# Capacity Evaluation of Two-Lane, Two-Way Highways by Simulation Modeling

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**A tool developed during the last four years, a microscopic Monte Carlo simulation model of a two-lane, two-way highway, was used to evaluate capacity more accurately. The model operates by processing individual vehicles traveling along a two-lane road where grades and no-passing zones can be specified. The performance of passenger vehicles and trucks is modeled in detail. The validity of the model is demonstrated by comparing specific simulated output to published data obtained under similar conditions. The model is applied in a comparison with the analysis procedures given in the Highway Capacity Manual for two-lane, two-way roads. Satisfactory agreement is obtained between the manual operating speed-volume to capacity ratio curve and a similar relation obtained from model runs. Poorer agreement is obtained between the manual truck equivalency factors for two-lane, two-way roads and similar factors derived from model runs. The conclusion is that the manual may overestimate the adverse effects of trucks on steeper grades. This paper should be of interest to practicing engineers because it introduces an important new tool for detailed evaluation of traffic operations on two-lane highways, and it provides evidence that revision is needed in two-lane highway analysis procedure in the Highway Capacity Manual.**

Chapter 10 of the 1965 Highway Capacity Manual (HCM) (1) presents methods for determining the effectiveness of operations on existing or proposed two-lane, two-way highways. This methodology, used for over 10 years, in many instances gives satisfactory, though conservative, results. Also the methodology is somewhat vague, and unsuitable for analyzing complex geometrics such as compound grades with irregularly intermixed passing and no-passing zones. Further, little information is provided regarding the microscopic aspects of the traffic flow. The methodology is based largely on the West Virginia study (2), dating from the 1950s, and so particular parameter values are proving to be out of date. Especially critical are the truck equivalency factors used by the HCM (1), based on performance tests of a single truck model conducted in the West Virginia study (2).

A recently developed Monte Carlo simulation model (3) of a two-lane road (SIMTOL) is used to assess questionable areas of previous studies. This model functions both as an aid in assessing generalized methodologies, as in chapter 10 of the HCM, and as a tool for the direct prediction of the operational effectiveness of roads with traffic characteristics or geometry too complex to be accurately assessed by using generalized techniques.

This paper presents the simulation model, validation results, and application in comparison with the HCM procedures for the analysis of two-lane highways. Particularly important are the conclusions regarding the need for improvement in the truck equivalency factors for two-lane roads presented in the manual.

## THE SIMTOL MODEL

The SIMTOL model considers cars and trucks. Cars are any vehicle with a low mass-to-power ratio, roughly 36.5 kg/W (60 lb/hp) or less. This includes standard passenger cars and most pickup trucks and vans. Recreational vehicles and cars heavily loaded for recreational uses (motor homes, campers, car-trailer combinations) are beyond the scope of the model. Trucks are commercial vehicles with high mass-to-power ratios and are subdivided into six classes as shown in Figure 5.3 of the HCM (1). Because of the lack of calibration data on trucks, the following report assumes that trucks do not pass. This limitation requires future research. Further, this report refers to both cars and trucks collectively as vehicles.

A number of additional assumptions have been made to limit the scope of the model to a tractable system. Only good-weather, daytime driving conditions are considered. Also, realistic applications of the model are limited to two-lane highways of fairly high design standards since speed reductions on horizontal curves are not modeled. Nor are speed reductions for comfort or caution on vertical curves modeled. Only one direction of traffic is explicitly simulated; in the other direction all simulated vehicles move at a constant speed, but with random headways. These two directions of traffic are referred to respectively as the primary direction and the opposing direction. This last assumption is not as surprising as it might seem. The two directions of traffic interact only through passing maneuvers. Studies

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of passing behavior by the Franklin Institute Research Laboratories (FIRL) (4) show that drivers considering a passing maneuver are primarily sensitive to the mean speed of opposing traffic, probably because these drivers cannot perceive the speed of an oncoming vehicle until it is quite close. In addition, considerable care has been taken to ensure that the user has the option of specifying a reasonably realistic headway distribution for the opposing lane. Project time, budget limitations, and computer efficiency considerations precluded the elimination of the above simplifying assumptions; such improvements are left for future research.

The model is based and calibrated to the extent possible on validated models of other authors (incorporated as submodels). However, in a few instances in which information is lacking, specific assumptions are necessary regarding the form of parameters for certain vital relationships. Budget limitations precluded a new data collection program within this project; the assumed relations appear adequate and have been held to a minimum.

