Effect of Trucks, Buses, and Recreational Vehicles on Freeway Capacity and Service Volume

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As part of a project sponsored by the Federal Highway Administration to revise and update Chapters 7, 8, and 9 of the 1965 Highway Capacity Manual, truck equivalents for specific grades have been recalibrated. The recalibration is based primarily on the results of freeway simulations conducted at Midwest Research Institute and studies of truck weight-to-power ratios and operating characteristics conducted at Pennsylvania State University. Approximate equivalents have also been developed for recreational vehicles, which form a significant portion of the traffic stream in selected areas.

The effect of trucks and buses on freeway flow is treated in the 1965 Highway Capacity Manual (HCM) (1) through the application of multiplicative correction factors to service volumes under ideal conditions drawn from Table 9.1 of the manual. The factors are based on automobile equivalents E_t or E_B, which represent the number of automobiles equivalent to one truck or bus under specified traffic and roadway conditions. Equivalents were calibrated by using a method developed for two-lane, two-way highways by Powell Walker. The manual (1), which uses the Walker method, states that

> for multilane highways, truck adjustment procedures are somewhat less well-defined, because the quantitative effect of trucks on the capacity of multilane highways for sustained grades is not as well known as it is for two-lane highways.

Multilane factors were eventually derived by manipulating the results of the California studies given in Chapter 5 of the HCM.

Since the publication of the 1965 HCM, a number of studies have been done on the effect of trucks on freeway flows, and others are in progress:

1. Simulation studies conducted by Midwest Research Institute (MRI) on the effect of trucks on freeway flow (2);
2. A study of the weight-to-power ratios of modern trucks and their operating characteristics conducted at Pennsylvania State University (3);
3. A study similar to the Pennsylvania State University work conducted in 1965 by Wright and Tignor (4);
4. The work of Werner and others on recreational vehicle and truck effects, primarily on two-lane highways (5); and
5. Unpublished studies of truck crawl speeds conducted by Rooney and Ching of the California Department of Transportation (DOT).

Under the sponsorship of the Federal Highway Administration (FHWA), we undertook to develop revised truck equivalents as well as similar equivalents for recreational vehicles. This paper presents the results of this work, which is based primarily on the results of the MRI and Pennsylvania State University studies mentioned above.

TRUCKS

MRI Simulations

A detailed simulation model of multilane highway flow that was developed and applied in a previous MRI contract was improved in a series of adjustments so that it duplicates the characteristics of mixed flows in level terrain and on grades. This model was adjusted and then validated by comparison with data collected on selected highway sites in California. Simulation results duplicate the important influences of grade, vehicle population, and flow rate for available cases.

The data collected for adjustment of the simulation model were taken at high flow rates on a 4 to 6 percent grade. In addition, data were collected on 2 percent grades. The parameters used in the simulation model included flow rate, distribution to lane by vehicle type, spot speeds, lane-changing frequencies, vehicle population, and overall travel speeds.

The simulation produces operating speed versus percentage capacity (V/C ratio) relations that would be observed in real traffic. Design charts were constructed by combining and interpreting the results from numerous simulation runs. The operating speed-percentage capacity relations were used to obtain an "implied capacity" for each simulation point (implied capacity is used because an actual test to obtain capacities has not been made at each location):

$$\text{Implied capacity} = \text{simulation flow rate} \div (\text{percentage capacity}/100) \quad (1)$$

The combination of simulation runs is used to define implied capacity as a function of grade and percentage of commercial vehicles.

The resulting values of implied capacity are considerably higher than any capacities observed to date—some as high as 2600-2800 vehicles/h/lane. The simulations, however, were based on 3-min flows so that the implied capacities represent maximum 3-min flow rates, not full-hour volumes. Nevertheless, the variance of these numbers from generally accepted figures is a cause of some concern.

Design information includes the following parameters: number of lanes, design speed, grade, total flow rate, percentage of trucks, implied capacity, service level, operating speed, and percentage of implied capacity. All of these factors can be examined by using a family of design charts. Figure 1 is an example of a typical design chart for a four-lane freeway with a 112-km/h (70-mph) design speed based on typical automobile and truck populations.

The Typical Truck

There is some question as to what the deceleration and acceleration characteristics of the typical truck are on

Figure 1. Implied capacities versus percentage of trucks and sustained grade (two lanes, 112-km/h design speed).

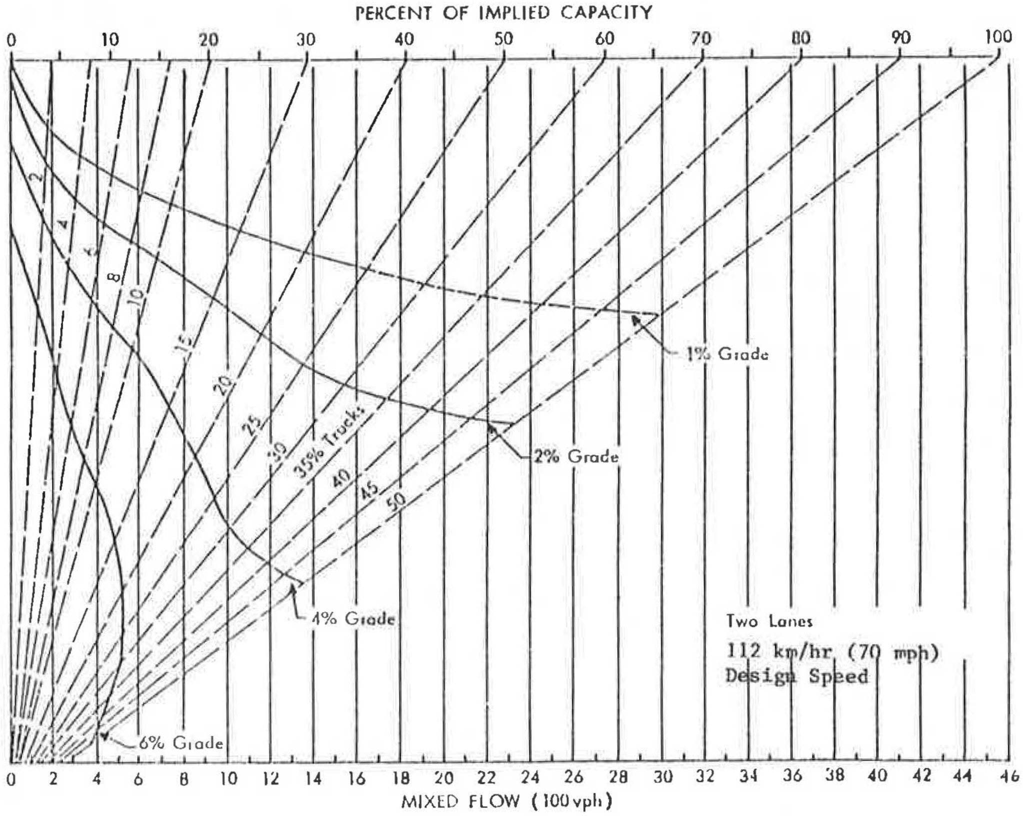


Table 1. Automobile equivalents for trucks on upgrades.

