20. S. C. Sharma and A. Werner. "Improved Method of Grouping Provincewide Permanent Traffic Counters." In *Transportation Research Record 815*, TRB, National Research Council, Washington, D.C., 1981, pp. 12–18.
21. H. Scheffe. *The Analysis of Variance*. John Wiley & Sons, Inc., New York, 1964.
22. B. B. Petroff. Experience in Application of Statistical Methods to Traffic Counting. *Public Roads*, Vol. 29, No. 5, 1956, pp. 110–117.
23. M. Morris. "Standard Deviation and Coefficient of Variation of Automatic Traffic Recorder Counts." *Proc. of the Highway Research Board*, HRB, National Research Council, Washington, D.C., Vol. 30, 1951, pp. 336–346.
24. S. C. Sharma. "Minimizing Cost of Manual Traffic Counts: Canadian Example." In *Transportation Research Record 905*, TRB, National Research Council, Washington, D.C., 1983, pp.1–7.
25. H. Westermann. *Determination of Design Hour Volume from Seasonal Traffic Counts*. Faculty of Engineering, University of Regina, Regina, Saskatchewan, Canada, 1985.

Developing Link Performance Functions Using Highway Performance Monitoring System Data Files

HOW-MING SHIEH AND C. MICHAEL WALTON

The principal objective of this paper is to propose a practical approach to developing highway performance functions and estimating annual truck activities using Highway Performance Monitoring System (HPMS) data files. This approach was applied to the Interstate highways. A highway performance function was defined as the relationship of average travel speed (or average travel time, operating speed) versus volume-to-capacity (V/C) ratio. A preliminary analysis was initially performed to summarize collected HPMS data and to revise data inconsistencies in HPMS data records. The revised HPMS data records were further analyzed and used to test underlying assumptions of the proposed approach. Because of substantial variation of traffic flow patterns in different time periods, especially the difference between the nighttime period and peak-hour and off-peak-hour periods, it was proposed to average traffic conditions for developing link performance functions in a 16-hr period, including both peak-hour and off-peak-hour periods. An expansion factor was then used to provide an estimate of average daily traffic volume by vehicle type. The relationship of average travel speed versus V/C ratio by average highway speed and total number of through lanes, as reported in the 1985 Highway Capacity Manual, was used as a basis for developing specific highway performance functions. It was found that in the year 2000 Texas would have 10 billion vehicle miles traveled (VMT) by local and intercity truck traffic on the existing Interstate highways. It was also predicted that there would be 89 billion VMT of truck traffic on the Interstate highways in the United States in the year 2000.

The impetus for this research was the need to develop highway performance functions for the highway segments (links) on a national designated highway network to facilitate the operations of large combination vehicles. This research stems from a research project at the Center for Transportation Research, the University of Texas at Austin *(1)*. Hence, the principal objective of this paper is to propose a practical approach to developing highway performance functions and, for the purpose of providing a preliminary analysis of national truck activities on the designated network, estimating annual truck activities by using, in part, the Highway Performance Monitoring System (HPMS) data files *(2)*.

The format of an HPMS data record includes variables needed to characterize the roadway segment: identification, operation, travel, geometry and configuration, traffic/capacity, environmental, and so forth. As indicated, each record characterizes one highway segment. Some variables, such as traffic and operations, may vary over time and some may not be uniform within an HPMS highway section. For instance, the geometric design of a highway section may be made up of several different highway grades and curvatures in the HPMS record. In this research the variables for highway infrastructure are assumed consistent over time; however, annual average daily traffic (AADT), operating speed, and volume-to-capacity (V/C) ratio vary over time.

In general, the average time taken for a driver to traverse a highway section depends on several factors. These factors may include, for example, section length, access control, longitudinal and vertical alignment, speed limits, traffic volume, traffic components, highway capacity, driver's behavior, vehicle characteristics, weather conditions, and traffic control devices. Most, if not all, of these factors may vary over time. In this research, the following factors were considered: traffic volume, traffic components, highway capacity, number of through lanes, topology, average highway speed, speed limit control, and time. These factors were considered important in deriving highway performance functions (i.e., the relationship of operating speed versus V/C ratio) using collected HPMS data. The basis for this derivation is the 1965 and the 1985 Highway Capacity Manuals (HCMs) *(3,4)*. The newly published 1985 Highway Capacity Manual updates speed-flow relationship

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by replacing operating speed with average travel speed as the dependent variable and takes into consideration the 55-mph speed limit. However, hourly traffic volume by vehicle type (i.e., for passenger cars and trucks) was not updated in the 1985 HCM.

