Nonlinear Truck Factor for Two-Lane Highways

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A microscopic simulation model for traffic flows on two-lane, two-way highways was developed to include all important factors known to affect these flows. This simulation provided results in agreement with field data and was applied to flows in level terrain, in rolling terrain, and on sustained grades. Results from the model indicated that the truck factor, currently of linear form, should be nonlinear. A nonlinear form was derived and successfully applied to summarize results for a variety of terrains and vehicle populations. This paper presents a brief description of the simulation, the evidence for a nonlinear truck factor, and the derivation and testing of the nonlinear factor.

The Highway Capacity Manual (HCM) (1) presents methods for estimating the speeds and service on two-lane, two-way highways. The methods and numerics are based on data collected in the 1950s with revisions to account for the general increase in speeds prior to the 88.5-km/h (55-mph) national speed limit. The changes in vehicle speeds and populations since the 1950s raise questions regarding the adequacy of the methods and numerics in the HCM. This paper presents results from a National Cooperative Highway Research Program (NCHRP) project that contained several tasks designed to update the information on the vehicle population and to improve the methods for estimating speed and service on two-lane highways (2).

METHODS EMPLOYED

The characteristics of two-lane flows were evaluated by using a microscopic simulation model. The model was developed and adjusted by using data from the literature and data collected by St. John and Kobett (2). The latter extended the scope of information on passing behavior and provided samples of overall travel speeds on a test section with limited passing opportunities on rolling terrain.

The vehicle characteristics and vehicle populations used in the simulation model were based on field data and data from the literature. A subcontractor performed acceleration tests on a few recreational vehicles and combinations. Acceleration and speed performance data on passenger cars, trucks, and recreation vehicles were obtained from the literature. Analytical expressions were developed to relate acceleration capability to speed and local grade for trucks, passenger cars and light pickup trucks, motor homes, and other recreational vehicles and combinations. Thirteen vehicle types were used in the simulation model: three passenger cars, three trucks, and seven recreational vehicles and combinations.

The simulation model incorporates all known parameters that influence two-lane, two-way traffic flows. The parameters include

1. Acceleration and speed capability limits for each type of vehicle including the effect of the local grade;
2. Driver preferences that can restrain the use of performance capability in acceleration and speed maintenance;
3. Overtaking and following characteristics that provide realistic representation over the full range of conditions from high speeds to congestion;
4. Acceptance (and rejection) of passing opportunities based on distance to the next oncoming vehicle if it is in sight, passing sight distance, speed of impeding vehicle, location in impeded platoon, distance to end of passing zone if it is in sight, and presence or absence of horizontal curvature within the range of passing sight distance;
5. Vehicle lengths treated explicitly in overtaking, following, and in passing maneuvers;
6. Passing maneuvers subject to the constraints of vehicle acceleration and speed performance and also to the restraints that field data indicate are used by drivers;
7. Passing sight distance as a separate variable in each direction and local magnitudes consistent with alignment and with passing and no-passing zones; and
8. Multiple passes, i.e., one or more vehicles passing more than one impeding vehicle or more than one vehicle passing an impeding vehicle.

In addition, the following assumptions are made:

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Figure 1. Mean speeds of passenger cars on 0 percent grades based on vehicle population of 100 percent passenger cars.

