Driver Deceleration Behavior on a Freeway in New Zealand

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The results of a study that monitored driver deceleration behavior on a freeway in New Zealand are presented. A series of axle detectors were placed over a 500-m interval and the speeds were recorded using a data logger. The speeds of the same vehicle at different stations along the road were established for more than 1,200 vehicles. The speed profiles showed that vehicles decelerated over the same distance irrespective of the initial speed. As a result, the deceleration rate was proportional to the initial speed. A relationship was developed to predict the speed at any time as a function of the approach speed.

To model traffic flow, most simulation programs resort to models of driver acceleration and deceleration behavior. These dictate the speeds adopted during the simulation and, thus, significantly influence the results.

This paper presents the results of a study of vehicle deceleration behavior on a freeway in New Zealand. It begins with an overview of the various techniques used to model acceleration and deceleration behavior, which is followed by the results of a specific study of decelerations on a freeway.

RESEARCH ON MODELING ACCELERATION AND DECELERATION

Given the importance of modeling driver deceleration and acceleration behavior, there are surprisingly few studies reported in the literature on this topic. The research that has been done essentially can be divided into four distinct areas: constant, linearly decreasing, polynomial, and driving power–based models.

Constant Acceleration Models

The simplest form of model is the constant acceleration model. [The generic term acceleration will be used to describe either acceleration (positive) or deceleration (negative) except when presenting specific equations or study results.] It assumes that the average acceleration is maintained throughout the acceleration maneuver. Table 1 presents some typical values reported in the literature for average acceleration rates (*1–7*).

Linearly Decreasing Acceleration Models

Constant acceleration models are not appropriate for developing detailed speed profiles. Accordingly, for these purposes researchers have tended to adopt a speed-dependent acceleration model. For example, Sullivan (*8*) presents curves showing the discretionary and maximum comfortable deceleration rates as a function of speed. These rates decrease linearly with increasing speed. This is an example of one of the most common forms of acceleration models: the linear-decreasing model.

Linear-decreasing models generally assume that the maximum acceleration occurs at the beginning of the maneuver, linearly decreasing to 0, or a constant value, at the final speed. Equation 1 is an example of such a model (*9*):

$$a = a_0 - a_1 v - Mg\frac{GR}{(M + M')} \tag{1}$$

where

a = acceleration (m/sec^2),
a_0, a_1 = model coefficients,
v = vehicle speed (m/sec),
M = vehicle mass (kg),
M' = effective vehicle mass (i.e., the mass considering inertial effects) (kg),
g = acceleration due to gravity (m/sec^2), and
GR = gradient (%).

Many researchers have used linear-decreasing models (*1,6,7,9,10*). At higher speeds the model can become asymptotic, taking a long time to reach the final speed. This is illustrated in Figure 1, which shows the time-versus-speed profile for accelerating from 0 to 100 km/hr for four vehicle classes using Equation 1 with the parameter values from N-ITRR (*11*).

The medium and heavy commercial vehicles do not reach the 100-km/hr final speed within a reasonable time, because the acceleration decreases to a very small value, on the order of 0.02 m/sec^2, for heavy commercial vehicles as time increases. This rate compares with 0.57 m/sec^2 for the same vehicles when they begin to accelerate at the onset of the acceleration maneuver. It is therefore prudent to assume a minimum acceleration rate to eliminate this problem. Doing so, however, creates a second problem in that when the vehicles reach terminal speed, there will be an instantaneous change in the acceleration rate. In reality, drivers slowly reduce their rates so as to experience zero "jerk" at the end of the acceleration.

Polynomial Acceleration Models

Because of the problems outlined previously, other researchers have preferred polynomial model forms. Samuels (*12*) investigated the acceleration and deceleration of vehicles at an intersection. The data

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TABLE 1 Values Used in Constant Acceleration Model

Source	Country	Acceleration or Deceleration Rate in m/s^2	
		Acceleration.	Deceleration.
Lay (1)	Australia	1.00 to 4.00	
McLean (2)	Australia	0.34 to 1.18	-0.50 to -1.47
Watanatada, et al. (3)	Brazil		-0.40 to -0.60
Lee, et al. (4)	New Zealand	0.28 to 0.95	-0.28 to -0.96
Brodin and Carlsson (5)	Sweden		-0.50
Lay (1)	U.K.	0.50	
Bester (6)	U.S.A.		-0.60 to -1.90
St. John and Kobett (7)	U.S.A.		-1.07

indicated that a nonlinear speed-time relationship was applicable, and an equation of the following form was fitted to the data:

$$v = a_0 + a_1 t + a_2 t^2 \quad (2)$$

where t is time in seconds and a_0, a_1, and a_2 are regression coefficients.