Because of data inconsistencies, primarily resulting from missing data or coding errors, or both, it was necessary to verify and revise collected HPMS data. The procedures used to revise the data are presented in the next section. To reflect average level of service for each link, an investigation of hourly traffic flow patterns was conducted. The findings suggest that there were significant fluctuations in traffic flow at different time intervals, which led to an averaging of hourly traffic flow pattern in a 16-hr period *(3,5)*. Because the majority of highway segments (83 percent) that constitute the candidate network for the operation of large combination vehicle (LCVs) are Interstate highways, this average would facilitate an estimate of annual vehicle miles traveled (VMT) by truck traffic on the Interstate system. A discussion of the formulation of highway performance functions follows along with the final discussion of the conclusions.

PRELIMINARY ANALYSIS OF COLLECTED HPMS DATA FOR INTERSTATE HIGHWAYS

Until recently not all states submitted annually collected HPMS data to the FHWA. In the development of this study, HPMS data for the years 1978, 1980, and 1981 were used. Three states, Oklahoma, Mississippi, and Rhode Island, had not submitted HPMS data by the end of 1982. In summary, HPMS data for the states of Arkansas and South Carolina were collected in 1978; HPMS data for 21 states were collected in 1980; data for 5 states were collected in both 1980 and 1981; and data for 17 states were collected in 1981 (Figure 1).

For the Interstate highways, 8,441 HPMS records were collected for 45 states. Those states for which HPMS records were not collected were Mississippi, Oklahoma, Rhode Island, Hawaii, and Alaska (Table 1). To complete the required data for the development of highway performance functions for the Interstate highways of the 48 contiguous states, 742 HPMS records from neighboring states of Mississippi, Oklahoma, and Rhode Island were assigned by route number to the Interstate highways of these three states, respectively. The process used to locate HPMS data records on the highways of the candidate network was developed and published in a report by the Center for Transportation Research, the University of Texas at Austin *(1)*.

The items of an HPMS record used to develop highway perfor-

TABLE 1 TOTAL NUMBER OF COLLECTED HPMS RECORDS BY STATE FOR INTERSTATE HIGHWAYS

State	No. of Records	State	No. of Records
Alabama	123	Nebraska	69
Arizona	199	Nevada	135
Arkansas	81	New Hampshire	35
California	343	New Jersey	176
Colorado	234	New Mexico	141
Connecticut	182	New York	239
Delaware	29	North Carolina	85
Florida	317	North Dakota	101
Georgia	203	Ohio	349
Idaho	161	Oklahoma	345
Illinois	258	Oregon	167
Indiana	228	Pennsylvania	330
Iowa	557	Rhode Island	145
Kansas	209	South Carolina	149
Kentucky	262	South Dakota	101
Louisiana	127	Tennessee	222
Maine	103	Texas	281
Maryland	161	Utah	181
Massachusetts	244	Vermont	91
Michigan	313	Virginia	231
Minnesota	129	Washington	199
Mississippi	252	West Virginia	145
Missouri	155	Wisconsin	148
Montana	173	Wyoming	75

Note: Total number of records collected = 9,183.

