, and 46-100 ft. The data used in this research was collected during the first half of 1999 between January and June. The number of data sets broken down by road class, land use, number of lanes, and speed limit are given in Table 1.

The raw data produced by the Peek classifiers is shown in Table 2. The first column represents the lane number. The second column indicates the vehicle length category: value 1 means the length is between 0'-20', value 2 is for the length within 21'-45', and value 3 is for the length within 46'-100'. The third column is the time of the day. For example, 0200 means the time interval between 01:00 and 02:00. The remaining 12 columns contain traffic counts in 12 speed bins: 0-35mph, 35-40 mph, 40-45mph, ..., 80-85 mph, 85-100 mph. Each column corresponds to a bin. The numbers in these

columns are vehicle counts that fall in a certain category. For example, the marked number 0008 says that eight vehicles shorter than 21 ft passed this monitoring site between 01:00 to 02:00 AM in lane 3.

The raw data was preprocessed to form a sample of observations. An observation applies to a traffic direction at a particular site, in a particular daytime period or nighttime period. The raw counts were first aggregated in one-hour intervals by traffic direction. The data allowed calculating hourly counts, percentage of trucks (vehicles longer than 20 feet), and average speeds for trucks, cars, and for the entire flow. The average speeds were then classified as free-flow speeds if the hourly volume was less than 1000 vehicles/hour in two lanes or less than 1500 vehicles/hour in three lanes. The hours with free-flow speeds were classified as daytime hours if they appeared between sunrise and sunset times. Nighttime data included counts during hours before sunrise and after sunset. The data during sunset and sunrise hours were excluded from the analysis. Additional data items recorded were number of lanes, speed limit, road classification and land use. Altogether 116 data sets were used in the analysis.

4. Regression Analysis

Ordinary least-square regression analysis was used to calibrate the four models. The calibrated models including the variables that were found significant at the 10% level are summarized in Table 3. The models' goodness can be considered satisfactory as the models explain between 87 % and 96 % of the site-to-site variance. All vehicle-specific models include the traffic heterogeneity term represented by the percent of trucks.

Figures 3 through 6 compare observed and predicted free-flow speeds obtained from the models. Most of the data points in all cases fall along the diagonal indicating a good match and lack of obvious bias. In Figure 3, the data points are clustered around 60 and 70 mph representing the daytime car free-flow speeds, while the daytime truck free-

flow speeds range between 57 and 67 mph as shown in Figure 4. While the range of nighttime car free-flow speeds (Figure 5) was similar to the daytime values, nighttime truck free-flow speeds (ranging from 57 mph to 63 mph), as shown in Figure 6, were lower than daytime truck free-flow speeds.

5. Discussion

The intercept in each model in Table 3 represents the average speed of vehicles in that category (cars or trucks, day or night) under the following conditions: the truck percentage approaches zero, speed limit is 55 mph, the roadway is 4-lane freeway in urban area. The average car free-flow speed was higher than the average truck speed under the same condition, and the daytime average speed was higher than the nighttime average speed for both cars and trucks. These results meet the expectations.

The flow heterogeneity term $a_{tij} \cdot t_j$ is significant in all the four models. It has a negative sign in the daytime models and positive sign in the nighttime models. To properly interpret these results, two situations observed on roads should be mentioned: (1) fast vehicles are impeded by slow vehicles; (2) some vehicles accelerate when passing other vehicles. Slowing down fast drivers may occur even in moderate-volume flows due to the tendency of traffic to form groups. The impeding effect dominates over the speed increasing effect in such conditions. The speed increasing effect is expected to prevail if traffic is indeed sparse and time of following a slow vehicle is negligible. It also may happen that some drivers slightly increase their speeds to follow another vehicles during conditions of limited visibility (night time). In such case, the second trend may be dominant and the traffic heterogeneity may increase the average speed.

In the models for nighttime a_{tij} is negative, which suggests that trucks impede cars even when volume is below 1,000 vehph. On the other hand, the nighttime models indicate the speed increasing effect. It has to be mentioned, that although the flow heterogeneity

impact is significant, the magnitude of the impact is indeed low and does not exceed two-mph speed reduction during a day and one-mph speed increase during night for assumed 40 percent of trucks in the flow.

Except for nighttime cars, for which speed limit had no significant impact, higher speed limit meant higher free-flow speeds. However, the impact varied between vehicle types. In daytime, both cars and trucks had an average increase about 6 mph in their free-flow speeds when the speed limit increased from 55(car)/55(truck) mph to 65/60 mph; while in night, trucks operated in a more stable speed, their average speed increase was only 1.23 mph when the speed limit increased from 55/55 mph to 65/60 mph.

In rural area, the free-flow speed was higher than in urban area for all models. Further, the difference in free-flow speed between rural road and urban road was higher in daytime than in night. Moreover, in rural area, the increase in truck free-flow speed was higher than that in car free-flow speed. These results are intuitive and confirmed what one could expect.

