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An Evaluation of Vehicle Deceleration Profiles

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Vehicles stopping at signalized intersections were examined for the purpose of evaluating the validity of the common assumption of constant and uniform deceleration rates. The data set consisted of the first vehicles to stop upon the onset of the yellow signal interval with measurements of the initial approach speed, deceleration time, and deceleration distance.

The deceleration rate may be computed using only two of the three measured values; thus the rate for each vehicle can be determined by three different equations. With nonuniform deceleration profiles, the equations will produce different values; and the degree of nonuniformity can be determined by comparing the differences in the computed deceleration rates.

The analysis of the field observations indicated that 69 percent of the vehicles demonstrated deceleration profiles associated with nonuniform deceleration rates. Furthermore, the deceleration profile and the degree of nonuniformity were found to be a function of the initial approach speed.

Introduction

The utilization of vehicle stopping characteristics is an integral part of many aspects of traffic and transportation design. More specifically, stopping sight distance is a basic element in the design or evaluation of highway alignment; and the time required to stop is a common calculation inherent in the determination of change intervals at signalized intersections. In the calculations associated with vehicle stopping characteristics, a coefficient of friction or deceleration rate is assumed for the solution of the problem. While it is possible that field measurements of the coefficient of friction may be made in special circumstances, the calculations will typically contain numerical values for friction values or deceleration rates based on published standards and accepted practice.

For the determination of traffic signal change intervals, the time required to stop a vehicle is based on concepts developed by Gazis et al., [Gazis, Herman, and Maradudin, 1960] approximately thirty years ago. The basis for the concept is an application of the kinematic equation; thus the time to stop is expressed as:

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$$y = t + (v / 2a)$$

where

$y =$ time to stop (feet),
$t =$ driver perception-reaction time (seconds),
$v =$ initial vehicle approach speed (feet / second), and
$a =$ deceleration rate (feet / second ^{2}).

In addition to evaluating the time to stop an approaching vehicle, it should be noted that the traditional approach to determining the signal change interval also considers the time needed for a vehicle to clear an intersection.

Based on the early work by Gazis et al., it was assumed that a deceleration rate of 15 feet / second^2 was appropriate for use. Subsequent studies [Williams, 1977; Stimson, Zador, and Tarnoff, 1977; Parsonson and Santiago, 1981] concluded that a deceleration rate of 10 feet / second^2 was a more reasonable value, and that was adopted for use.

During the early 1980's, there was increasing concern about numerical values assumed in the determination of the change interval. At that time, the focus of the concern was on the value of the deceleration rate that was being used in the kinematic model. The value of the deceleration rate that had been used to that time was based on very limited field data; thus there was interest in validating and re-evaluating deceleration rates. Two rather comprehensive studies were initiated, and both included rather extensive field data collection. The first study [Wortman and Matthias, 1983, 1983a] was conducted for the Arizona Department of Transportation, and the second study [Chang and Messer, 1984; Chang, Messer, and Santiago, 1984] was undertaken as part of the Federal Highway Administration research program. While both studies found somewhat similar results, there was considerable unexplained variation in the observed deceleration rates. Because of the results of those studies, subsequent research [Wortman, Witkowski, and Fox, 1985; Wortman and Fox, 1985] was undertaken in Arizona in an attempt to examine other variables that could potentially influence the deceleration rate.

On the basis of the Arizona data, a detailed examination of driver deceleration characteristics was undertaken. This research assessed the deceleration profiles of drivers and the validity of the use of the kinematic model as a means of predicting stopping characteristics. In the discussion that follows, the field studies are described along with the theoretical basis for the analysis and the findings of the research.

Field Studies

The initial research in Arizona [Wortman and Matthias, 1983, 1983a] involved field data collection at six intersections in the Tucson and Phoenix metropolitan areas. Only one approach at each of the intersections was included in the field studies. All intersections included in the study were on urban or suburban arterial streets that are typical for the area.