In spite of the limitations described above the capabilities of the model are extensive. The path of each simulated vehicle is traced as it travels along the road. Each driver attempts to maintain a desired speed, but may be prevented from doing so by other drivers or by the limitations of the vehicle. Simulated cars, trapped behind slower vehicles, attempt passing maneuvers. These maneuvers may be successful or may be aborted. Decelerations of trucks on upgrades are modeled in detail by using an analytical submodel. Vehicle performance parameters and driver behavioral characteristics (such as desired speeds) are all quantified as appropriately distributed random variables.

An arbitrarily complex road geometry that satisfies the above assumptions can be specified by a user. For example, no-passing zones can be alternated with passing zones to reflect sight distance restrictions. Less restrictive sight distance limitations within passing zones can also be indicated. Up and down grades and compound grades can be specified. An arbitrary mix of cars and trucks can be specified; the trucks are further stratified into six classes. Thus, realistic configuration of present traffic on a present two-lane road can be simulated.

The entire section of road to be simulated is divided into adjacent but nonoverlapping units called subsections. Within these subsections all roadway characteristics are held constant. Sections of road with characteristics that change in some continuous manner (such as a vertical curve) can be approximated in the model by a series of adjacent, short subsections. Similarly, time is automatically divided by the model into fixed, short time increments of lengths ($\Delta t$). The size of these increments, typically 1 or 2 s, is selected by the user.

Simulated vehicles in both primary and opposing directions arrive at their respective entries to the road section with random headways. A probability theory (5, 6) may be applied to the distribution of these headways, or the headways can be exponentially distributed. A warm-up period and an optional warm-up level subsection for primary direction vehicles are included to eliminate transient effects.

## Structure

The model is organized through operating modes (3) as shown in Figure 1. During every time interval ($\Delta t$), every simulated vehicle is assumed to be traveling in one and only one operating mode. The model logic is constructed so that one mode never overlaps another. The following seven operating modes are defined in the model and collectively describe all possible operating conditions on the simulated road.

1. Desired speed is selected when the driver is unimpeded by his vehicle's performance or by other vehicles. Desired speeds follow separate normal distributions; parameters are specified by the user.
2. Car following is used when a driver decelerates to match speeds with a lead vehicle. Car following employs a log-normal distribution of car-following distance whose mean is a function of speed (7); the distribution is modified to allow for tailgating (3).
3. Performance limited is used primarily for drivers of simulated trucks unable to maintain desired speeds on or following upgrades. Performance characteristics of an individual simulated truck are determined by its mass-to-power ratio. This parameter is assumed to be distributed among the U.S. trucks as specified by the curves in Figure 3 of Wright and Tignor (9), reproduced as Figure 5.3 of the HCM. These curves show the distribution of mass-power ratios within various axle configurations; however, the specification of the percentages of trucks within these classes is specified by the SIMTOL user. The performance of each individual truck is simulated in detail in SIMTOL, using the model of Firey and Peterson (10).
4. Acceleration after pass enables the driver to attain the desired speed after completing a pass. Acceleration employed in this mode is a function of the acceleration employed during passing.
5. Deceleration after pass enables the driver to decelerate after completing a pass (coasting in gear with foot off the accelerator and without braking is the assumed behavior). Decelerations are quantified from data in Table 2.5 of the Traffic Engineering Handbook (11).
6. Flying pass and accelerative pass, modes 6 and 7 respectively, both use acceleration and depend on the randomized individual performance capabilities of the passing car. A flying pass is initiated at a speed greater than, or equal to, the passing driver's desired speed; an accelerative pass is initiated at a speed less than the driver's desired speed. Acceptance or rejection of each passing opportunity is determined by using gap acceptance curves developed from U.S. studies by FIRL (4) and Swedish studies by Ahman (12).

In commencing the simulation the time periods can be thought of as starting at time $t_b$, being incremented in units of $\Delta t$, and ending when $t_e$ is attained (i.e., $t = t_b$, $t_b + \Delta t, \ldots, t_e - 2\Delta t, t_e - \Delta t, t_e$). At each time scan point t the position of every vehicle on the road is updated. First, opposing vehicle positions are updated; then primary direction vehicle positions are updated, a more complex task because speeds and modes are included. Primary direction vehicles are processed from downstream to upstream, so that the actions of following vehicles can be simulated based on the actions of lead vehicles. The actions of every primary direction vehicle are analyzed at every time scan point t by the logic of the mode-to-mode matrix shown in Figure 1. Given the mode that resulted at the vehicle's previous time scan point $t - \Delta t$, only specified new modes are possible. These new possibilities are given by the matrix. Each cell containing an asterisk designates a possible mode-to-mode transition; blank cells represent impossible transitions. This routine must be recalled if the vehicle being processed has entered a new subsection at some time during the interval ($t - \Delta t$, t), to take account of the effects of possibly different subsection geometric characteristics. After every vehicle has been processed, the exit point of the road is checked

for the removal of vehicles from the system. If needed, new vehicle arrivals are generated and entered down the road. The entire process is repeated until the simulation clock reaches $t_e$.