Grade (%)	Length (m)	E_t Percentage Trucks on Four-Lane Freeways 2	4	6	8	10	15	20	E_t Percentage Trucks on Six- or Eight-Lane Freeways 2	4	6	8	10	15	20
0	All	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1	0-400	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	400-800	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	800-1200	4	4	4	3	3	3	3	4	4	3	3	3	3	3
	1200-1600	5	4	4	3	3	3	3	5	4	4	3	3	3	3
	1600-2400	6	5	5	4	4	4	3	6	5	4	4	4	3	3
	>2400	7	5	5	4	4	4	3	7	5	5	4	4	3	3
2	0-400	4	4	3	3	3	3	3	4	4	3	3	3	3	3
	400-800	7	5	5	4	4	4	4	7	5	5	4	4	4	4
	800-1200	8	6	5	5	4	4	4	8	6	5	5	4	4	4
	1200-1600	8	6	6	5	5	5	5	8	6	6	5	5	5	5
	1600-2400	9	7	7	6	6	5	5	9	7	6	5	5	5	5
	>2400	10	7	7	6	6	5	5	10	7	6	5	5	5	5
3	0-400	6	5	5	4	4	4	3	6	5	5	4	4	4	3
	400-800	9	7	6	5	5	5	5	8	7	6	5	5	5	5
	800-1200	12	8	7	6	6	6	6	10	8	6	5	5	5	5
	1200-1600	13	9	8	7	7	7	7	11	8	7	6	6	6	6
	>1600	14	10	9	8	8	7	7	12	9	8	7	7	7	7
4	0-400	7	5	5	4	4	4	4	7	6	5	4	4	3	3
	400-800	12	8	7	6	6	6	6	10	8	6	5	5	5	5
	800-1200	13	9	8	7	7	7	7	11	9	8	7	6	6	6
	1200-1600	15	10	9	8	8	8	8	12	10	9	8	7	7	7
	>1600	17	12	11	9	9	9	9	13	10	9	8	8	8	8
5	0-400	8	6	6	5	5	5	5	8	7	6	5	5	5	5
	400-800	13	9	8	7	7	7	7	11	8	7	6	6	6	6
	800-1600	20	15	14	11	11	11	11	14	11	10	9	9	9	9
	>1200	22	17	16	13	13	13	13	17	14	13	12	11	11	11
6	0-400	9	7	7	6	6	6	6	10	7	6	5	5	5	5
	400-800	17	12	11	9	9	9	9	13	10	9	8	8	8	8
	>800	28	22	21	18	18	18	18	20	17	16	15	14	14	14

Notes: 1 m = 3,3 ft.
Longest length category indicates equivalency at crawl speed.

modern multilane freeways, particularly with respect to those characteristics assumed in the MRI work.

Several different parameters determine the performance characteristics of motor vehicles. The most significant of these is the weight-to-power ratio. To determine the weight-to-power ratio of the typical truck, a search of the existing literature was undertaken. The following results were obtained:

1. A study conducted at Pennsylvania State University for NCHRP (3) used a 183-kg/kW (300-lb/hp) vehicle as their typical truck. This figure is based on information received from truck manufacturers and the operator of a major truck fleet.
2. The MRI study used for the generation of truck equivalents (2) uses a truck population with an average weight-to-power ratio of 138 kg/kW (225 lb/hp). A.D. St. John, one of the principal MRI researchers on this study, has indicated that the data collected in the study may not represent the typical situation on the nation's freeways and that the average truck probably has a higher weight-to-power ratio.
3. An MRI study of grade effects on traffic-flow stability and capacity (6) has indicated a population of trucks on grades with a typical vehicle of 183 kg/kW (48 percent of truck traffic on primary routes).

On the basis of this information, the 183-kg/kW vehicle was selected as the typical truck on which to base the generation of truck equivalents. Note that, as indicated in the Pennsylvania State University work, the crawl speeds of 183-kg/kW vehicles on grades are similar to those of 122-kg/kW (200-lb/hp) vehicles on multilane highways given in the 1965 HCM (1).

Since the MRI design charts were designed by using a concept called "percentage reference trucks", they can be used to generate truck factors for the 183-kg/kW (300-lb/hp) vehicle even though they were calibrated for MRI's typical truck population.

The concept of percentage reference trucks allows for the adjustment of any truck population to a common or reference base that can be used with the design charts. The relationship for this concept is