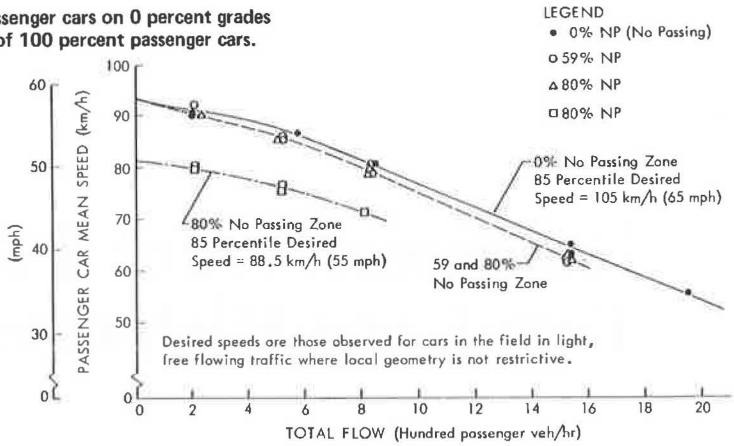
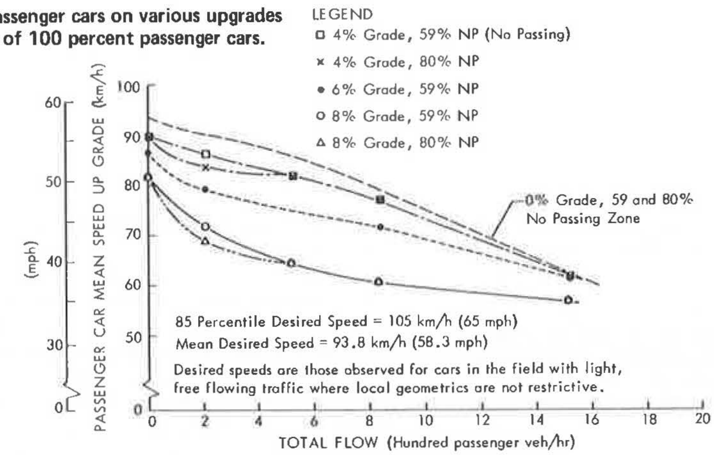


Figure 2. Mean speeds of passenger cars on various upgrades based on vehicle population of 100 percent passenger cars.



1. Vehicles in the model slow to negotiate horizontal curves that have combinations of curvature and superelevation requiring speed reduction;
2. Flying passes (where the impeded vehicle still has a speed advantage) are permitted, but before the pass decision, closure speeds are constrained by overtaking characteristics;
3. Passing maneuvers that become infeasible are aborted if the passer is not already committed to complete the pass (restraints on the use of vehicle performance are abandoned by the passer committed to pass when the maneuver becomes infeasible); and
4. Trucks use crawl speeds to descend sustained grades of 4 percent and steeper.

Results from the model combine to produce speed versus flow rate curves similar to those displayed in the HCM (1). When vehicle performance characteristics appropriate for the data collection period are used, the model also provides pass frequencies in agreement with data collected by Normann (3). When the features of the data collection site and observed vehicle population are used, the model also produces a distribution of passenger car speeds in close agreement with data collected in rolling terrain. When the overall speed data were collected in the field, the traffic flow contained a large percentage of trucks and a small percentage of recreational vehicles. However, during data collection only small changes occurred in the truck and recreational vehicle percentages. Consequently, the model has not been validated for its sensitivity to variations in the percentage of trucks.

BASIS FOR QUANTIFYING TRUCK FACTORS

A truck factor (F_T) is conventionally used to adjust the flow of mixed vehicles at a rate of Q vehicles/h to the equivalent flow rate of passenger cars only (Q_E).

$$Q_E = Q/F_T \qquad (1)$$

This relationship and application are retained here; as shown later the nonlinearity arises in the functional from of the truck factor.

The flow rate (Q) may consist of a mixture of passenger cars, recreational vehicles, and trucks. Q is equivalent to a Q_E of 100 percent passenger cars in only one respect. In the present case mean speed of passenger cars has been chosen as the measure for equivalence; other aspects of the flows are not necessarily similar.

If mean speed of passenger cars is the measure for equivalence, knowing and using these mean speeds are necessary for traffic flows with 100 percent passenger cars. Figure 1, based on simulation results, shows how the mean speeds vary in relation to highway properties and total flow rate on level terrain. The total flow is two-way, and the depicted results are obtained from the simulation model with nearly balanced flows.