## Computerization

The model has been programmed in FORTRAN IV for a digital computer and has been run on a CDC 6400. Computer running time is variable, depending on many parameters, especially the expected number of vehicles to be simulated. An example run for 4.8 km (3 miles) of road, including a 1.61-km (1-mile) warm-up subsection and a grade, took 30 s of computer time to amass a 200-vehicle sample. The simple program form consists of three sequential blocks: input-initialization, simulation, and output. The input for a single simulation run consists of only a few (usually 10 to 20) cards. The required input data can be divided into three categories: traffic parameters, roadway parameters, and run parameters. The traffic parameters specify arrival distributions, expected flow for the primary and opposing directions, expected percentage of trucks and distribution of trucks within the subclasses, and desired speed distributions. The roadway parameters primarily specify length, steepness of grades, passing and no-passing zones, and sight distances. The run parameters specify timing and accounting details such as period of time to be simulated, time increment $\Delta t$, random number seed, and various output control options. The basic model output is a prediction of the highway performance in terms of such variables as travel times and travel speeds, spot speeds and time headways at specified observation stations along the road, and platooning. An optional binary tape containing detailed simulated microscopic data can be requested. In addition, histograms can be drawn on the printer showing the observed density functions of most output random variables (Figure 2), and a time-space diagram graphically showing individual vehicle trajectories can be drawn. (Since this model was designed for customary units only, values in this and other figures are not given in SI units.)

Figure 1. SIMTOL mode-to-mode matrix.

| From Mode \ To Mode | | Name | Desired Speed | Car Following | Performance Ltd. | Acceleration after pass | Deceleration after pass | Flying pass | Accelerating pass |
|---|---|---|---|---|---|---|---|---|---|
| Name | No. | No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Desired Speed | 1 | | * | * | *[a] | | | *[b] | |
| Car Following | 2 | | *[c] | * | * | | | | * |
| Performance, Ltd. | 3 | | * | * | * | | | | |
| Acceleration after pass | 4 | | * | * | *[d] | * | | | *[b] |
| Deceleration after pass | 5 | | * | * | *[a] | | * | * | |
| Flying pass | 6 | | | * | *[e] | | * | *[b] | |
| Accelerating pass | 7 | | * | * | *[e] | * | * | * | * |

Dashed lines denote submatrices used in processing. * in cell indicates a possible transition; blank cells represent impossible transitions.

Notes:

a. Can only occur at the time a new subsection is entered, since grade changes only occur at subsection boundaries.

b. Can only occur when the transition from Modes 1, 4, or 5 to Mode 2 will occur if the passing opportunity is not accepted.

c. Can occur if lead vehicles accelerates to a speed greater than the follower's desired speed.

d. Can occur at the time a new subsection is entered, and rarely, when passed vehicle's speed < passer's crawl speed < passer's desired speed.

e. Can occur only at the entry to a new subsection and causes the pass to be immediately aborted.

f. Very rare; probability for such a transition virtually zero.

## VALIDATION OF THE MODEL

Component validation assessed the realism of separate subparts; system validation assessed the realism of the subparts working in coordination with one another.

### Component Validation

Component validation, done during formative stages of model development, resulted in early changes for realism. For example, during early development of the passing submodel, simulated passing times were excessive compared to FIRL data (4). Therefore pre-pass tailgating was incorporated into the car-following submodel, and acceptable simulated passing times were achieved (3).

One of the more important component validations performed on SIMTOL was of the truck performance submodel, Firey and Peterson's model (10) with randomly distributed mass-power ratios from Wright and Tignor (9). The comparative actual human behavior data were obtained from the published results of a study by Williston (13). Williston used a radar meter to sample the speeds of trucks unimpeded by other traffic on four-lane Connecticut highways. Although the highway used in SIMTOL is two-lane, comparison was felt to be acceptable because only unimpeded trucks, unaffected by their surrounding traffic environment, were considered. The comparative SIMTOL runs simulated only unimpeded trucks. Figure 3 shows the comparison of the simulated and observed data for tractor-trailer trucks at Williston's study site 3 (13). The agreement is very close. For the faster single-unit trucks, the modeled speeds are somewhat higher, to about 13 km/h (8 mph), than the corresponding speeds observed by Williston. However, this discrepancy seems to be largely attributable to one or two sources of bias caused by Williston's data collection technique. Sampling only unimpeded trucks introduces a negative or downward bias into the sample because lighter (faster) trucks, which are more likely to be impeded by other traffic, are underrepresented. A negative bias could also occur if the radar meter were obvious to the passing drivers, again probably affecting the faster trucks most. In both cases, the biases would cause the speeds of the faster trucks to be depressed, precisely the behavior observed. Similar comparison runs were also made for Williston's other study sites, again with acceptable results (3). Therefore, the SIMTOL truck submodel has been accepted as performing in a realistic manner.