Time-lapse photography was used to record driver behavior and vehicle operation. Vehicles approaching an intersection were filmed for a few seconds before the onset of the yellow interval, during the change interval, and until the vehicle either stopped or cleared the intersection. Given the onset of the yellow signal indication, the study focused on the first vehicle to stop and the last vehicle to pass through the intersection. Where there were multiple approach lanes, the information was determined for each lane. It was not possible to determine driver related information such as age, sex, driving experience, or route familiarity. The camera was located so that it was possible to record the intersection and the signal operation as well as the operation of approaching vehicles within 350 - 400 feet of the intersection. For the first vehicles to stop, the initial approach speed, the time during deceleration, and the distance during deceleration were determined from the film record.

The mean approach speeds for the first vehicles to stop at each of the six intersections ranged from 31.6 to 39.0 mph. The variation in the computed mean deceleration rate ranged from 7.0 to 13.9 feet per second squared.

Subsequent to the initial research effort, a second project [Wortman, Witkowski, and Fox 1985; Wortman and Fox, 1985] was undertaken for the purpose of addressing variables such as a) the duration of the yellow interval, b) the effect of enforcement, and c) intersection approach grades. Further field studies using time-lapse photography were conducted at four intersections. Again, the results revealed considerable variation in the traffic characteristics with mean intersection approach speeds ranging from 35.8 to 47.5 mph. The mean deceleration rates for the intersections in the later study ranged from 8.3 to 13.2 feet / second^2.

The magnitude of the field studies is significant in view of the fact that actual field data collection to that time had been quite limited. For example, the early work of Gazis et al., [Gazis, Herman, and Maradudin, 1960] included only 87 observations. As a contrast, the field studies in Arizona attempted to obtain 100 observations at each of the intersections. Consequently, the data base that was developed was much more extensive in terms of intersection locations and observations than with previous work.

Analysis Concept

Because of the variation in the observed deceleration rates at the intersections, further analysis of the stopping behavior and characteristics was undertaken. As has been noted, it was possible to determine the approach speed, the deceleration time, and the deceleration distance from the film record of the stopping vehicles. With this information, the deceleration characteristics and profiles were examined. The analysis concept is based on a comparison of results from equations associated with deceleration rate calculations.

In applying the kinematic equation concept to stopping vehicles, a common assumption is constant and uniform deceleration. Three basic equations may be used to calculate deceleration rate. The differences in the equations are a function of which two of the variables (initial speed, deceleration distance, or deceleration time) are used. the equations are as follows:

$$a_1 = v^2 / 2x \qquad \text{(Eq. 1)}$$
$$a_2 = 2x / t^2 \qquad \text{(Eq. 2)}$$
$$a_3 = v / t \qquad \text{(Eq. 3)}$$

where

a_1, a_2, and a_3 = deceleration rate based on each equation (ft / sec^2),
v = initial vehicle speed (feet per second),
x = deceleration distance (feet), and
t = deceleration time (seconds).

It is important to note that these equations are appropriate for applications with constant and uniform deceleration. If constant and uniform deceleration occurs, all three equations will yield the same deceleration rate as expressed by the following equality:

$$a_1 = a_2 = a_3$$

When nonuniform deceleration occurs, the three equations will yield different results; and the following possible sets of inequalities will result:

$$a_1 < a_3 < a_2$$

$$a_2 < a_3 < a_1$$

The development of the first inequality equation can be shown as follows:

Assume: $a_1 < a_2$

Then: $v^2 / 2x < 2x / t^2$
$v^2 < 4x^2 / t^2$
$v < 2x / t$
$v / t < 2x / t^2$

Thus: $a_3 < a_2$

Also: $v^2 / 2x < 2x / t^2$
$v^2 / 4x^2 < 1 / t^2$
$v^4 / 4x^2 < v^2 / t^2$
$v^2 / 2x < v / t$

Thus: $a_1 < a_3$

Therefore: $a_1 < a_3 < a_2$

A similar analysis can be used in the development of the second inequality equation.