Samuels and Jarvis (*13*) investigated the maximum rates of deceleration and acceleration for a sample of 17 passenger cars. The models developed were of the following form:

- *Accelaration:*

$$v^2 = a_0 + a_1 t \quad (3)$$

- *Deceleration:*

$$v = a_2 - a_3 t \quad (4)$$

Jarvis (*14*) examined the acceleration behavior of drivers departing from a rural intersection. A regression was performed using Equation 3 along with a second-order model. The second-order term markedly improved the fit of the model, and parameters were presented for five classes of vehicles, from passenger cars to heavy trucks. These results were later modified (*15*) to consider speed as a function of distance.

In New Zealand a study on acceleration behavior was conducted in the small rural city Palmerston North at four roundabouts, five signalized, and four priority intersections using arrays of pneumatic tubes connected to a data logger (*16*). The analysis consisted of the fitting of a fourth-degree polynomial equation to the speed/distance profiles. This equation was of the form

$$S = a_0 + a_1\,\mathrm{DISPL} + a_2\,\mathrm{DISPL}^2 + a_3\,\mathrm{DISPL}^3 + a_4\,\mathrm{DISPL}^4 \quad (5)$$

where DISPL is the cumulative distance traveled in meters, and a_0 through a_4 are regression constants.

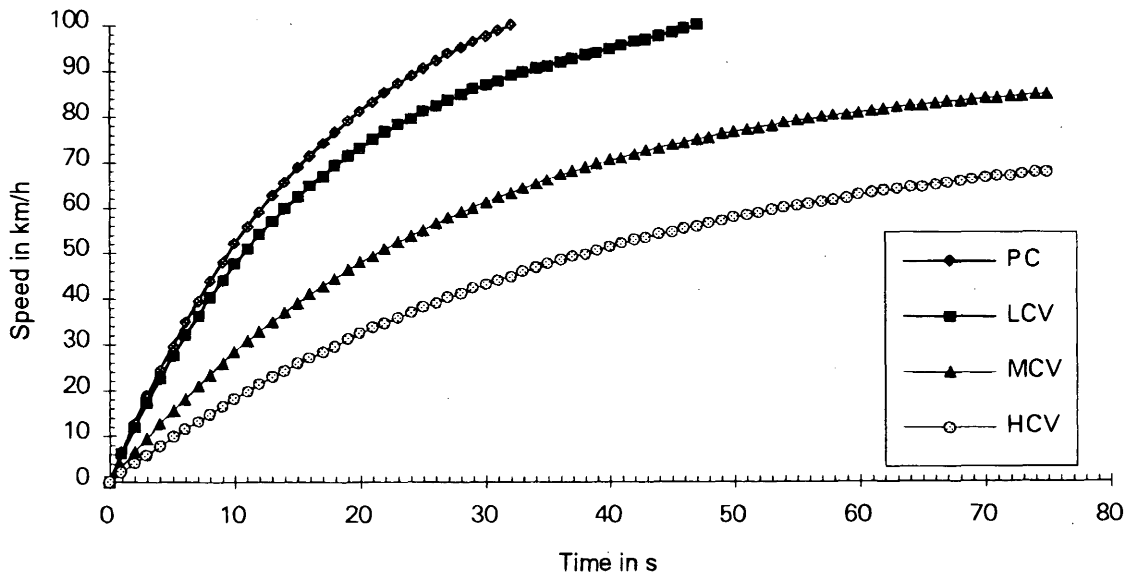

FIGURE 1 Speeds predicted by South African acceleration model.