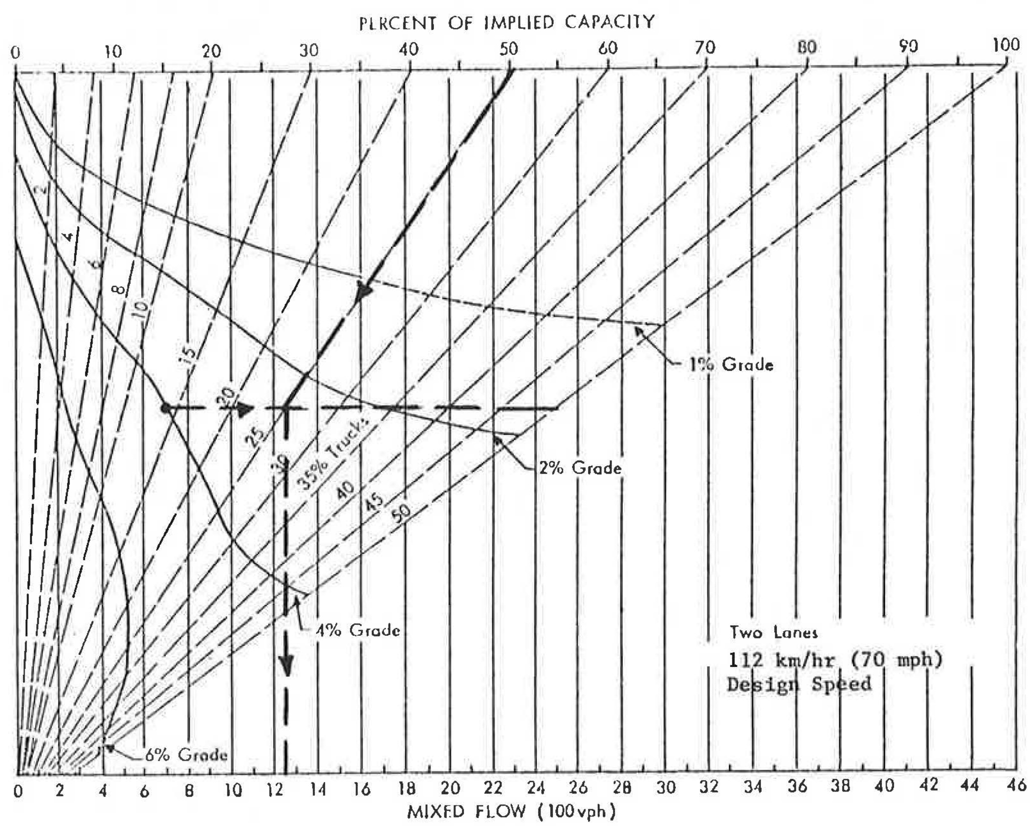
$$\text{Percentage reference trucks} = (100/F)(3.16f_{10} + 1.41f_9 + 0.14f_8 + 0.06f_7) \quad (2)$$

where percentage reference trucks = percentage in terms of the reference population defined in Table 1, F = total flow rate of mixed vehicles, and f_i = flow rate of index number of trucks.

The 183-kg/kW (300-lb/hp) vehicle falls into the category of index 9 trucks. To use the MRI charts, it was assumed that F = 100 vehicles/h, $f_7 = f_8 = f_{10} = 0$, and f_9 = the percentage of trucks in the traffic stream. The table below gives the results of converting to percentage reference trucks (1 kg/kW = 1.63 lb/hp):

Typical 183-kg/kW Trucks (%)	Reference Trucks (%)
2	2.8
4	5.6
6	8.4
8	11.2
10	14.0
15	21.0
20	28.0

Figure 2. Computation for E_t based on MRI simulation.



It is the percentage reference trucks that is used to obtain automobile equivalents of trucks by using the MRI simulations.

Equivalents for Trucks on Sustained Grades

The following procedure is used to calculate automobile equivalents for any percentage of trucks on any severity of sustained grade (length of grade greater than or equal to the length at which the truck reaches its crawl speed for an indicated severity of grade) by using MRI simulation. The procedure is illustrated here for a specific case but has been applied in the generation of a complete table of equivalents.

Problem 1

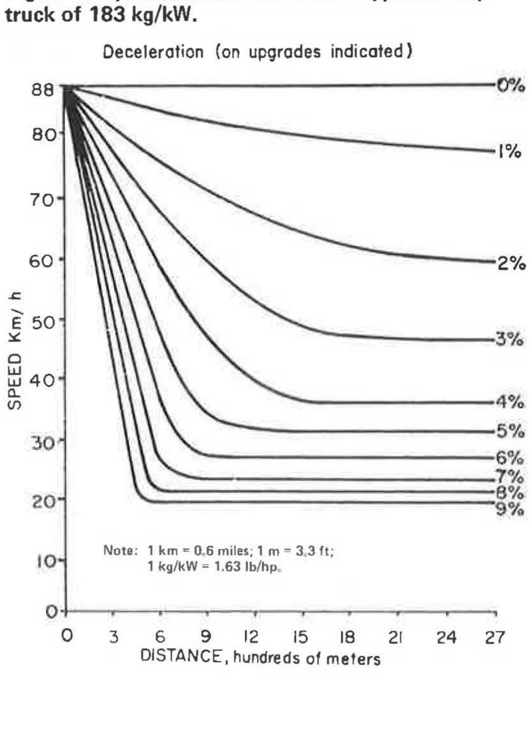
Find automobile equivalents E_t for a traffic flow that consists of 10 percent trucks on a 4 percent sustained grade of a four-lane freeway where V/C = 0.5 and design speed = 112 km/h (70 mph).

Solution

1. Enter Figure 2 with 14 percent reference trucks and 4 percent grades. Find the point of intersection as shown in Figure 2. From this point, draw a horizontal line across the figure.
2. Enter Figure 2 on the "Percent of Implied Capacity axis with 0.5 and construct a line parallel to the fan of "% trucks" lines to the intersection of the line drawn in step 1.
3. Drop a vertical line from the point of intersection in step 2 to the mixed flow scale and read 1230 vehicles/h.
4. If

SV = service volume in automobiles/h implied by the chart in Figure 2 for V/C = 0.5,
Q = mixed flow (vehicles/h) (step 3),

Figure 3. Speed-distance curves for a typical heavy truck of 183 kg/kW.



Y = percentage trucks/100, and
E_t = automobile equivalents for one truck under the conditions specified for this problem,

then

$$SV = Q(1.00 - Y) + E_t YQ \tag{3}$$

and

$$E_t = [SV - Q(1.00Y)/YQ] \tag{4}$$

The value of SV, which is taken from Figure 2 so as to remain consistent with the simulation used to generate the charts, is found by taking the mixed-flow value that corresponds to 0 percent grade, 0 percent trucks, and 100 percent implied capacity and multiplying by V/C. In this case, SV = 4550 × 0.5 = 2275 automobiles/h and E_t = [2275 - 1230 (0.90)]/ [(0.10) (1230)] = 9.5.