The deceleration rate calculated for a_1 must always be the smallest or largest value compared with that obtained using the other equations. The deceleration rate for a_2 must always be the opposite extreme of a_1, and the calculated rate for a_3 must always fall between the other two values.

The effect of nonuniform deceleration and the results from the equations can be further explained in more detail using the diagrams illustrated in Figure 1. In the diagrams, various deceleration profiles of vehicles are depicted. The time axis identifies the elapsed time from the beginning of the deceleration, and the speed axis identifies the corresponding speed of the vehicle. The area under the curve reflects the distance over which stopping has occurred, and the slope at every point along the profile is the deceleration rate.

If constant and uniform deceleration occurs, the deceleration profile is a straight line, as illustrated in Figure 1a, and $a_1 = a_2 = a_3$. Conversely, a curved deceleration profile represents nonuniform deceleration that reflects one of inequalities as shown in Figures 1b and 1c.

To further explain Figure 1, consider the following example. Assume vehicle 1 has an initial speed (v) = 66 fps prior to the onset of braking. Also assume that the stopping distance (x) = 200 feet and the

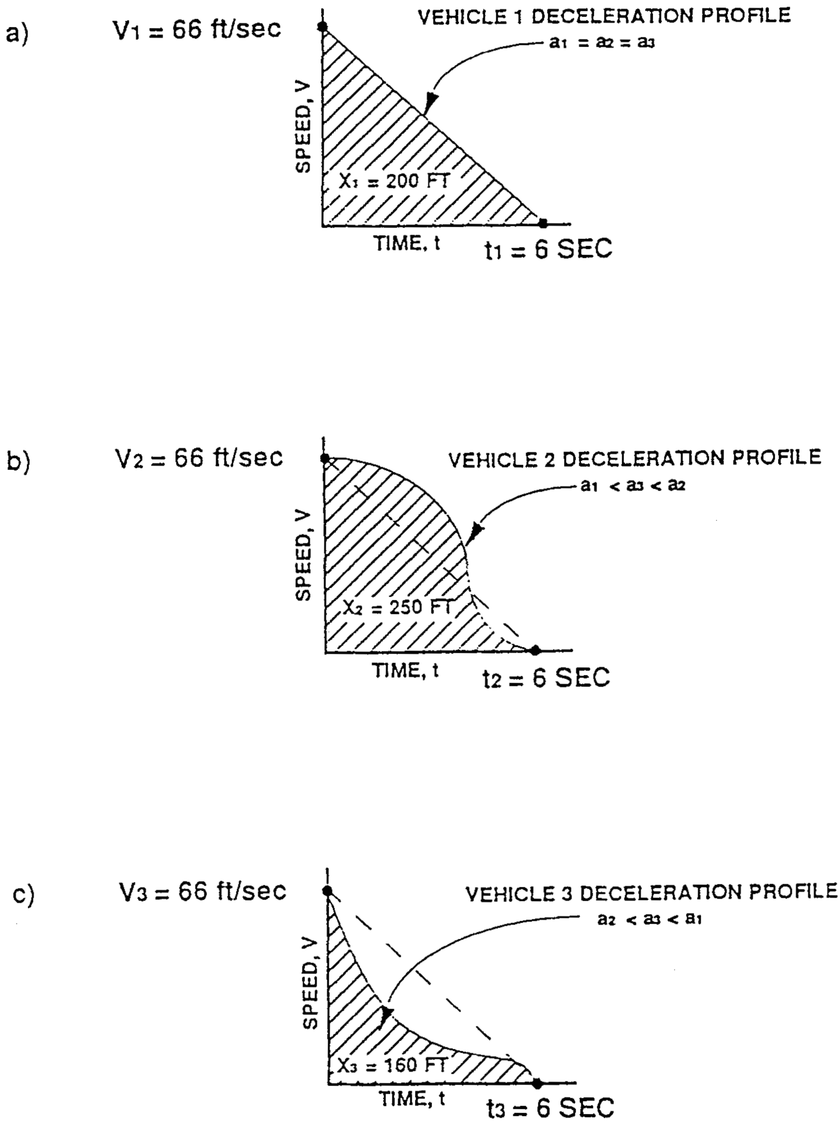

Figure 1. Deceleration Profiles.

time (t) required to stop = 6 seconds. The application of the three equations to determine the deceleration rate results in a value of 11 feet / second^2 in each case; thus $a_1 = a_2 = a_3$ with the deceleration profiles as shown in Figure 1a.