### System Validation

System validation runs were made against five of the six speed distribution curves shown in Figure 3.28 of the HCM (1), which represent typical behavior at various flow levels for a two-lane, two-way highway under ideal conditions (level, no trucks, good sight distances). The manual does not specify whether these speed distributions were taken over space or time, so for convenience they were assumed to be taken over time, enabling their comparison to spot speeds output by SIMTOL. A normal

approximation to the speed of 200 vehicles/h [mean 88.5 km/h (55 mph), standard deviation 14.5 km/h (9 mph)] was used as the desired speed distribution for all flow levels within the simulation. The comparative SIMTOL spot speed distributions were taken 6.4 km (4 miles) from the entry point of the simulated road to ensure the elimination of transient effects. Arrivals in both simulated directions were exponentially distributed; the expected traffic flows were split equally between the directions. Of course, the SIMTOL runs were made for the same ideal conditions. The results of these runs are shown in Figure 4. The agreement between the observed (presumably smoothed) and simulated spot speed distributions is very close. For all five simulation runs, the time mean speeds also all agree with the means of the observed curves to within a 3-km/h (2-mph) range. The simulated distributions evidence an increasingly discrete nature with increasing flow level because most vehicles are platooned for high flow levels and all vehicles within a platoon are traveling at nearly the same speed. Therefore, the 1700-vehicles/h curve is a sampling of only about eight platoons. The simulation sample sizes were based on the criterion that at least eight platoons be sampled, but that the sample size never be fewer than 100 vehicles. This criterion dictated expected sample sizes of 100 vehicles for flow levels of 200 to 1400 vehicles/h and 200 vehicles for flow levels of 1700 vehicles/h. The criterion was compulsory be-

Figure 2. Sample spot speed histogram output from SIMTOL.

```
SPOT SPEED MEASUREMENTS AT STATION 1,
   BETWEEN SUBSECTIONS  0 AND  1 AT  X = 0.0FT

   RANGE      NUM.
    MPH       OBS.
                      ++++++++++++++++++++++++
   41.-  42.     0  +
   42.-  43.     2  +**
   43.-  44.     2  +**
   44.-  45.     0  +
   45.-  46.     2  +**
   46.-  47.     1  +*
   47.-  48.     2  +**
   48.-  49.     2  +**
   49.-  50.     7  +*******
   50.-  51.     3  +***
   51.-  52.    10  +**********
   52.-  53.    11  +***********
   53.-  54.    11  +***********
   54.-  55.    17  +*****************
   55.-  56.     5  +*****
   56.-  57.    10  +**********
   57.-  58.     5  +*****
   58.-  59.     4  +****
   59.-  60.     3  +***
   60.-  61.     5  +*****
   61.-  62.     3  +***
   62.-  63.     2  +**
   63.-  64.     0  +
   64.-  65.     2  +**
   65.-  66.     1  +*
   66.-  67.     0  +
   67.-  68.     0  +
   68.-  69.     1  +*
   69.-  70.     0  +
   70.-  71.     1  +*
   71.-  72.     0  +
   72.-  73.     0  +
   73.-  74.     0  +
   74.-  75.     1  +*
   75.-  76.     0  +

MEAN SPEED          =   54.560      MPH
EST. STD. DEV.      =    5.282      MPH

  CARS              =   104.
  TRUCKS            =     9.
                      -----
  N (TOTAL)         =   113.
```

Figure 3. Observed versus simulated speeds for tractor-trailer trucks.

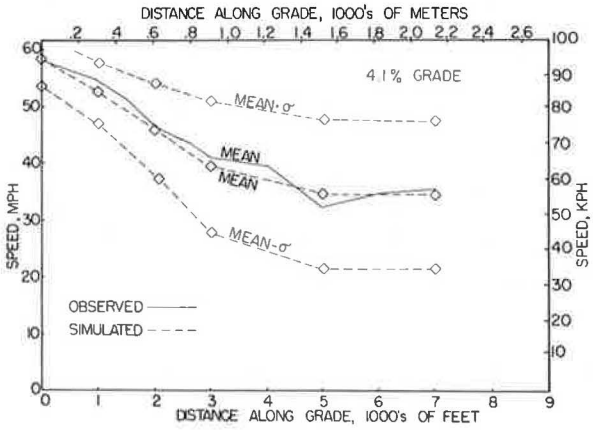



Figure 4. Simulated versus capacity manual speed distributions.