This procedure has been used to generate automobile equivalents for a wide selection of combinations of truck traffic and sustained grade. It can generate a set of truck factors for various design speeds, V/C ratios, and numbers of lanes. From these sample calculations, it was found that changing the V/C ratio or freeway design speed does not change the equivalent significantly. The size (number of lanes) of the freeway, however, does prove to be important in cases of a high percentage of trucks and/or a steep grade. It appears that there is justification for calibrating equivalents separately for two lanes and for freeways with three or more lanes. As the number of lanes increases, the difference in the effect of trucks on flow should stabilize. Since the MRI method does not treat freeways that have more than six lanes, truck factors are computed for four-lane freeways and for freeways with six or more lanes.

It is critical to note the meaning of truck equivalents that are computed in this way. The resulting truck equivalents will convert a service volume in automobiles per hour (from Table 9.1 of the 1965 HCM or equivalent) to a volume in mixed vehicles per hour that will consume the same percentage of roadway capacity. Thus, truck equivalents are based on keeping constant the effective value of V/C for any given level of service.

The procedure described above led to the calculation of automobile equivalents of trucks on sustained grades. Equivalents for lengths of grades on which the crawl speeds of trucks have not yet been reached must be computed differently.

Equivalents for Trucks on Grades Shorter Than Critical Length

Deceleration curves for a 183-kg/kW (300-lb/hp) vehicle are shown in Figure 3 (3). The Pennsylvania State University curves compare favorably with those presented in the MRI report for the index 9 truck [153-215 kg/kW (250-350 lb/hp) vehicle]. The difference in these curves is the speed of trucks on a level grade. The Pennsylvania curves assume a speed of 88 km/h (55 mph) on a level grade compared with 70 km/h (44 mph) in the MRI study. But St. John of MRI indicates that the 70-km/h speeds are lower than average.

The 88-km/h speed and the Pennsylvania curves are used here because informal observations have indicated that trucks keep up with the flow of automobile traffic in situations of 0 percent grade on freeways. In fact,

Table 2. Values of E_t for heavy-truck populations.

Grade (%)	Length (m)	E_t: Percentage Trucks on Four-Lane Freeways: 2	4	6	8	10	15	20	Percentage Trucks on Six- or Eight-Lane Freeways: 2	4	6	8	10	15	20
0	All	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1	0-400	4	3	3	3	3	3	3	4	3	3	3	3	3	3
	400-800	5	4	4	4	4	3	3	5	4	4	4	4	3	3
	800-1200	7	5	5	4	4	4	4	7	5	4	4	4	4	4
	1200-1600	8	6	6	5	5	4	4	8	6	5	5	5	4	4
	1600-2400	10	7	6	5	5	4	4	10	7	6	5	5	4	4
	>2400	11	8	7	6	6	5	5	11	8	7	6	6	5	5
2	0-400	8	6	6	5	5	4	4	7	5	5	5	5	4	4
	400-800	10	7	7	6	6	5	5	9	6	6	6	6	5	5
	800-1200	12	9	8	8	7	6	6	11	8	7	7	7	6	6
	1200-1600	14	10	9	9	8	7	7	13	9	8	8	7	6	6
	1600-2400	16	11	9	9	8	8	8	15	10	9	9	8	7	7
	>2400	16	12	10	10	9	8	8	15	11	10	9	8	7	7
3	0-400	11	10	9	8	8	7	7	9	8	8	7	7	6	6
	400-800	13	12	11	9	9	8	8	11	10	9	8	8	7	7
	800-1200	16	14	12	11	10	10	10	13	12	11	10	9	8	8
	1200-1600	19	15	14	13	12	12	12	16	13	13	12	11	10	10
	>1600	22	16	15	15	14	14	14	18	14	14	13	12	11	11
4	0-400	13	11	10	10	9	8	8	11	9	9	9	8	8	8
	400-800	18	13	13	12	12	12	12	13	11	11	11	10	9	9
	800-1200	22	15	15	14	14	14	14	16	13	13	13	12	11	11
	1200-1600	24	18	18	17	17	17	17	19	15	15	15	14	13	13
	>1600	26	20	19	19	19	19	19	21	17	17	16	16	14	14
5	0-400	19	16	16	16	16	16	16	17	13	12	12	12	11	11
	400-800	26	21	21	21	21	21	21	22	17	16	16	16	15	15
	800-1200	33	27	27	27	27	27	27	27	21	20	20	20	19	19
	>1200	40	32	32	32	32	32	32	31	25	24	24	24	23	23

Note: 1 m = 3.3 ft.

Table 3. Values of E_t for light-truck populations.

Grade (%)	Length (m)	E_t: Percentage Trucks on Four-Lane Freeways: 2	4	6	8	10	15	20	Percentage Trucks on Six- or Eight-Lane Freeways: 2	4	6	8	10	15	20
0	All	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1	All	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2	0-1200	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	>1200	3	3	3	3	3	3	3	3	2	2	2	2	2	2
3	0-400	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	400-800	3	3	3	3	3	3	3	3	2	2	2	2	2	2
	800-1200	4	4	3	3	3	3	3	3	3	3	3	3	2	2
	1200-1600	4	4	3	3	3	3	3	3	3	3	3	3	3	3
	1600-2400	5	5	4	4	3	3	3	4	3	3	3	3	3	3
	>2400	6	5	4	4	4	3	3	4	3	3	3	3	3	3
4	0-400	3	2	2	2	2	2	2	3	2	2	2	2	2	2
	400-800	5	3	3	3	3	3	3	3	3	3	3	3	3	3
	800-1200	6	4	4	3	3	3	3	4	3	3	3	3	3	3
	1200-2400	7	5	5	4	4	3	3	4	4	3	3	3	3	3
	>2400	8	6	5	4	4	3	3	5	4	3	3	3	3	3
5	0-400	4	3	3	3	3	3	3	4	3	3	3	3	3	3
	400-800	6	4	4	4	4	3	3	5	4	3	3	3	3	3
	800-1600	7	5	5	4	4	3	3	6	4	3	3	3	3	3
	1600-2400	9	6	6	4	4	3	3	7	5	4	4	4	3	3
	>2400	12	8	7	5	5	4	4	8	6	4	4	4	3	3
6	0-400	5	4	3	3	3	3	3	4	4	3	3	3	3	3
	400-800	8	6	5	4	4	3	3	6	5	4	3	3	3	3
	800-1600	12	8	7	5	4	3	3	8	6	4	4	4	3	3
	>1600	16	10	8	6	5	4	4	10	7	5	4	4	3	3

Note: 1 m = 3.3 ft.

this observation has led to the HCM automobile equivalent of 2 for trucks on 0 percent grade, which is based on the greater space that trucks need and the larger headways they command.