Figure 2, based on simulation results, shows mean speeds of passenger cars on sustained grades of 0, 4, 6, and 8 percent. All results are for highways on which the mean spot speed of passenger cars is 93.80 km/h (58.28 mph) in very light traffic at locations with good geometrics and essentially 0 percent grade. (The 85th percentile speed is 105 km/h or 65 mph.) The results are for balanced flows; however, the speeds for the 4 to 8 percent grades are those in the upgrade direction. (The downgrade traffic is modeled just as accurately.) Based on 100 percent passenger vehicles, the downgrade mean speeds are slightly, but not significantly, higher than the 0 percent grade values.

The speed-flow rate relations in Figure 2 are the base for quantifying the equivalences described in this paper. The curves provide the necessary relations between mean speeds of passenger cars and flows of 100 percent passenger cars. The 0 percent grade curve is used for 0 percent grades, rolling terrain, downgrades, and 2 percent grades. The 4, 6, and 8 percent upgrade curves are used for sustained grades of those magnitudes. Application in this paper is restricted to the highway speed indicated, to essentially balanced flows, and to highway sections with 46 to 80 percent no-passing zones. (The extension to 46 percent no-passing was indicated by favorable experience with this value when the curves in Figure 2 and figures that follow were used.)

The following is an example of equivalent flows: Passenger cars in a mixed flow over rolling terrain have an overall mean speed of 76.8 km/h (47.7 mph), and the nearly balanced mixed flow rate is 600 vehicles/h. Since the equivalent flow rate of passenger cars has the same overall mean speed, the equivalent flow rate is read in Figure 2 on the 0 percent grade curve at 76.8 km/h as 925 passenger cars/h.

The speeds in Figure 2 may appear low for the 4, 6, and 8 percent grade. All vehicles in the model, including the population of passenger vehicles, have realistic acceleration and speed capabilities. Also, our analysis of data supplied by Werner (4) indicates that the drivers of passenger cars, light pickup trucks, and recreational vehicles do not use all the available vehicle power for extended periods. Consequently, the combination of performance characteristics and driver restraint does have a significant effect on passenger car flows on sustained grades of 4 percent and steeper. St. John, in presenting this topic in detail (2), shows that the speed data collected by Williston (5) are explained by the combined effects of performance limits and driver restraint. (In contrast, all of the available power in intercity transport trucks is used for extended periods.)

EVIDENCE FOR A NONLINEAR TRUCK FACTOR

Results from the simulation model supply strong evidence that the truck factor should have a nonlinear form. Figure 3 shows equivalents calculated from the linear form of the truck factor for three truck types, a low-performance camper, and a low-performance travel trailer combination. The equivalents are based on model results from simulation runs in which a single type of impeding vehicle is present. The equivalents are plotted against the travel speed of the impeding vehicle. The relation between the equivalent and the speed of the impeding vehicle has the general form shown in the HCM. However, there are two distinct curves. One curve connects points from model results in which there are 8 to 9 percent of one of the impeding vehicle types; the second curve connects points where there are 18 to 21 percent of the impeding vehicle type. These results indicate a type of nonlinearity. For example, if 65.8-km/h (40.9-mph) vehicles replace 10 percent of a passenger car flow, the 65.8-km/h vehicles are each equivalent to 15 passenger cars. However, if 20 percent of the passenger cars are replaced, each of the slow vehicles would be equivalent to only 8.5 passenger cars. From an incremental standpoint, the second 10 percent are less disruptive to the flow than the first 10 percent. (The first 10 percent have already depressed speeds.) The equations currently employed to obtain truck factors with equivalents assume a linearity that is inconsistent with the simulation results.

Figure 3 and the above example deal with instances in which different fractions of the same vehicle type were compared for effect. A similar and consistent nonlinearity is found for cases in which two or more types of impeding vehicles are involved. The effect of the mixture is not predicted correctly from the effects of the individual types when they are combined by using the current linear expression for the truck factor.