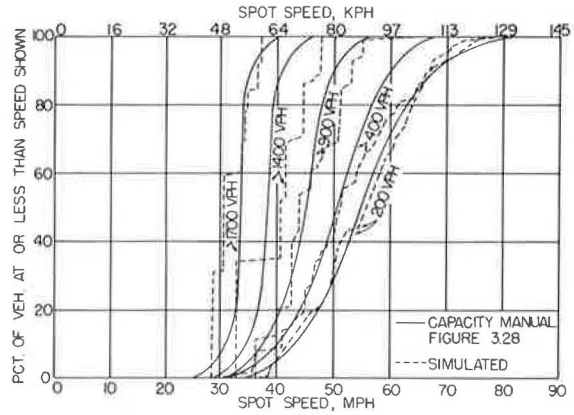



Figure 5. Simulated versus observed travel speed distributions on Ca-37.

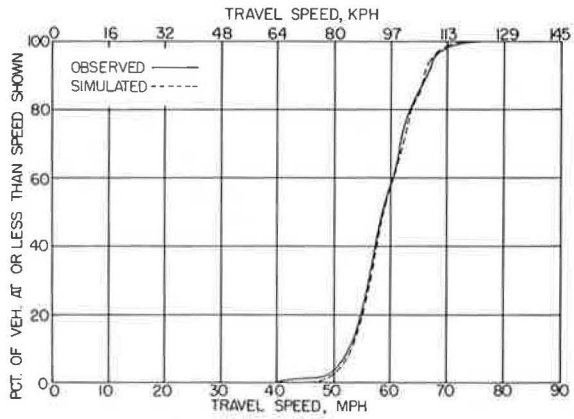
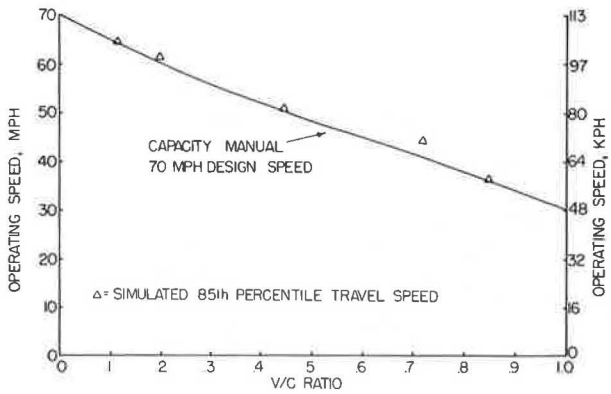



Figure 6. Operating speed versus v/c ratio.



cause the limited project budget kept the acceptable sample size to a minimum. Nonetheless, comparison to the HCM is still valid, especially in view of the overall similarity of results to the set of distributions in Figure 4 and the agreement in mean speeds.

Additional system validation runs were made for the above HCM curves by using Schuhl (5) headways for the opposing traffic. These results agreed nearly as well. Data were also obtained for a two-lane California highway (Ca-37) west of Vallejo. When comparative SIMTOL runs were made for the specific configuration of Ca-37, a satisfactory comparison was again obtained (3), as shown in Figure 5. As a result of all validations, SIMTOL is believed to yield realistic results and can indeed be a useful tool in assessing the operations of two-lane, two-way roads.

## APPLICATION TO THE HCM

Next an evaluation was conducted of the accuracy of the methodology presented in the HCM for two-lane highways. Because budget limitations prevented simulation runs of large sample sizes, the following analyses do not yield accurate new quantitative values but emphasize obtaining approximate estimates of certain variables used in the manual. The overall behavior of the variables can then be compared with the HCM and areas for further research and possible revision pointed out.

The basic equation given by the HCM for the analysis of two-lane highways is

$$SV = 2000\ (v/c)\ W_L T_L \qquad (1)$$

where

SV = service volume in mixed vehicles per hour,
v/c = volume to capacity ratio,
$W_L$ = width adjustment factor, and
$T_L$ = truck adjustment factor.

Since SIMTOL is not specifically concerned with lane width (lane width is reflected only through the desired speed distributions input by the user), this analysis considers only situations of adequate width. Therefore, $W_L$ has been set to 1.0, and, since SIMTOL assumes a modern alignment, all comparisons have been based on the 130-km/h (70-mph) design speed curves in Figure 10.2a of the HCM. Thus, only the v/c ratio and $T_L$ terms are examined in the next two sections.