Truck equivalency is based on the premise that trucks travel slower than automobiles on grades. Their deceleration curves can therefore be used to obtain automobile equivalents for vehicles that have not yet reached their crawl sped if one equates the speed of the truck to that of a similar vehicle on a grade on which the indicated speed would be the crawl speed. The E_t for this grade is then used as the truck equivalent. The problem and solution given below illustrate this procedure.

Problem 2

Assuming that the 10 percent truck population of problem 1 has proceeded 600 m (2000 ft) along the grade, find the automobile equivalent of any truck.

Solution

1. Enter Figure 3 with length of grade = 600 m and intersect curve for 4 percent grade. Read speed = 57.6 km/h (36 mph). This is almost the same speed as the crawl speed of trucks on a 2 percent grade.
2. Enter Table 1 with 10 percent trucks and 2 percent grade (at crawl speed) and find E_t = 6.

By using this procedure and the design charts of the MRI report, a complete set of automobile equivalents is generated. These are given in Table 1.

To account for instances in which the truck population may not be typical, truck equivalents were also computed for light trucks [those with an average weight-to-power ratio of 92 kg/kW (150 lb/hp)] and for heavy trucks [those with ratios higher than 215 kg/kW (350 lb/hp)]. These are given in Tables 2 and 3.

Some of the values in Table 1 are unusual in that they tend to indicate that equivalents decrease as the percentage of trucks increases beyond 10 percent. This is not totally unreasonable. In fact, values of E_t in Table 9.4 of the 1965 HCM show a similar trend. At high truck percentages, trucks tend to separate from other traffic. Thus, their flow becomes less disruptive. Although the cumulative effect continues to increase, the effect of each truck decreases.

RECREATIONAL VEHICLES

Since recreational vehicles are taking on added importance on the nation's highways, it would be desirable to develop a set of automobile equivalents (E_R) for these vehicles. Although Werner has done work in this area (7), the discussion here is based primarily on Walker's methodology and is exclusively for two-lane highways.

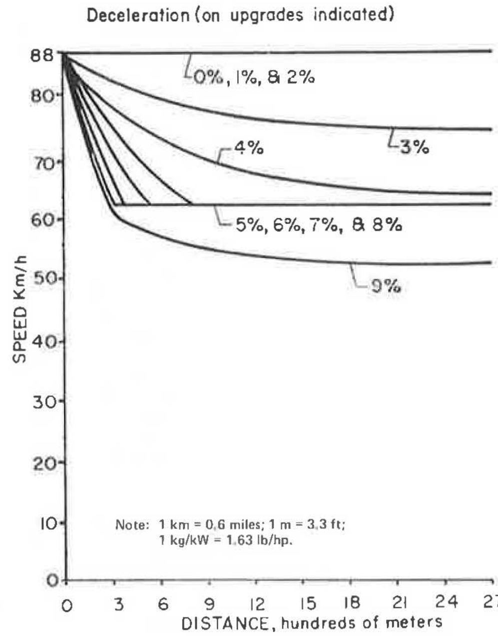
In the approach used here to generate representative automobile equivalents for recreational vehicles, the Pennsylvania State University deceleration curves for a 37-kg/kW (60-lb/hp) vehicle [Figure 4 (3)] and the truck equivalents previously computed are used. Values of E_R have been developed based on the speed of the recreational vehicle at various points along a grade. These speeds are found from the Pennsylvania curves for a weight-to-power ratio of 37 (60). The position of a truck with an equivalent speed is found on the Pennsylvania truck curves, and the appropriate E_R is selected. This technique is approximate and does not account for the differing driver characteristics for trucks and recreational vehicles, but it is the best that can be formulated given the extant data base. The values computed for E_R are given in Table 4.

It is recommended that such equivalents be used. Recreational vehicles take on great importance in certain areas of the country. Using even approximate E_R values would be better than not accounting for such vehicles at all or assuming that they are trucks. Further, the existence of E_R values in a formal document such as the HCM may spur additional research efforts in this area.

BUSES

Literature on the subject of bus equivalents and bus operating characteristics is virtually nonexistent. Thus, it appears that the values of E_B given in Tables 9.3a (generalized sections) and 9.5 (specific grades) in the 1965 HCM (1) should be continued.

Figure 4. Speed-distance curves for a typical trailer combination of 37 kg/kW.



FACTORS

Tables of the form given in the 1965 HCM can be used for the conversion of E_t, E_R, and E_B to factors that reflect the impact of these vehicles on traffic flow. Table 5 (1) in this paper can be used in the case of a population of automobiles and trucks only (or automobiles and recreational vehicles only or automobiles and buses only). In the case of a population in which automobiles, trucks, recreational vehicles, and buses are all present in significant percentages, a commercial vehicle factor should be computed from the following formula:

$$C = 100/(100 - P_t - P_R - P_B + P_tE_t + P_RE_R + P_BE_B) \quad (5)$$

where

C = adjustment factor;
P_t, P_R, P_B = percentage of trucks, recreational vehicles, and buses, respectively, in the traffic stream; and
E_t, E_R, E_B = automobile equivalents of trucks, recreational vehicles, and buses, respectively, in the traffic stream.

By using this combined factor, service volumes may be corrected for the combined effect of vehicles other than automobiles in the traffic stream:

$$SV = MSV \times \underline{C} \times W \quad (6)$$

It is recommended that this combined commercial vehicle factor be used in all cases where buses and recreational vehicles are present in quantities significant enough to be separately considered. Where only trucks are considered, a table that converts E_t to a factor (Table 5) may be used. Development of a nomograph to simplify the computation of C is being investigated.

Table 4. Values of E_R on upgrades.