Now consider a condition where vehicle 2 has the same initial speed of 66 fps and has the same stopping time of 6 seconds; however, the distance required to stop = 250 feet. The determination of the deceleration rate for these conditions results in a_1 = 9 feet / second^2, a_2 = 14 feet / second^2, and a_3 = 11 feet / second^2. Consequently, the three deceleration equations yield the inequality $a_1 < a_3 < a_2$, which indicates that nonuniform deceleration occurs as shown in Figure 1b.

A second example provides a comparison of conditions indicated in Figures 1a and 1c. Again, assume that the conditions associated with vehicle 1 remain the same with a resulting constant and uniform deceleration rate of 11 feet / second^2. The conditions for vehicle 3, however, are v = 66 fps, x = 160 feet, and t = 6 seconds. In this case, the nonuniform deceleration profile yields the opposite inequality $a_2 < a_3 < a_1$ with values of a_1 = 14 feet / second^2, a_2 = 9 feet / second^2, and a_3 = 11 feet / second^2.

These examples hardly cover all the possible variations in initial speed, deceleration distance, deceleration time, and the deceleration profile exhibited by a specific vehicle. Nevertheless, the application of the three equations for computing deceleration rates will yield one of the two inequalities if nonuniform deceleration occurs.

Quantifying Deceleration Profiles

Given the occurrence of nonuniform deceleration, it is possible to quantify the deviations in deceleration profiles by:

$$Q = a_1 / a_2$$

The deceleration rates a_1 and a_2 are used because they determine the greatest difference between the values resulting from the deceleration equations. In essence, the deceleration rates are presented in a numerical form that accounts for the difference between the two sets of inequalities. Q values less than one will result from conditions associated with the inequality $a_1 < a_3 < a_2$ and represent profiles resembling Figure 1b. Conversely, Q values greater than one will result from conditions related to the inequality $a_2 < a_3 < a_1$ and represent profiles resembling Figure 1c.

When the differences between the computed deceleration rates from the three equations decrease, the resulting inequalities tend towards an equality with Q values approaching one. Values of Q that equal one represent a constant and uniform deceleration profile where $a_1 = a_2 = a_3$. Conversely, when the difference between the values yielded by the deceleration equations becomes greater, the degree of inequality increases, the deceleration profiles display more pronounced curvature, and Q values become significantly greater than or less than one.

Analysis of Data

The evaluation of actual vehicle deceleration profiles utilized field measurements of stopping vehicles from five of the intersections in the Tucson area studies. For the analysis, the three equations for deceleration rates were applied with the resulting determination of a Q value for each of the vehicles. The data set included a sample size of 716 stopping vehicles for which approach speed, stopping time, and stopping distance had been determined.

In conducting the analysis, it was recognized that some errors in the field measurements were possible due to the data collection techniques that were utilized. For example, the determination of distance was accomplished by measurements from the film of the intersection and the approaching vehicles. While distance reference points were placed on the intersection approach during the filming, there is the potential for some error in extracting distance measurements from the film. Given the techniques that were used, it was estimated that the reliability of the distance measurements was $\pm$ 5 feet.

The filming of the intersection approaches was accomplished with the camera operating at 18 frames per second, and the operating speed was checked as part of the data reduction process. At this filming speed, the time between subsequent frames was 0.056 seconds; thus the potential error in time measurements due to data collection techniques is $\pm$ 0.056 seconds.