### Basic Equation Under Ideal Conditions

This section considers equation 1 under ideal conditions, that is, with no trucks and passing sight distance everywhere in excess of 457 m (1500 ft). Therefore, the truck adjustment factor $T_L$ is set to 1.0, and equation 1 simplifies to

$$SV = 2000\ (v/c) \qquad (2)$$

The limiting value of v/c for each level of service is given in Table 10.7 of the HCM as a function of a number of variables, mainly, operating speed—the primary measure of the level of service in the manual. The limits for the v/c ratio given in Table 10.7 were determined directly from the four-curve families of Figure 10.2 of the manual. The accuracy of these curves is therefore central to the methodology for the capacity analysis of two-lane highways.

SIMTOL operating speed might be considered as the average realized travel speed of that group of vehicles whose desired speed is within 3 to 5 km/h (2 to 3 mph) of the design speed. Unfortunately, SIMTOL does not use the design speed as an input; rather design speed enters the model only through the choice of the desired speed distribution. Instead, the 85th percentile overall travel speed obtained from the simulation is used as a substitute for operating speed. Although operating speed and 85th percentile travel speed are not quite the same, the comparison is acceptable because of the agreement of the 85th percentile speeds in Figure 3.28 of the HCM (reproduced in part in Figure 4) with the operating speed for a 130-km/h (70-mph) design speed shown in Figure 10.2a of the manual (Figure 6). The 85th percentile travel speeds obtained from the SIMTOL runs for ideal conditions used for Figure 4 are also portrayed in Figure 6, and since the correspondence between the curves in Figure 4 is close, the correspondence in Figure 6 is also close. Thus, the 85th percentile travel speed obtained from SIMTOL corresponds closely to the operating speed used in the manual; therefore the modeled results and the manual are in close agreement under ideal conditions.

### Basic Equation Under Truck Grade Conditions

On upgrades trucks decelerate, adversely affecting other traffic. When this is quantified, a wide range of parameters must be considered, including grade steepness and length, percentage of trucks, mix of truck types, traffic flow, and split of the flow between the directions.

The HCM quantifies the effect of trucks by using the truck adjustment factor $T_L$ identified in equation 1. However, $W_L$ has already been assumed to be 1.0; therefore, equation 1 reduces to

$$SV = 2000\ (v/c)\ T_L \qquad (3)$$

The factor $T_L$ is in turn based on the passenger car equivalent, $E_T$, for a truck and the percentage of trucks in the stream. $E_T$ is the number of passenger cars one truck is supposed to equal. In the HCM, $E_T$ is a variable dependent on steepness and length of grade and flow (i.e., level of service). $E_T$ is specifically assumed to be independent of the percentage of trucks on the highway and is also generally assumed to be independent of the split of flow between directions. The values for this factor are based on the deceleration profiles of the one supposedly average 1950 model truck tested in the West Virginia study (2, Figure 8, which was reproduced as Figure 5.1 in the HCM). The equivalency factor values given by the manual were calculated by using the relative number of passings that would occur per kilometer (mile) of highway if each vehicle continued at its normal speed for the conditions under study. This definition is rather vague, giving no details of actual quantitative meaning, although a study by Werner (14) belatedly gives some details of the computational methodology employed. Since the adverse effects of trucks are quantified in terms of $E_T$, this section investigates $E_T$ for several parameter combinations.

Twenty-four simulation runs were made for all combinations at all levels of the following four parameters:

1. Grades of 2, 4, and 6 percent;
2. Grade lengths of 1.9 and 5.6 km (1 and 3 miles);
3. Expected proportion of trucks of 10 and 20 percent; and
4. Expected mixed vehicle flow of 250 and 1000 vehicles/h.

An expected sample size of 200 primary direction vehicles was used in each run, as dictated by budget limitations. This in turn precluded analyzing situations

with less than 10 percent trucks; the expected sample size of 20 trucks for this case was considered an absolute minimum for accuracy. The directional distribution of flows was equal. As previously mentioned, the 85th percentile overall travel speed obtained from the simulation was used in place of operating speed. The HCM is not exact in its definition of the length of road to which the adverse characteristics of truck-grade conditions are assumed to apply. For example, do the analysis procedures allow for the length of road required by trucks for acceleration following the top of the grade? In the present study, the travel speeds were calculated between the bottom of the grade and three points on the crest vertical curve (assuming a level road downstream of the grade):

1. The vertical point of curvature (VPC),
2. The point on the highway directly below the vertical point of intersection (VPI), and
3. The vertical point of tangency (VPT).

The points that gave the lowest 85th percentile travel speed were used in each case analyzed. In all runs a level warm-up subsection appropriate for the elimination of transient effects was used. After the warm-up subsection came the 1.6-km (1-mile) or 4.8-km (3-mile) grade as appropriate, followed by a 1.6-km (1-mile) level subsection to permit trucks to accelerate. The vertical geometrics of the simulated highways were selected according to American Association of State Highway Officials (AASHO) practices (15); this policy dictated the length of the no-passing zone at the top of each grade

Figure 7. Relation between capacity manual predicted v/c ratio and operating speed under truck-grade conditions.