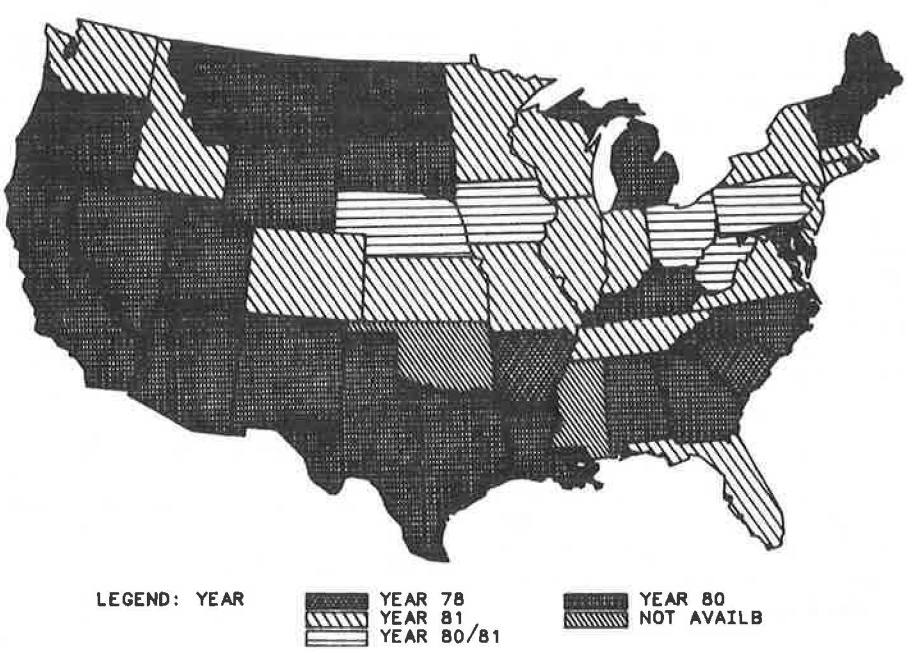

FIGURE 1 HPMS data collected by state and year.

mance functions include the following elements associated with the highway infrastructure, traffic condition, environment, and identification specification:

- Annual average daily traffic (AADT),
- Average highway speed (mph),
- County code,
- Estimated future AADT (year 2000 AADT),
- *K*-factor (the 30th highest hourly traffic volume that constitutes the AADT),
- Percentage of truck traffic in peak hours,
- Estimated operating speed (mph),
- Route number,
- Section length (in thousandth mile),
- Federal Information Processing Standards (FIPS) state code,
- Type of terrain,
- Number of through lanes,
- Computed V/C ratio (percentage),
- Feasibility of widening, and
- Year data were collected.

Some items of the HPMS records were found to be incomplete or inconsistent, primarily because of missing data or coding errors, or both. In general, the identification variables, including the year the data were collected, FIPS state code, and county code, were found to be complete. Other items required special treatment to complete or revise. Some items were found to be unreliable. For instance, some records indicated a speed limit of less than 20 mph or a *K*-factor of less than 5 percent of AADT for an Interstate highway section. Such inconsistencies were treated in the following manner:

- Items that were considered unrealistic (i.e., too low or too high) were eliminated. Default values were substituted. These default values could be either the averages or the upper bounds of corresponding items.
- Missing data were justified by other available items in the same record. For instance, some missing terrain data types were justified by highway grades and their corresponding lengths if applicable.
- Missing data files were computed by substituting the values given for the same items of neighboring observations.
- Because collected HPMS data on a coded highway link do not always match the distance measured from state maps, the length of an HPMS record was proportionally adjusted by this constraint.
- Remaining unjustifiable items were replaced with default values.

The revised HPMS data were then preliminarily analyzed for the year 2000, assuming that the Interstate highways would be adequately maintained to perpetuate existing road conditions and that some of the traffic-related characteristics would remain consistent over time. These traffic-related consistency items include *K*-factor and percentage of truck traffic in both peak-hour and off-peak-hour periods, assuming that current state regulations on truck size and weight limits and dispatching strategies of truck carriers remain essentially static or unchanged. The objective of this assumption is to provide a basis for assessing impacts resulting from the introduction of large combination vehicles on the candidate network. The items selected for preliminary analysis included 1977 and year 2000 AADTs, *K*-factor, percentage of truck traffic in peak hours, percentage of truck traffic in off-peak hours, terrain type, number of through lanes, speed limit, average highway speed, computed V/C ratio, and operating speed. The 1977 AADTs were obtained by extrapolating linearly the AADT of the year the HPMS record was collected and the year 2000 AADT supplied by each of the state highway departments. In general, each selected item was categorized in one of four groups on the basis of its quartiles. The first quartile (less than 25 percent) was categorized as the low-value group; the second and the third quartiles (between 25 percent and 75 percent) as the moderate-value group; and the other two groups as the high-value group (ranging from 75 percent to 95 percent) and the extremely high-value group (higher than 95 percent). Extreme values for each selected item were also discussed.