As for the road classification item, vehicles on freeways had higher speed than on non-freeways. We can see that the impact of freeways was much higher for cars than for trucks indicating that trucks had a stable driving speed on all arterials.

The variables representing the number of lanes had a negative effect on free-flow speed. An increase in the number of lanes possibly makes drivers more careful about vehicles on other lanes causing a drop in free-flow speed. This item had no significant influence on free-flow speed of trucks in the night. Traditionally, more lanes is regarded as a positive factor to vehicle speed, but under free-flow conditions, it seems that the effect is just the contrary.

6. Conclusions

This paper addresses modeling of the free-flow speed on arterial roads in Indiana. The model developed explored the impact of truck percentage, speed limit, land use type, road classification and number of lanes to free-flow speed. It also considered the different driving characteristics for cars and trucks and separated the modeling for night and day, respectively. Statistical analyses indicated a good performance of all the models, which can be used not only in Indiana, but also in other midwestern states.

Arterial traffic heterogeneity influences the flow speed even when volumes are low (less than 1,000 veh/h). It can either reduce or increase the average speed. The magnitude of this effect can be neglected in most cases though.

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Table 1 Sample Distributions by Four Characteristics

	Road Class		Land Use		Number of Lanes		Speed Limit	
	Freeway	Non-Freeway	Rural	Urban	4 Lane	6 Lane	65 mph	55 mph
Sample Size	82	34	76	40	90	26	70	46

Table 2 Example Raw Data

02	01	0200	0000	0000	0000	0000	0000	0000	0001	0000	0004	0004	0002	0000
02	02	0200	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000
02	03	0200	0000	0000	0000	0000	0000	0001	0002	0001	0001	0000	0000	0000
03	01	0200	0000	0000	0001	0000	0000	0007	0008	0008	0001	0000	0000	0001
03	02	0200	0000	0000	0000	0000	0002	0000	0000	0001	0000	0000	0000	0000

Table 3 Predictive Models

Model	Equation	R ² (%)	Std. Err. (mile/h)
Daytime cars	$v_{cd} = 61.7 - 3.31 \cdot t_d + 5.8 \cdot V_c + 1.18 \cdot r + 6.8 \cdot f - 8.3 \cdot n$	96.6	0.85
Daytime trucks	$v_{td} = 58.7 - 3.77 \cdot t_d + 6.42 \cdot V_t + 2.98 \cdot r + 4.52 \cdot f - 7.27n$	86.9	1.17
Nighttime cars	$v_{cn} = 59.9 + 1.89 \cdot t_n + 0.124 \cdot r + 8.29 \cdot f - 4.95 \cdot n$	91.0	1.28
Nighttime trucks	$v_{tn} = 58.0 + 2.16 \cdot t_n + 1.23 \cdot V_t + 2.47 \cdot r + 1.37 \cdot f$	87.0	0.97



Figure 1 INDOT ATR (Automated Traffic Recorder) Permanent Count Station.