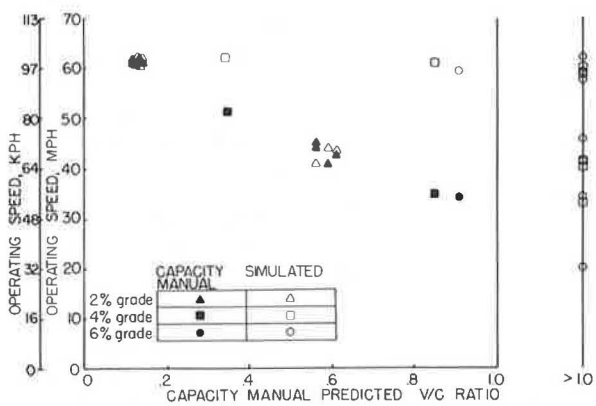
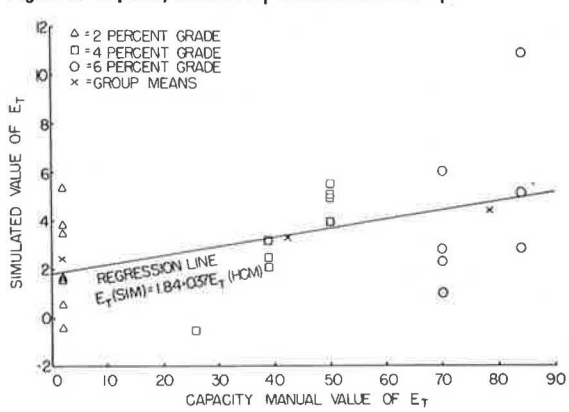



Figure 8. Capacity manual $E_T$ versus simulated $E_T$.




and the overall sight distance. The horizontal geometry was assumed to be linear. The number of trucks used for these runs used an average distribution of types obtained from Figure II-10 of the AASHO policy (15).

These simulation results were compared with those shown in the HCM (Figure 10.2a), previously found to agree with the simulation under ideal conditions. Under truck-grade conditions, the HCM methodology inflates the actual flow of mixed vehicles to an equivalent flow, consisting of cars only, giving the same operating speed as the mixed flow. The v/c ratio corresponding to this inflated flow is found by solving equation 3, obtaining

$$v/c = SV/2000\ T_L \tag{4}$$

Thus, the relation between the operating speed and the v/c ratio still falls on the upper limb curves in Figure 10.2a of the manual. The 24 points on these curves corresponding to the various parameter combinations were calculated by using the FREHIS program (16), a strict computerization of chapters 9 and 10 of the HCM. The operating speed predicted by the manual was then simply read from Figure 10.2a by using the curve for the appropriate sight distance as restricted by the visibility over the crest. These points (for the cases in which the capacity was predicted not to be exceeded) are plotted in Figure 7. In addition, for each simulation run corresponding to a particular set of truck-grade parameters, one can use the manual's predicted v/c ratio (for the specified set of parameters) and the simulated 85th percentile travel speed as operating speed to locate a second point on the v/c-operating speed plane. If the simulation and the manual are in agreement, then this second set of points should also fall approximately on the curves of Figure 10.2a. This procedure has been followed in plotting the simulated points shown in Figure 7. Thus 24 comparisons are shown in Figure 7. For those cases in which the manual predicts congestion by yielding calculated v/c ratios in excess of 1.0, the operating speed, other than when the prediction is to be less than 56 km/h (30 mph), cannot be determined from Figure 10.2a. Therefore, only the simulated speeds are indicated for such cases, on a vertical line to the right of the graph. As is evident in Figure 7, except for the eight cases on the 2 percent grade where the agreement is close, the simulated results do not agree with the manual predictions. In fact, although the manual predicts congestion in 13 of the 16 cases for the 4 and 6 percent grades, the simulation predicts congestion for only one case.