DERIVATION OF A NONLINEAR TRUCK FACTOR

An alternative version of the truck factor equation that may be derived to establish a relation that depends exclusively on the speed of the low-performance vehicle is applicable to a range of truck (or recreational vehicles) percentages, and correctly combines and predicts the influence of a mix of low-performance vehicle types.

We retain the concept expressed in equation 1. The factor $1/F_T$ is written

$$1/F_T = 1 + (P_T/100)(E_T - 1) \tag{2}$$

where

P_T = percentage of trucks, and
E_T = equivalents of trucks.

However, the application of the above form is restricted to adding small increments of percentages of trucks as shown by the following equation.

$$1/F_T = 1 + (\delta P_T/100)(\nu - 1) \tag{3}$$

where

δP_T = small increment of total percentage of trucks, and
ν = form of equivalence associated with the incrementally added trucks.

When the first increment of passenger cars is replaced by the increment of trucks, the equivalent flow is Q_{E1}.

$$Q_{E1} = Q[1 + (\delta P_T/100)(\nu - 1)] \tag{4}$$

Now, before the second increment of cars is replaced by trucks the traffic has characteristics associated with flow rate Q_{E1}, which is larger than Q. Consequently, the effective percentage of the second increment is $(Q/Q_{E1})\delta P_T$. After the second increment is added the equivalent flow is Q_{E2}.

$$Q_{E2} = Q[1 + (\delta P_T/100)(\nu - 1)(1 + Q/Q_{E1})] \tag{5}$$

We now recognize that the incremental change in Q_E is $Q_{E2} - Q_{E1}$, which can be written as

$$\delta Q_E = Q[(\delta P_T/100)(\nu - 1)(Q/Q_{E1})] \tag{6}$$

In the limit the incrementals δQ_E and δP_T become differentials, and equation 6 becomes a differential equation that integrates to

$$(Q_E/Q)^2 = 2(P_T/100)(\nu - 1) + \text{constant} \tag{7}$$

However, when $P_T = 0$, $(Q_E/Q) = 1.0$ so that the equation has the form

Figure 3. Vehicle equivalents depending on speed and percentage of impeding vehicle.