Grade (%)	Length (m)	E_R: Percentage Recreational Vehicles on Four-Lane Freeways: 2	4	6	8	10	15	20	Percentage Recreational Vehicles on Six- or Eight-Lane Freeways: 2	4	6	8	10	15	20
0-2	All	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	0-400	3	2	2	2	2	2	2	3	2	2	2	2	2	2
	400-800	4	3	3	3	3	3	3	4	3	3	3	3	3	3
	800-1200	6	4	3	3	3	3	3	5	4	3	3	3	3	3
	1200-1600	7	5	4	4	4	4	4	6	5	4	4	4	4	4
	>1600	7	5	5	4	4	4	4	6	5	5	4	4	4	4
4	0-400	5	4	4	4	4	3	3	5	4	4	3	3	3	3
	400-800	7	5	5	4	4	4	4	6	5	4	3	3	3	3
	800-1200	8	6	5	4	4	4	4	6	5	4	3	3	3	3
	1200-1600	9	7	6	5	5	4	4	7	6	5	4	4	4	4
	>1600	9	7	6	5	5	4	4	7	6	5	4	4	4	4
5	0-400	5	4	4	4	4	3	3	5	4	4	4	4	3	3
	400-800	8	6	6	5	5	4	4	7	6	5	4	4	4	4
	>800	10	7	7	6	6	5	5	10	7	6	5	5	5	5
6	0-400	5	4	4	4	4	3	3	5	5	5	4	4	3	3
	400-800	10	7	7	6	6	5	5	10	7	6	5	5	5	5
	>800	10	7	7	6	6	5	5	10	7	6	5	5	5	5

Note: 1 m = 3.3 ft.

Table 5. Adjustment factors where only one type of nonautomobile vehicle is present in significant percentages.

Automobile Equivalent[a]	Adjustment Factor $C^{b,c}$ by Percentage of Trucks, Buses, or Recreational Vehicles: 1	2	3	4	5	6	7	8	9	10	12	14	16	18	20
2	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.93	0.92	0.91	0.89	0.88	0.86	0.85	0.83
3	0.98	0.96	0.94	0.93	0.91	0.89	0.88	0.86	0.85	0.83	0.81	0.78	0.76	0.74	0.71
4	0.97	0.94	0.92	0.89	0.87	0.85	0.83	0.81	0.79	0.77	0.74	0.70	0.68	0.65	0.63
5	0.96	0.93	0.89	0.86	0.83	0.81	0.78	0.76	0.74	0.71	0.68	0.64	0.61	0.58	0.56
6	0.95	0.91	0.87	0.83	0.80	0.77	0.74	0.71	0.69	0.67	0.63	0.59	0.56	0.53	0.50
7	0.94	0.89	0.85	0.81	0.77	0.74	0.70	0.68	0.65	0.63	0.58	0.54	0.51	0.48	0.45
8	0.93	0.88	0.83	0.78	0.74	0.70	0.67	0.64	0.61	0.59	0.54	0.51	0.47	0.44	0.42
9	0.93	0.86	0.81	0.76	0.71	0.68	0.64	0.61	0.58	0.56	0.51	0.47	0.44	0.41	0.38
10	0.92	0.85	0.79	0.74	0.69	0.65	0.61	0.58	0.55	0.53	0.48	0.44	0.41	0.38	0.36
11	0.91	0.83	0.77	0.71	0.67	0.63	0.59	0.56	0.53	0.50	0.45	0.42	0.38	0.36	0.33
12	0.90	0.82	0.75	0.69	0.65	0.60	0.57	0.53	0.50	0.48	0.43	0.39	0.36	0.34	0.31
13	0.89	0.81	0.74	0.68	0.63	0.58	0.54	0.51	0.48	0.45	0.41	0.37	0.34	0.32	0.29
14	0.88	0.79	0.72	0.66	0.61	0.56	0.52	0.49	0.46	0.43	0.39	0.35	0.32	0.30	0.28
15	0.88	0.78	0.70	0.64	0.59	0.54	0.51	0.47	0.44	0.42	0.37	0.34	0.31	0.28	0.26
16	0.87	0.77	0.69	0.63	0.57	0.53	0.49	0.45	0.43	0.40	0.36	0.32	0.29	0.27	0.25
17	0.86	0.76	0.68	0.61	0.56	0.51	0.47	0.44	0.41	0.38	0.34	0.31	0.28	0.26	0.24
18	0.85	0.75	0.66	0.60	0.54	0.49	0.46	0.42	0.40	0.37	0.33	0.30	0.27	0.25	0.23
19	0.85	0.74	0.65	0.58	0.53	0.48	0.44	0.41	0.38	0.36	0.32	0.28	0.26	0.24	0.22
20	0.84	0.72	0.64	0.57	0.51	0.47	0.42	0.40	0.37	0.34	0.30	0.27	0.25	0.23	0.21
21	0.83	0.71	0.63	0.56	0.50	0.45	0.41	0.38	0.36	0.33	0.29	0.26	0.24	0.22	0.20
22	0.83	0.70	0.61	0.54	0.49	0.44	0.40	0.37	0.35	0.32	0.28	0.25	0.23	0.21	0.19
23	0.82	0.69	0.60	0.53	0.48	0.43	0.39	0.36	0.34	0.31	0.27	0.25	0.22	0.20	0.19
24	0.81	0.68	0.59	0.52	0.47	0.42	0.38	0.35	0.33	0.30	0.27	0.24	0.21	0.19	0.18
25	0.80	0.67	0.58	0.51	0.46	0.41	0.37	0.34	0.32	0.29	0.26	0.23	0.20	0.18	0.17

[a] Computed by $100/(100 - P_R + E_R P_R)$ or $100/(100 - P_a + E_a P_a)$ (1, Ch. 5). Use this formula for larger percentages.
[b] From HCM, Table 9.4 or Table 9.5 (1).
[c] Trucks and buses should not be combined in entering this table where separate consideration of buses has been established as required because automobile equivalents differ.

COMPOSITE GRADES

In the 1965 HCM, composite grades are normally accounted for by finding truck and bus equivalents based on the average grade. Thus, equivalents for a 2 percent upgrade of 300 m (1000 ft) followed by a 4 percent upgrade of 300 m are computed as if for a 3 percent grade of 600 m (2000 ft).

Leisch (8) has developed a more exact technique that uses typical acceleration and deceleration curves for a truck to determine the actual speed of a truck at any point along a composite grade. For lengthy composite grades, the difference between the HCM technique and that of Leisch can be significant. It is recommended, therefore, that the Leisch method be included in the freeway procedures being developed as an alternative where composite grades of many sections or great length are involved. Guidelines for when to use it and when to rely on the simpler average grade approach should also be developed. The Pennsylvania State University deceleration and acceleration curves can be used to analyze these composite sections for truck and recreational vehicle traffic.