Only vehicles with headways above 5.0 were included in the analysis, and equations were developed for each individual site and three composite equations for the different intersection types. Unfortunately, the model formulation does not lend itself to extrapolating for different approach speeds. A better method would have been to use the approach speed as an independent variable and to dispense with the constant a_0. Although limits for the equations are not given, it appears that the maximum approach speed in the study was on the order of 70 km/hr, so these equations are not appropriate beyond this speed.

Akçelik et al. (*10*) presented three models for passenger car acceleration profiles, a two-term sinusoidal, a three-term sinusoidal, and a polynomial model. These models were compared with constant and linear-decreasing acceleration models using data collected during fuel consumption testing. It was found that the polynomial model gave the best overall predictions and the linear-decreasing model the worst. This led to the development of the Australian Road Research Board (ARRB) polynomial model (*17*).

The ARRB polynomial model uses the time to accelerate or decelerate and the average, initial, and final speeds to predict a model parameter δ. This is a shape parameter that indicates whether the maximum acceleration occurs early or late in the profile. If δ is known (or assumed), only the times to accelerate and decelerate are required. A series of other model parameters are derived that result in a speed-time equation.

A series of equations were developed to predict the time to accelerate/decelerate and the acceleration/deceleration distances from field data collected in Australia (*17*). However, Bennett (*18*) indicates that there were problems with the ARRB equations in that their predictions were inconsistent for some speed combinations. Because of this, a linear model was adopted for acceleration in New Zealand (*18*). This linear acceleration model was less than ideal in that it predicted the same acceleration rate irrespective of speed (i.e., 0 to 20 km/hr would take as long as 80 to 100 km/hr).

Vehicle Power–Based Acceleration Models

The maximum acceleration of a vehicle is governed by the available acceleration reserve. Several researchers who have developed speed simulation models have used the acceleration reserve as the basis for predicting acceleration. (*3,5,8*). The underlying philosophy in this approach is that drivers use all the available power to accelerate their vehicle. (Since the acceleration reserve applies to positive power only this method is not used for deceleration.) Since the acceleration reserve decreases nonlinearly with increasing speed, this approach gives a nonlinear decreasing speed model. However, these sources (*3,5,8*) do not state explicitly whether an upper limit was used with the acceleration reserve to reflect the fact that drivers may use different power levels under acceleration than under steady-state driving.

GEIPOT (*19*) employed a variation of this approach. It adopted a nonlinear acceleration-speed relationship that gave the acceleration or deceleration as a function of gradient, roughness, and surface type. A single function was used that gave both acceleration and deceleration.

GRAFTON MOTORWAY DECELERATION STUDY

Introduction

A study was conducted at the Grafton Motorway exit ramp in Auckland, New Zealand, to monitor vehicle deceleration behavior. Seven pairs (stations) of axle detectors were installed on the ramp over a distance of 500 m upstream from the traffic signal at the end of the ramp. The first station was positioned to record approach speeds, and the last station was 10 m before a traffic signal.

The ramp was straight and had very high sight distances (>750 m) and a slight downgrade (<3 percent) over the initial 300 m. It had a single lane except for 75 m upstream from its end, where there were two lanes. The detectors at Stations 1 to 3 were spaced at 100-m intervals and thereafter at 50-m intervals. The experiment was conducted over a 24-hr period, but only data from daytime were used in the analysis.

Data were recorded at each station using a VDDAS data logger (*20*). The time of each axle crossing a detector was recorded to the nearest millisecond. The speeds were then calculated on the basis of these times and the distances between the detectors. VDDAS allowed for continuous sampling, which eliminated sampling biases in data collection that may arise with manual methods such as radar. More important, it allowed the speeds of the same vehicle to be tracked as it crossed successive detectors, thereby giving speed profiles for individual vehicles. The vehicles were classified into one of 44 classes based on the number of axles and their spacing. Special software was written both for the data reduction and establishing the speed profiles as described by Bennett (*22*.)

A total of 1,200 valid speed profiles were obtained in the study; they were stored in a FoxPro data base. A valid profile was considered to be one in which the same vehicle was identified and had its speed monitored at four or more stations.