Figure 2 Temporary Sensors Installation

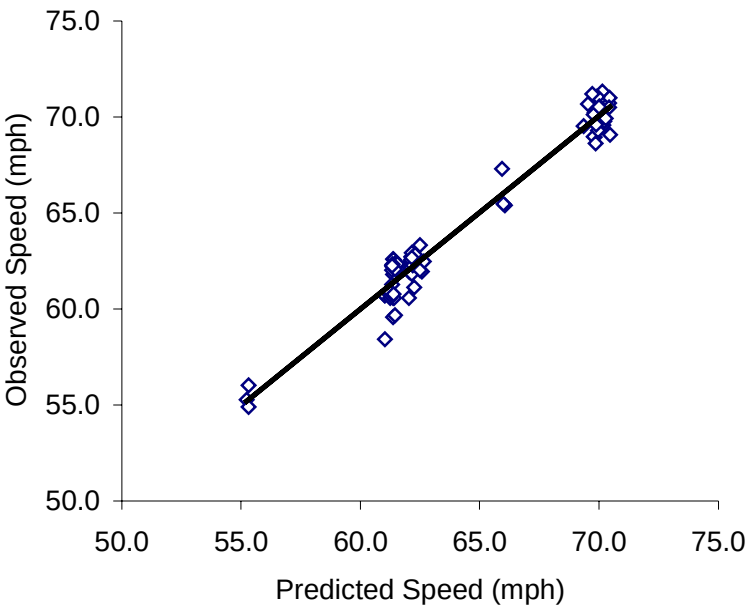


Figure 3 Daytime Car Free-Flow Speed

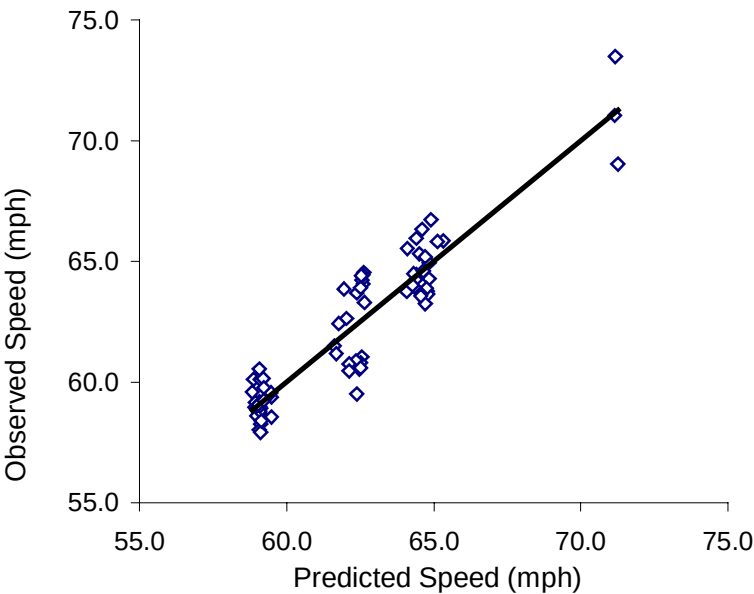


Fig 4 Daytime Truck Free-Flow Speed

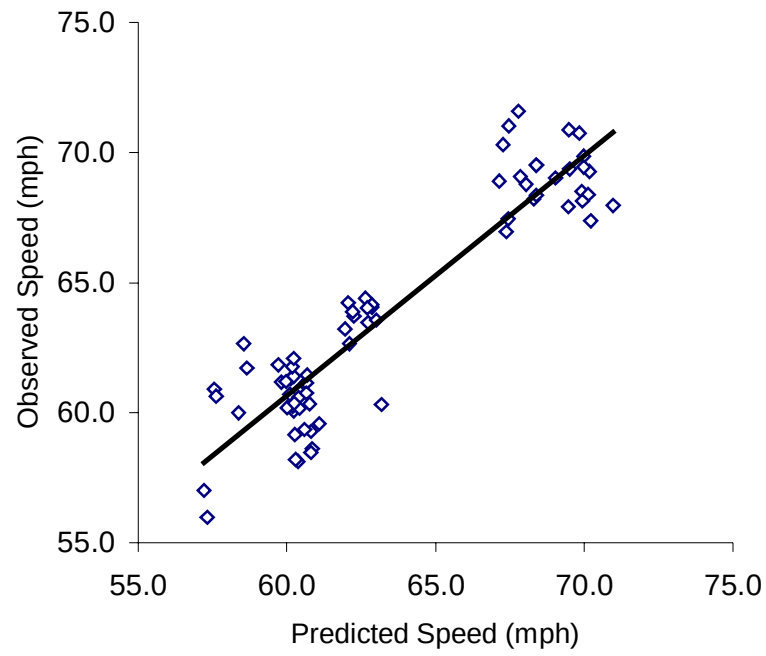


Fig 5 Nighttime Car Free-Flow Speed

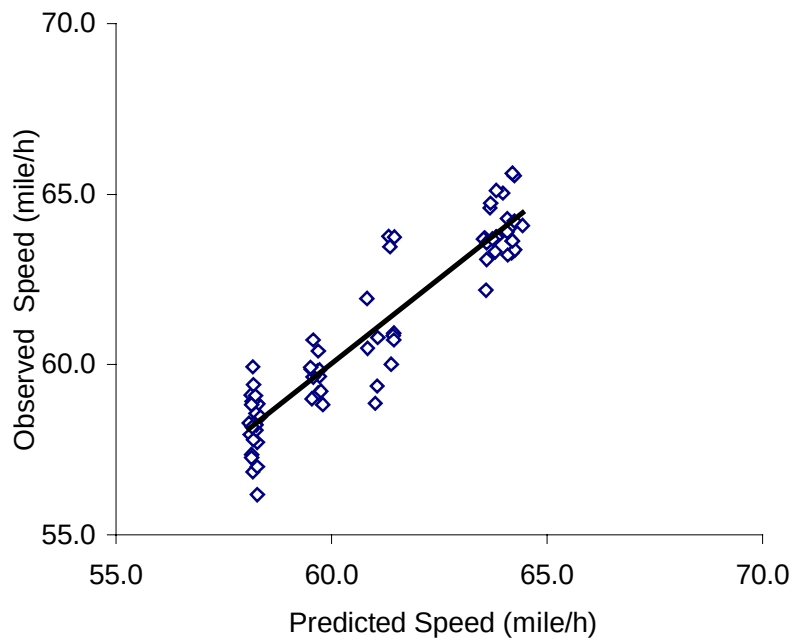


Fig 6 Nighttime Truck Free-Flow Speed

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