Research into the effect of nonpassenger vehicles on freeway downgrades is sparse. The MRI work contains some downgrade simulations, but these are not detailed enought to permit the generation of downgrade factors. The HCM recommends that freeway downgrades be treated as level grades in the absence of specific performance data on downgrade operations. This is reasonable except where trucks and other vehicles are forced to shift into lower gears. Procedures now being developed would caution users on this point and would present general recommendations for handling it.

CONCLUSIONS AND RECOMMENDATIONS

The automobile equivalents discussed in this report were obtained from the best available information on this subject. More research on the topic is needed, however, especially in the areas of recreational vehicles and buses and downgrade effects. It would also be of interest to see studies conducted on the effect on traffic flow of truck populations composed of vehicles with different performance characteristics. The MRI concept of percentage reference trucks presents a good base for future studies of this kind.

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The views presented here are ours. They do not necessarily represent the official views of FHWA or established policies or standard practices endorsed by FHWA.

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Discussion

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The speeds presented in the paper by Linzer, Roess, and McShane for typical trucks on grades are much slower than the speeds of typical trucks on grades along rural freeways and expressways in California.

The speeds of more than 14 000 trucks and 2600 recreational vehicles, pickup trucks, vans, and other vehicles were measured on grades along rural freeways and expressways in California during 1977, 1978, and 1979. Speed measurements were obtained during free-flow traffic conditions when wind velocities were 3.6 m/s (7 knots) or less. Speeds were not recorded for trucks that were following other trucks along a lane at intervals of less than 7 s. The speeds of trucks were measured without regard to whether the trucks were empty, partially loaded, or loaded.

The horizontal alignment at all locations where speeds were measured is suitable for high speeds. All upgrades where sustained speeds were measured, except the 4.0 percent grade, are over 3.2 km (2 miles) in length.

The measured speeds along the 4.0 percent grade were not sustained speeds. The distance from the beginning of the grade near a truck scale to the location where the speeds were measured is only 2.1 km (1.3 miles). Loaded trucks were required to slow to 5 km/h (3 mph), and empty trucks were required to slow to 8 km/h (5 mph) at this truck scale. This apparently affected the measured average speed of five-axle trucks by approximately 1 km/h (0.6 mph) and the 12.5 percentile speed of five-axle trucks by approximately 2 km/h (1.2 mph). The deceleration measurements were obtained along a 4.0 percent grade at a different location where there is not a truck scale.

Measured speeds along the 6.0 percent grade were slightly affected by variable grades in advance of the location where speed measurements were obtained. These variable grades did not cause the measured speeds to differ much from sustained speeds. The measured speeds along this grade are therefore referred to in this discussion as sustained speeds.

The table below gives average sustained speeds along grades for all trucks (both trucks and truck combinations are referred to as trucks in this discussion). The speeds were calculated, by using the measured speeds, for 15 percent two-axle trucks, 5 percent three-axle trucks, 5 percent four-axle trucks, and 75 percent five-axle trucks. These are typical percentages along the rural freeways and expressways where the speed measurements were obtained. The measured speeds of 6400 trucks were used in preparing the table (1 km/h = 0.6214 mph):

Grade (%)	Speed (km/h)	Grade (%)	Speed (km/h)
1.78	82.74	5.0	58.02
3.0	71.89	6.0	52.29
4.0	63.23	7.0	49.33

The following table gives average sustained speeds along grades for five-axle trucks (measured speeds of 4900 trucks were used):

Grade (%)	Speed (km/h)	Grade (%)	Speed (km/h)
1.78	80.98	5.0	56.15
3.0	69.73	6.0	51.64
4.0	61.14	7.0	48.55

The next table gives 12.5 percentile sustained speeds along grades for all trucks:

Grade (%)	Speed (km/h)	Grade (%)	Speed (km/h)
1.78	70.20	5.0	38.70
3.0	53.91	6.0	30.79
4.0	42.39	7.0	26.30

Speeds given in these three tables for the 4.0 percent grade are not sustained speeds.

The following table gives average speeds of five-axle trucks decelerating along upgrades [the measurements were obtained at 152-m (500-ft) intervals, and the speeds of a minimum of 150 trucks were measured at each location]:

Speed (km/h)			
2.88 Percent Grade	4.0 Percent Grade	5.0 Percent Grade	5.89-6.0 Percent Grade
87.60	88.31	88.63	69.40 (5.89 %)
85.38	83.80	83.19	63.04 (5.89 %)
83.03	79.21	77.04	58.00
81.43	75.96	73.05	55.81
79.94	72.79	68.70	54.83
77.49	69.85	65.32	54.04
76.85	66.24	61.59	53.30
75.95	63.17	59.53	
75.06	61.96	57.53	

Initial speed measurements were made near the beginning of each grade, and final measurements were made where average speeds were near the average sustained speeds previously determined.

The table below gives average speeds of five-axle trucks along 1372 m (4500 ft) of a -0.14 percent grade near a truck scale. Loaded trucks were required to slow to 5 km/h (3 mph), and empty trucks were required to slow to 8 km/h (5 mph) at this scale. The speeds of 100 trucks were measured at each of the first 10 locations, and the speeds of 150 trucks were measured at each of the last 3 locations (1 m = 3.3 ft; 1 km = 0.6214 mile):

Distance From Scale (m)	Speed (km/h)	Distance From Scale (m)	Speed (km/h)
30	16.06	610	67.48
61	22.92	762	72.32
91	27.84	914	76.99
122	34.05	1067	78.81
152	37.21	1219	81.59
305	51.45	1372	84.93
457	59.72		

Speed information was also obtained along a 3.0 percent grade and a 4.0 percent grade (farming area to urban area and return) when there were a significant number of agricultural trucks traveling. The measured average speeds of five-axle trucks were 1.67 km/h (1.04 mph) slower along the 3.0 percent grade and 2 km/h (1.24 mph) faster along the 4.0 percent grade when there were a significant number of agricultural trucks traveling. The difference in speeds between the grades was apparently caused by whether the agricultural trucks were loaded or empty.