In analyzing the deceleration profiles, the recognition of potential error due to data collection techniques is extremely important. If the differences in the deceleration rates yielded by the three equations can be totally attributed to potential measurement errors, then it becomes equivocal to argue that any differences are the result of nonuniform deceleration. On the other hand, if the differences are greater than those associated with potential measurement errors, there is credence to the argument that nonuniform deceleration was the reason for the variation in the deceleration rates.

The evaluation of 716 stopping vehicles revealed that 69 percent of the sample had differences in the deceleration rate that were greater than could be expected even with consideration of the potential errors in the measurements. Consequently, a major portion of the vehicles displayed nonuniform deceleration characteristics. The remaining 31 percent of the vehicles either had (a) a deceleration profile that approximated a uniform deceleration rate or (b) differences in deceleration rates that could be attributed to the measurement errors.

Given that a majority of the stopping vehicles had nonuniform deceleration profiles, the next step in the analysis was to assess the degree to which the vehicles deviated from a uniform deceleration rate. In addition, the evaluation attempted to relate the deceleration profiles to traffic characteristics. For this analysis, a Q value was determined for each of the stopping vehicles, and the relationship between the initial approach speeds and the Q values was evaluated. The results of the analysis are graphically depicted in Figure 2 in which Q values are plotted against vehicle speeds.

On the basis of the information shown in Figure 2, a nonlinear regression equation was developed to reflect the relationship of the variables. The following equation with a regression coefficient (r^2) of 0.80 resulted;

$$Q = 0.3 + 0.04\ (V / 15)^{2.5}$$

where

$V =$ initial vehicle approach speed (miles per hour)

This analysis indicates a strong relationship between the Q value and the vehicle approach speed. Furthermore, the analysis suggests that the deceleration profiles are related to vehicle approach speeds. At approximately 48 miles per hour, the Q value is equal to one, illustrating that the deceleration profile would reflect a constant and uniform deceleration rate.

With approach speeds less than 48 miles per hour, the Q value is less than one and decreases with reductions in approach speeds. This suggests that at speeds of less than 48 miles per hour the deceleration profile is typified by the curve shown in Figure 1b, and the departure from a constant and uniform deceleration profile becomes more pronounced with reductions in approach speeds. In practical terms, drivers will select lower initial deceleration rates. These findings tend to support the work conducted in Australia in which deceleration characteristics of motorists were examined [Akcelik and Biggs, 1987]. In particular, their research noted a similar nonuniform deceleration profile.