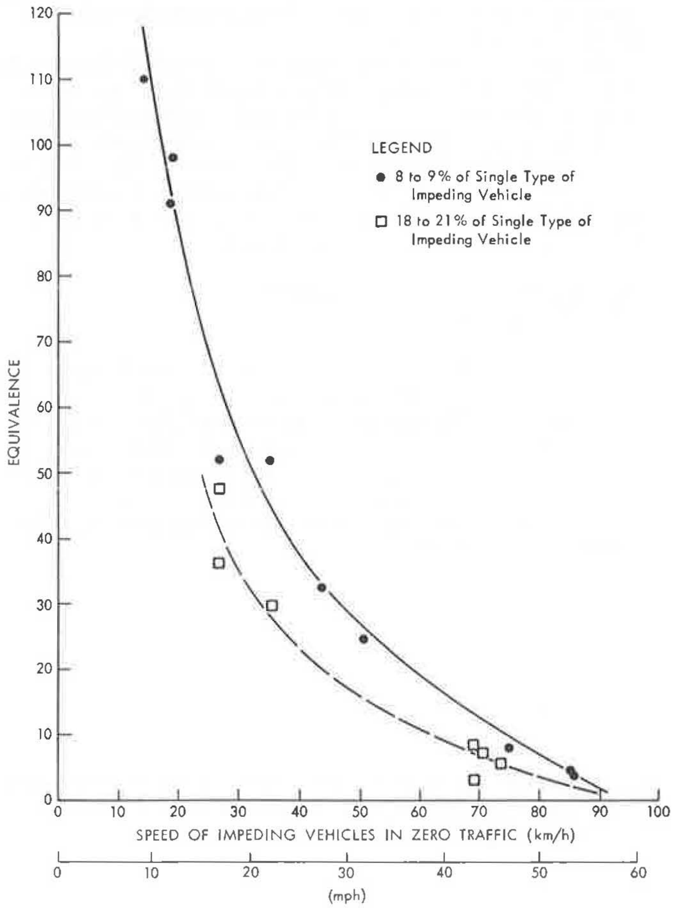
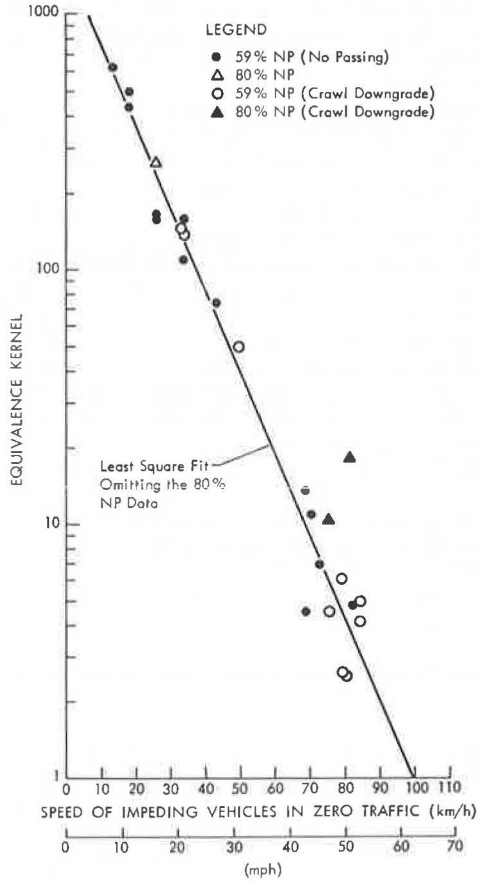


Figure 4. Equivalence kernel versus speed for a 105-km/h (65-mph) speed limit.



$$(Q_E/Q) = (2r + 1)^{1/2} \tag{8}$$

The truck factor becomes $1/(2r + 1)^{1/2}$ and, for the simple case of one impeding vehicle type,

$$r = (P_T/100)(\nu - 1) \tag{9}$$

where ν is defined as the equivalence kernel, a new term that means magnitude depends on the speed of the impeding vehicle type.

In the more general case of n types of impeding vehicles, r is obtained from

$$r = \sum_{i=1}^{n} (P_i/100)(\nu_i - 1) \tag{10}$$

where ν_i is the equivalence kernel for the i th type, which occurs with percentage P_i.

For a flow with only one type of impeding vehicle present at percentage P, the magnitude of the equivalence kernel is obtained from equation 8 as

$$\nu = (50/P)[(Q_E/Q)^2 - 1] + 1 \tag{11}$$

Equation 8 is a fundamental relation. As shown later this equation provides passenger vehicle flow rates that are the equivalents of mixed flows. The mixed flows can contain impeding vehicles in varying quantities and mixes. Equation 10 provides the format to assemble r for a mix of impeding vehicles. Equation 11 provides a format to evaluate ν for an impeding vehicle type when ν is the single impeding vehicle type in the mixed flow Q.

The ν (or the set of ν_i) are not equivalents; they are defined as equivalence kernels. That is, the kernels are assembled and subjected to a nonlinear process in equation 8 before equivalence in the usual sense is quantified.