The paper by Linzer, Roess, and McShane includes development of truck equivalency factors but does not include measurements of the actual speeds of trucks on grades. The truck equivalency factors were calculated by using information from a report prepared by Pennsylvania State University and information from the Midwest Research Institute. Again, the measured speeds of typical trucks on grades along rural freeways and expressways in California are much faster than the calculated speeds of the typical truck used in the paper.

Truck characteristics should be measured at various locations. The best procedure would be to measure the sustained speeds of trucks on various grades. Another procedure might be to measure truck accelerations near locations such as truck scales.

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The contents of this Discussion reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the state of California or FHWA. This discussion does not constitute a standard, specification, or regulation.

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In addition to the studies referenced in the paper by Linzer, Roess, and McShane, independent studies of the speed of trucks and recreational vehicles on grades were conducted in Texas in 1973 and 1974 (9, 10). Speed histories of 431 trucks and 260 recreational vehicles operating on grades between 2 and 7 percent were developed from direct field observations, and predictive equations relating several vehicle and driver characteristics were formulated through a stepwise regression analysis. A total of 11 factors were included in the analysis. Although weight-to-power ratio was found to have a significant effect on vehicle performance on grades, as noted by the authors, other factors such as entering speed, length and percentage of grade, and driver behavior also affected the speed history of both trucks and recreational vehicles.

It is interesting to note that the speed-distance relations selected by the authors for a typical heavy truck (Figure 3) agree within about 10 percent on upgrades up to 450 m (1500 ft) long with such composite curves for the typical heavy truck recommended by Walton and Lee for climbing lane design (10, Figure 8). These relations apply only to trucks entering the upgrade at 89 km/h (55 mph). Similarly, there is very good agreement between the respective curves shown in Figure 4 and those of Walton and Lee (9, Figure 48), which describe the speed-distance relation for typical recreational vehicles operating on 0 to 6 percent grades as long as about 600 m (2000 ft) after the vehicles enter the grade at 89 km/h. Again, these relations apply only for the specific entry speed. The Texas data therefore support the authors' selected vehicle performance data for these representive conditions.

The effects of vehicles entering upgrades at speeds other than 89 km/h are apparently not evaluated in the development of the new equivalency factors. The Texas observations indicate that entry speed has a considerable effect on deceleration rates for both trucks and recreational vehicles.

We commend Linzer, Roess, and McShane for their pragmatic approach to revising equivalency factors so that engineers can account for the changes that have occurred during the past two decades in vehicle performance and in the composition of the mixed traffic stream. The authors' assumptions concerning the performance of typical vehicles appear to be reasonable, and their use of previously accepted research results is innovative.

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Street Capacity for Buses in the Honolulu Central Business District

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A bus demonstration conducted in January 1978 in Honolulu is reported. The purpose of the demonstration was to determine the bus capacity of Hotel Street, the major bus corridor in the Honolulu central business district, under existing traffic and roadway conditions. Although buses were metered into both directions of Hotel Street at flow rates of 60, 120, 138, and 150 buses/h, only 100 to 120 buses/h could actually enter the system. Restrictions within the system further reduced bus flow. Major bottlenecks are identified, and the resulting impacts on vehicles, pedestrians, and the environment are assessed. It is concluded that directional bus capacity on Hotel Street was 95-100 buses/h at average speeds that ranged from 3 to 5 km/h (2 to 3 mph).

A major transit trip generator in Honolulu is the central business district (CBD), which encompasses an area of about 0.5 km^2 (0.2 $mile^2$). This generator is served by 22 of the 39 available scheduled bus routes. The primary east-west roadway used by bus routes through the CBD is Hotel Street, which is approximately 0.8 km (0.5 mile) long and is intersected by nine one-way side streets, seven of which are signalized (see Figure 1). There are 10 bus stops along Hotel Street, 6 on the north side and 4 on the south side. Fifteen of the 22 bus routes use some section of Hotel Street, and 7 bus routes intersect Hotel Street. During the off-peak period, Hotel Street handles between 50 and 56 buses/h in each direction. This increases to 72-80 buses/h during the morning peak period.

Hotel Street is a two-lane collector approximately 11 m (36 ft) wide that serves mixed traffic. At some intersections, the roadway flares to 12 m (40 ft), which allows both left and through movements in one lane. Although there are no bus bays on Hotel Street, it is not unusual for vehicles to pass one or two buses loading or unloading at a bus stop.

The land use adjacent to Hotel Street is zoned B-4, CBD, which is intended to denote the metropolitan center for financial, commercial, government, professional, and cultural activities. Also in the surrounding area are the state capitol, city hall, government offices, and major tourist attractions of historical interest.

In terms of transit, the city and county of Honolulu currently maintains a fleet of 350 buses. The system is wholly owned by the city and county of Honolulu, but its operation is contracted to a private carrier—MTL. This bus system is well received in the community. Although the urban portion of Honolulu ranks forty-third in population, bus ridership is the thirteenth highest in the country. Ridership figures for 1977 indicate a total ridership of 66.6 million, composed of 47.5 million paying passengers, 11.8 million transfers, and 7.3 million free senior citizen passengers.

PURPOSE OF THE STUDY

On January 20, 1978, the Honolulu Department of Transportation Services (DTS) conducted a study that involved the regulation of the major bus flow through the Honolulu CBD. The purpose of the Hotel Street bus demonstration was to determine the maximum bus volume Hotel Street can carry under present roadway and traffic conditions. The existing literature (1, 2, 3) indicates a wide range of values. The study also attempted to identify major bottlenecks and to quantify the resulting impacts on vehicles, pedestrians, and the environment.

The bus study was conducted under two constraints. First, the study occurred on Friday between 10:00 a.m. and 12:30 p.m., during the normal work periods of the department staff. Because of this, the observed traffic measures do not reflect peak-hour traffic conditions that occur on Hotel Street. Second, efforts were made to maintain current patterns of automobile use and bus patronage. Traffic signal timings and bus routes were not changed for the study.

PROCEDURE

During the bus demonstration, the flow of buses into Hotel Street was controlled in both directions. During various phases of the 10:00 a.m. to 12:30 p.m. test period, buses were scheduled to enter both ends of Hotel Street