Data Reduction

The speed profile data base contained the speed of the vehicle at each station along with the time between stations. It was necessary to manipulate these data into a format suitable for statistical analysis. It was postulated that the deceleration behavior would vary by vehicle type, so it was also necessary to disaggregate the data by vehicle type.

The data base was filtered so that only vehicles with a minimum headway of greater than 4.5 sec at all stations were included in the analysis. An upper limit of 15.0 sec was placed on the data to eliminate any unusually slow vehicles. This upper limit affected less than 0.1 percent of all available data. The profile data were filtered and converted into a sequential data base. Because of the limited amount of data available, the analysis could be conducted only for three vehicle types: (*a*) passenger cars and small light commercial, (*b*) medium commercial, and (*c*) heavy commercial vehicles. The total number of speed-time observations available by vehicle class were as follows:

Class	*No. of Speed-Time Observations*
Passenger cars and small LCV	1,604
Medium commercial vehicles	255
Heavy commercial vehicles	131

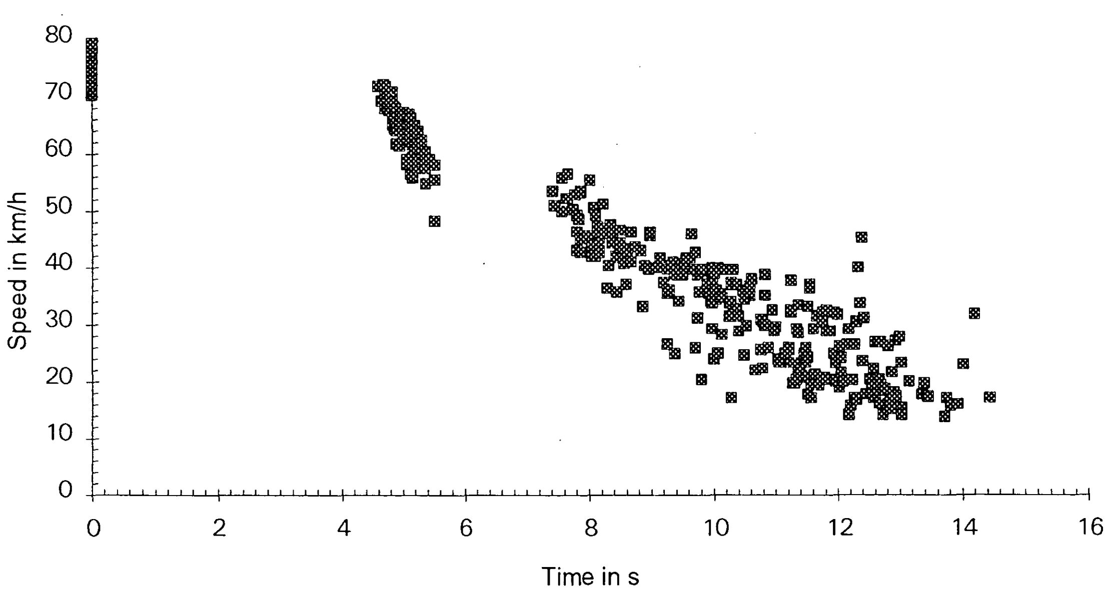

FIGURE 2 Elapsed time versus speed for vehicles approaching at 70 to 80 km/hr.

Results of Analysis

The literature review presented earlier indicated that deceleration behavior was probably a function of speed, so the analysis first concentrated on investigating such a relationship for passenger cars since these vehicles had the most data available. Figure 2 is an example of speed versus the elapsed time from the first detection for passenger cars traveling at an initial speed of between 70 and 80 km/hr at Station 3.

When the data were plotted for different approach speeds, it became apparent that deceleration behavior varied as a function of approach speed. Furthermore, there was little deceleration at the first two stations, so the initial station for deceleration purposes was treated as Station 3. The data were segmented into files from 50 to > 100 km/hr in 10-km/hr increments. For each file a regression analysis was conducted that investigated the effect of time on speed. A variety of linear and nonlinear models were tested with the equations in Table 2 being selected as the most appropriate for modeling deceleration behavior.