A somewhat reverse condition occurs at speeds greater than 48

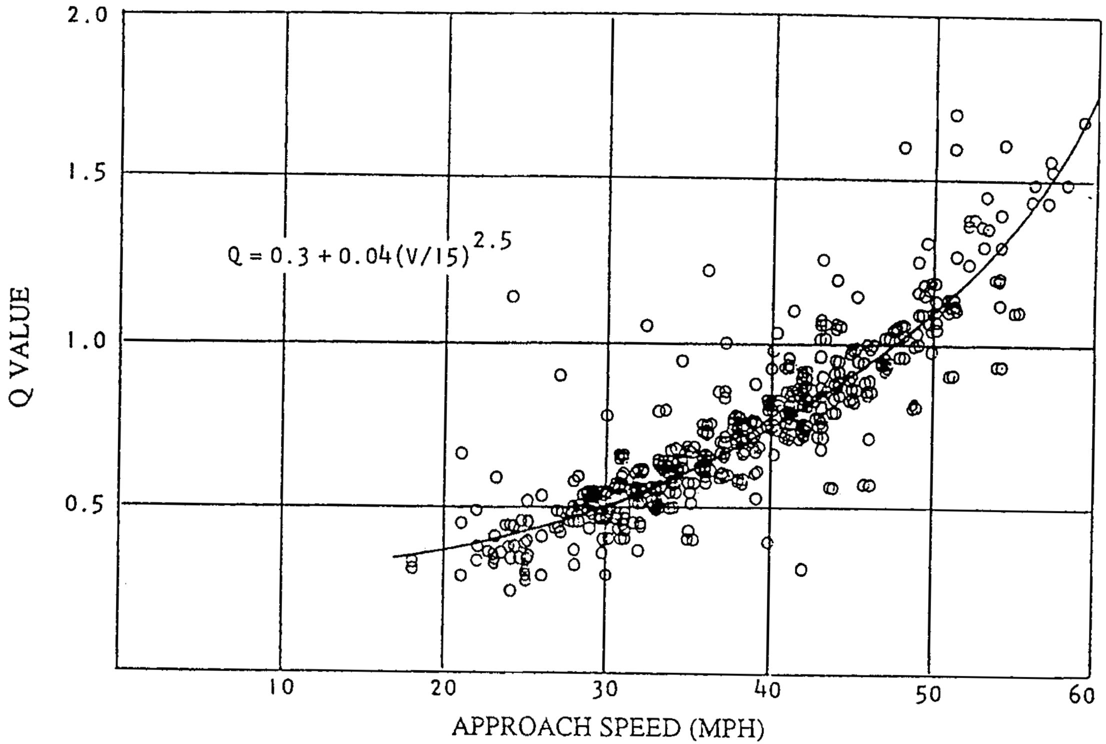

Figure 2. Relationship Between Approach Speed and Q Values.

miles per hour in that the resulting Q values are greater than one and increase as approach speeds increase. The deceleration profile for this condition is depicted by the shape of the curve shown in Figure 1c. In this case, the departure from a constant and uniform deceleration profile is more pronounced with increases in approach speed. Also, this suggests that drivers will select higher initial deceleration rates at higher approach speeds.

Conclusions

The analyses described in this paper have addressed the validity of assuming a constant and uniform deceleration rate when computing the time or distance required for a vehicle to stop. For the study, the findings reflect a theoretical analysis the computation of deceleration rates and profiles as well as the evaluation of data from observations of vehicles stopping at signalized intersections. On the basis of the findings of the study, several conclusions may be drawn that are significant to traffic engineering problems where vehicle stopping time or distance is a necessary aspect of the solution.

First, the determination of whether the deceleration rate is uniform or nonuniform can be determined by comparing the results of the three equations that are commonly used. In addition, the deviation from a constant and uniform deceleration profile can be quantified by comparing the deceleration rates resulting from the equations. This deviation is expressed as a Q value.

Second, the analysis of the field observations revealed that 69 percent of the stopping vehicles demonstrated deceleration profiles that were associated with nonuniform deceleration rates. This value excludes vehicle samples where a decision about uniform or nonuniform deceleration fell within the realm of possible measurement errors. It can be concluded that the majority of the vehicles did not have a deceleration profile that is associated with constant and uniform deceleration.

Third, there is a relationship between the Q value and the approach speed of the vehicle. This relationship may be expressed a $Q = 0.3 + 0.04\,(V / 15)^{2.5}$ where V is the approach speed of the vehicle. The field data suggests that constant and uniform deceleration does occur at approximately 48 miles per hour and nonuniform deceleration increases or decreases with deviation for that approach speed. In addition, this relationship indicates that vehicles with approach speeds more than 48 miles per hour have different deceleration profiles than those at lower speeds. At the higher speeds, drivers will utilize higher initial deceleration rates.

Finally, these findings have major significance with respect to design situations requiring the determination of vehicle stopping time or distance. The use of the uniform deceleration rate in the kinematic equation for vehicle stopping does not reflect the nonuniform deceleration characteristics employed by most drivers. While the equation based on kinematic concepts is convenient for computations, the use of a single deceleration rate value over a range of vehicle approach speeds does not conform to the reality of changes in deceleration profiles with variations in speed. Rather than using a uniform deceleration rate value for all conditions, the deceleration rate should be related to the approach speed of the vehicle with higher rates being associated with higher velocities.

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Conversion Factors

1 mile per hour = 1.6093 kilometers per hour
1 kilometer per hour = 0.6214 miles per hour
1 foot = 0.3048 meter
1 meter = 3.2808 feet