In explaining the reasons for the discrepancy between the manual and simulation predictions, the truck equivalency factors $E_T$ predicted by the model must first be determined and compared with the equivalency factors used in the manual. Therefore equation 3 for $T_L$ is solved, yielding

$$T_L = SV/[2000\ (v/c)] \tag{5}$$

A new v/c ratio can be determined by entering Figure 10.2a with the operating (i.e., 85th percentile) speed observed in the simulation, and then reading v/c from the appropriate curve. SV is the expected flow of 250 or 1000 vehicles/h. Finally, the equivalency factor $E_T$ can be found from $T_L$ by using the relation given in the footnote of Table 10.12 of the manual. This procedure has been followed to obtain values for $E_T$ for 23 of the 24 runs for which the simulated operating (85th percentile) speed was in excess of 56 km/h (30 mph). This method does not yield a solution for the one point for which the simulated operating speed is less than 56 km/h (30 mph). Thus, the 23 resulting simulated values for $E_T$ are shown in Figure 8, plotted against the corresponding values

from the manual. Although there is an ample amount of scatter in the simulated values of $E_T$, the group means and the regression line through the 23 points give an approximate idea of the comparison between the simulated and manual values for $E_T$. As can be seen, the simulated truck equivalency factors for the 2 percent guide are in general agreement with those in the manual. However, the simulated equivalency factors for the 4 and 6 percent grades are a whole order of magnitude less than those in the manual.

This discrepancy in the quantification of the effects of trucks can be ascribed to several causes. First, the truck decelerations on grades from the West Virginia study (2) used in Figure 5.1a of the HCM do not agree with those predicted by the Firey and Peterson model used in SIMTOL for the same 197.6-kg/W (325-lb/hp) mass-power ratio. For example, the Firey and Peterson model predicts a crawl speed of 70 km/h (38 mph) on a 2 percent grade, while Figure 5.1a gives a crawl speed of 41 km/h (22 mph). Similar results apply throughout the entire range of steeper grades; for a 6 percent grade, the values are respectively 13 and 26 km/h (8 and 16 mph). While the curves of Figure 5.1a have been obtained from the actual measurement of a test truck, the Firey and Peterson model has also been satisfactorily validated, first by the original authors (10 and 17) and later as a submodel in SIMTOL (3), as shown in Figure 3 in this paper. Because the Firey and Peterson model in SIMTOL is confirmed by more extensive field experimentation and validation, SIMTOL is being relied on; nonetheless, further investigation is required.

Second, the decision taken in the West Virginia study to consider a mass-power ratio of 197.6 kg/W (325 lb/hp) is questionable in light of present data. This value exceeds the median mass-power ratio for every truck class given in Figure 3 of Wright and Tignor (9) (Figure 5.3 of the HCM). Indeed, this value exceeds the maximum mass-power ratio for four of the six truck classes of that figure. While the selection of 197.6 kg/W (325 lb/hp) may be defended on the basis of conservatism, in the light of Wright and Tignor's work 197.6 kg/W (325 lb/hp) may be overly conservative for today's trucks. Work needs to be undertaken to obtain the current distribution of the mass-power ratio in the truck population.

There are two lesser reasons for the discrepancy. One is the vagueness of some portions of the HCM, particularly in the calculation of the truck equivalency factors; the computational methodology employed in this paper largely overcomes this difficulty. Vagueness also exists in the manual's definitions of operating speed and length of grade; the assumptions employed for this project have already been discussed and are not felt to play a significant role in the discrepancy of results. Finally, the noise in the simulated output, while certainly causing some random error, is not sufficiently great to account for the discrepancy. Not even the greatest extremities in Figure 8 approach the values used in the manual for the 4 and 6 percent grades; therefore the true expectation for these simulated points is far from the corresponding values given by the manual. More extensive simulation runs should be performed for the above as well as additional parameter combinations to more thoroughly quantify the adverse effects of trucks on grades.

The present method used by the HCM to quantify the adverse effects of trucks on two-lane, two-way highway grades overestimates the detriment of trucks to the traffic flow. Because this error is not great the conclusions should not result in any underdesigns. However, now when highway funding is dwindling, overdesign of highways must also be avoided. Therefore, the manual must be capable of reasonably predicting the actual traffic operations expected on a road. This study attempts not to offer revised truck equivalency factors for the manual but to point out some possible problems in the present factors so that these might be identified as a future research need.

## CONCLUSIONS

This study should be of interest for two reasons. It introduces a useful new modeling tool, SIMTOL, for the evaluation of two-lane, two-way highways, and it brings attention to an area of the two-lane analysis procedure of the HCM that needs to be updated.

The model satisfactorily replicated actual human behavior in a series of validation runs. The model was applied to capacity studies of two-lane, two-way roads. Close agreement was evidenced between the model and the manual under ideal conditions, but the model predicts better traffic operations under truck-grade conditions than does the manual. This discrepancy is ascribed to several possible causes and emphasizes a need for revision of the effects of trucks as quantified in the manual.

Future work should investigate this weak area of the HCM addressed in the preliminary research presented here. Both modeling and empirical work need to be conducted. A particular need exists to expand the experimental design used here in the truck equivalency factor runs and to use larger simulation sample sizes and multiple realizations for each run.

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