The simulation results used to construct Figure 3 are used to calculate ν by equation 11. The results are shown in Figure 4. The variance around the least squares fit in Figure 4 does not depend systematically on percentage of impeding vehicles as in Figure 3. The fitted equation for equivalency kernels is

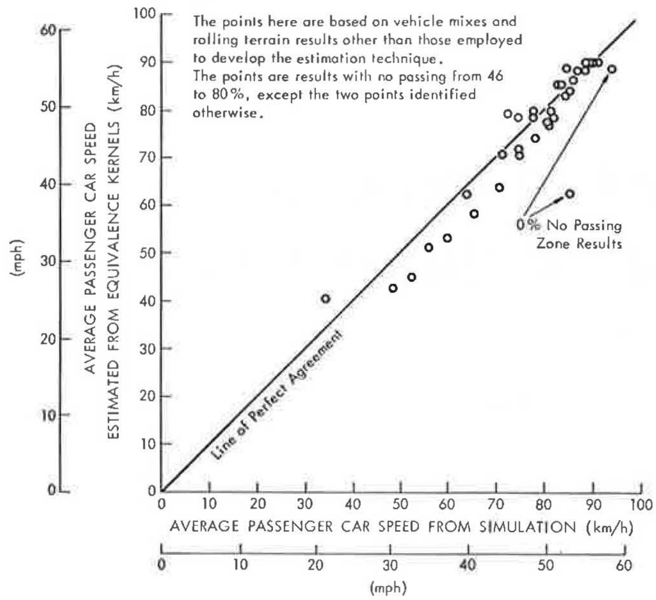
$$\nu = e^{(7.440436 - 0.0749846\ V)} \tag{12}$$

where V = impeding vehicle speed in kilometers per hour. Equation 12 is applicable for flows that are nearly balanced on highways where the percentage of no-passing is 46 to 80 percent and where the 85th percentile speed of passenger cars is about 105 km/h (65 mph) in light free-flowing traffic. The numerics in equation 12 should change for highways with different design speeds or speed limits and for highways with a percentage of no-passing outside the range 46 to 80 percent. With lower design speeds and limits, the intercept $\nu = 1$ should occur at a lower impeding-vehicle speed. With a smaller percentage of no-passing zones, ν should change less rapidly with V.

SUPPORT FOR THE NONLINEAR TRUCK FACTOR

Other results from the simulation have been used to further test the concept of an equivalence kernel and the associated equations. The additional test uses simulation

Figure 5. Comparison of estimated values and simulation results of mean speeds of passenger cars.



results in which there are a mix of impeding vehicle types, rather than a single type, and cases of rolling terrain as well as steady grades. The tests involve the ability to predict passenger car mean speeds (or equivalent passenger car flows) by using equations 10, 8, and 12 (Figure 4, then Figure 2). The procedure for prediction involves the following steps:

1. Estimate the mean speed of each impeding vehicle type over the terrain of interest by using the vehicle performance equations and the mean speed of light free-flowing traffic on sections with good geometrics as the speed desired;
2. Using the mean speed available for each impeding vehicle type, apply equation 12 or Figure 4 to obtain an equivalence kernel, ν_i, for each impeding vehicle type;
3. Apply equation 10 to obtain r;
4. Apply equation 5 to obtain the equivalent flow rate of passenger cars only; and
5. Enter Figure 2 and read passenger car mean speed versus Q_E (use the curve for the grade involved for long, steady upgrades and the curve for the 0 percent grade for long, steady downgrades, 2 percent grades, or rolling terrain).

The values calculated by using the above procedure are compared with simulation results in Figure 5. The agreement indicates that the estimation method provides useful results. However, there is a small systematic deviation that is not associated with grade, grade length, vehicle population, or the choice of 59 percent or 80 percent no-passing. The estimated speeds below 70 km/h (43 mph) are consistently low by 5 to 9 km/h (3 to 6 mph). However, this deviation should be considered in perspective. Similar tests employing the equivalents associated with the linear truck factor currently in use provide very high equivalent flows and correspondingly low estimates of mean speed when mixes of impeding vehicle types are used.

EQUIVALENCE KERNELS FOR USE IN THE NONLINEAR TRUCK FACTOR

Equivalence kernels are given in another report (2) for trucks and recreational vehicles in rolling terrain and on sustained grades. The values available are limited to the highway speeds and percentages of no-passing previously identified. There is a need to extend the results from the simulation model to other highway speeds and to a wider range of no-passing percentages.

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