The deceleration equations used are all of the form $S = a_0 - a_1 t - a_2 t^2$. In comparing the models it can be observed that the coefficients a_1 and a_2 increase with increasing approach speed. This indicates that faster vehicles decelerate at a higher rate. However, there is a problem with these models in that they provide inconsistent predictions at lower speeds. The predictions cross because the faster drivers do not begin decelerating until late in the maneuver and thus have a different time base than the lower speeds.

Although the preliminary models developed were inadequate for general use, they did indicate that the higher the approach speed, the higher the rate of deceleration. This characteristic was further investigated by stratifying the data into various speed intervals and determining the average deceleration over these intervals for each approach speed group. It was not possible to use identical intervals with each approach speed group since there were often marked variations in the deceleration rate with time. Table 3 presents the average deceleration rates as a function of approach speed and deceleration speed for speeds below 100 km/hr.

Table 3 verifies that there is a marked difference in deceleration behavior by approach speed. Vehicles traveling at low speeds experienced a low deceleration rate, whereas those at high speeds had much higher rates. This suggests that rather than taking a much longer distance, or time, to decelerate, high-speed drivers prefer to decelerate more rapidly.

For comparative purposes, the New Zealand deceleration rates were assessed against those used in the ARFCOM model from Australia (*21*). For speeds below 80 km/hr, the observed New Zealand deceleration rates were similar to those in ARFCOM. However, in the 100 to 80 km/hr area, the New Zealand rates were approximately

TABLE 2 Preliminary Regression Models by Approach Speed

Approach Speed	Speed Model	R_a^2
60 - 70 km/h	$S = 66.66 - 0.96\,t - 0.18\,t^2$	0.96
70 - 80 km/h	$S = 75.68 - 1.64\,t - 0.22\,t^2$	0.96
80 - 90 km/h	$S = 84.46 - 2.59\,t - 0.25\,t^2$	0.96
90 -100 km/h	$S = 94.36 - 3.65\,t - 0.30\,t^2$	0.98
> 100 km/h	$S = 105.69 - 4.95\,t - 0.41\,t^2$	0.97

Note: R_a^2 = the adjusted coefficient of determination

TABLE 3 Mean Deceleration by Approach Speed and Speed During Deceleration

Mean Deceleration Rate by Approach Speed and Speed During Deceleration							
60 - 70 km/h		70 - 80 km/h		80 - 90 km/h		90 -100 km/h	
Decel. Speed (km/h)	Mean Decel. (m/s^2)	Decel. Speed (km/h)	Mean Decel. (m/s^2)	Decel. Speed (km/h)	Mean Decel. (m/s^2)	Decel. Speed (km/h)	Mean Decel. (m/s^2)
65 - 55	0.46	75 - 62	0.78	85 - 68	1.23	95 - 75	1.39
55 - 45	0.93	62 - 50	1.11	68 - 58	1.39	75 - 58	1.89
45 - 20	1.39	50 - 19	1.78	58 - 18	2.22	58 - 22	2.34

90 percent higher. This difference could reflect the fact that the ARFCOM data are primarily urban-based whereas the New Zealand data pertain to open road speeds.

It is interesting that the maximum deceleration observed in another New Zealand study conducted in the rural city of Palmerston North (*16*) was -1.72 m/sec^2. This result is similar to the *average* deceleration for the approach speed of 80 to 90 km/hr, verifying that drivers on open roads use a higher deceleration rate than do drivers in urban areas.

The Grafton Motorway data indicate that vehicles generally start decelerating at the same point on the road irrespective of the approach speed. Faster drivers then accept a higher deceleration rate than the slower drivers. This has the effect of producing deceleration times and distances that are of the same magnitude irrespective of the initial and final speeds.

A number of models were investigated for predicting the speed profile. These included sigmoidal models, the polynomial model from ARRB, as well as various polynomial equations. One of the main problems in developing a suitable model was the need to consider the variation in the deceleration rate as a function of approach speed and the predictions as vehicles approached stopping. It was found that the following formulation gave the most suitable overall predictions:

$$S = S_a + a_0 S_a t^2 \quad (6)$$

where S is the speed of the vehicle at time t in kilometers per hour, and S_a is the approach speed of the vehicle in kilometers per hour.

Taking the derivative of this equation with respect to time gives the following model for predicting acceleration:

$$a = a_1 S_a t \quad (7)$$

Table 4 presents the coefficients and regression statistics for the previous two models by vehicle class. The values for coefficient a_0 indicate that light vehicles decelerate 22 percent faster than heavy vehicles. The differences between passenger cars and medium trucks is so small that it is negligible. Figure 3 illustrates the predicted speed profiles of passenger cars from different approach speeds using Equation 6.

Equation 7 predicts that the higher the approach speed, the greater the deceleration rate. This was observed from the raw data. It also indicates that the maximum deceleration will occur at the very end of the speed profile. This is a deficiency in the model since at the end of the profile the drivers will actually experience zero jerk.

CONCLUSIONS

This analysis has developed equations for predicting deceleration behavior of vehicles as a function of approach speed and the cumulative time. Although the equations pertain to a specific situation—vehicles decelerating from the open road speed toward a stop—the analysis has provided useful insight into driver deceleration behavior.

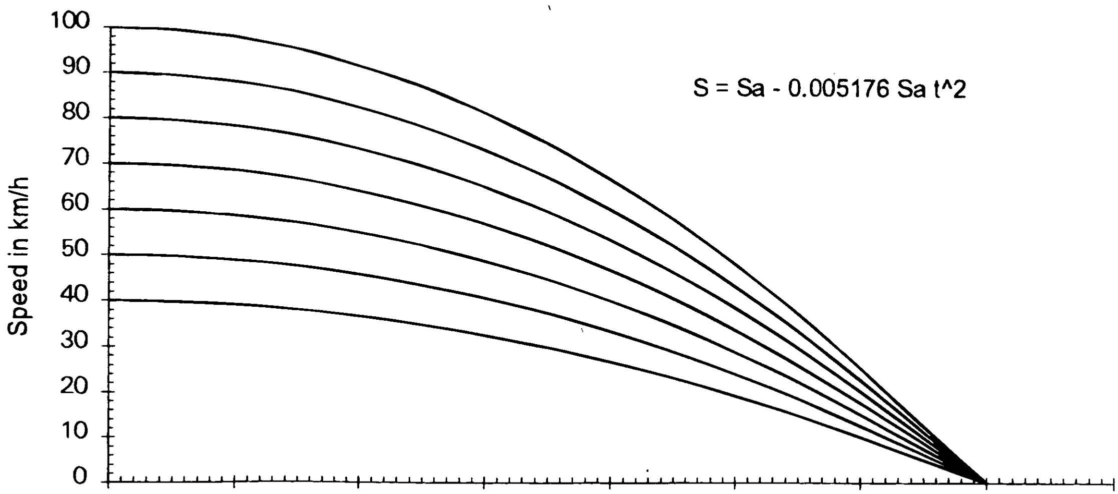

FIGURE 3 Predicted deceleration profiles for passenger cars and small commercial vehicles.

TABLE 4 Final Deceleration Model Regression Coefficients

Vehicle Class	Regression Model Coefficients		R_a^2
	a_0	a_1	
Passenger Cars and Small LCV	-0.005176	-0.002876	0.83
Medium Commercial Vehicles	-0.005129	-0.002849	0.86
Heavy Commercial Vehicles	-0.004244	-0.002358	0.83

Notes: a_0 and a_1 = model coefficients
R_a^2 = the adjusted coefficient of determination

It was found that higher-speed drivers decelerate over a short period of time, thereby experiencing high deceleration rates instead of gradually decelerating over a long period. This is different than what is predicted by the equations for applying the ARRB polynomial model (*10*), which imply that drivers decelerate over a longer distance with higher speeds.

The average deceleration rate for drivers with an approach speed of 80 to 90 km/hr was similar to the maximum deceleration rate observed in an urban study in New Zealand. This indicates that open road drivers have much higher deceleration rates than urban drivers employ.

ACKNOWLEDGMENTS

The work presented in this paper was undertaken at the University of Auckland as part of a research project to develop a speed prediction model for rural highways (*22*). The funding and support for the research were provided by Transit New Zealand.

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