1977 AADT

On average, 25,000 vehicles per day per mile (vpdm) traveled on the Interstate highways. Of the overall Interstate highway system (41,560 mi), about 3 percent (1,229 mi) of total mileage accommodated more than 76,000 vehicles per day (vpd) (Figure 2). The following three highways were found to have vpd of more than 222,000 in some highway sections:

- Between the city of Chicago and loop I-90,
- I-405 between Los Angeles and Anaheim, and
- I-10 near Los Angeles.

California was found to have 283 mi of Interstate highways with extremely high daily traffic volume. Illinois, Texas, Ohio, and New Jersey had more than 70 mi of Interstate highway segments with heavy daily traffic volumes.

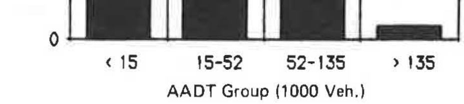

FIGURE 2 Total 1977 Interstate highway mileage by AADT.

Year 2000 AADT

The average daily vehicles per mile of the Interstate highways in the year 2000 was computed as 1.7 times that of 1977 (i.e., approximately 42,400 vpdm). Of the Interstate highways, 1,176 mi were predicted to have more than 135,000 vehicles per day (i.e., V/C ratio of about 90 percent in a 16-hr period for four-lane highways). These highly utilized Interstate highways were found distributed in Texas (203 mi), California (199 mi), and Florida (154 mi). Specifically, parts of three highways were predicted to have more than 300,000 vpd in the year 2000:

- I-95 between Miami and West Palm Beach;
- I-635 loop of Dallas; and
- I-5 between Everett, Washington, and Lynnwood, Washington.

Average Highway Speed

The 1985 HCM *(3)* defines average highway speed as "the weighted average of the design speeds within a highway section, when each subsection within the section is considered to have an individual speed." As expected, most of the HPMS records for the Interstate highways indicated an average highway speed of 70 mph. However, there existed 17 mi of Interstate highways with average highway speeds of less than 60 mph, and 897 mi with speeds between 60 and 69 mph. Kentucky, Montana, Pennsylvania, and Arizona were the four states that had average Interstate highway speeds of less than 60 mph.

K-Factor

It was estimated that the average *K*-factor for the Interstate highways was 12.79 percent based on the collected HPMS data. There were 355 mi of Interstate highways (0.9 percent) that had *K*-factors greater than 17 percent. Texas (200 mi), Kansas (67 mi), Illinois (59 mi), and California (21 mi) had very high *K*-factors on sections of their Interstate highways. Most Interstate highways (95.3 percent) had *K*-factors of less than 15 percent.

Percentage of Off-Peak Truck Traffic

For the Interstate highways, the average off-peak truck traffic was estimated to be 16.31 percent. It was found that about 30 percent of the Interstate highways (12,880 mi) had off-peak truck traffic greater than 24 percent (Figure 3). The following three sections of I-80 were found to have extreme values for this item:

- Between Pine Bluffs, Nebraska, and Big Springs, Nebraska, (46 percent);
- Between Wheatland, Pennsylvania, and Mercer, Pennsylvania, (45 percent); and
- Between Columbus, Ohio, and Toledo, Ohio, (45 percent).

Texas, Pennsylvania, Ohio, and Wyoming were found to have more than 300 mi of Interstate highways with a heavy truck traffic component (more than 32 percent). Heavy trucks made up more than 32 percent of the traffic stream on 240 mi of Interstate highways in California.

Percentage of Truck Traffic in Peak Hour

In general, the percentage of truck traffic on Interstate highway sections during peak hours was found to be less than that in off-peak hours. Maybe this is because of the significant increase of passenger car traffic volume. On average, peak-hour truck traffic for Interstate highways was 13.60 percent. The extremes of this item were similar to those found for off-peak hours.

Speed Limit Controlled

About 97 percent of Interstate highway mileage (40,327 mi) is controlled by a posted maximum speed limit of 55 mph; however, 578 mi of Interstate highways are controlled by a posted maximum speed limit of less than 40 mph. Most of these lower speed limit sections (384 mi) were in Florida. Texas and Maryland had 50 mi of Interstate highways controlled by a speed limit equal to or less than 40 mph.

Type of Terrain

After necessary verification and revision, it was estimated that 2,194 mi of Interstate highways can be classified as being in mountainous terrain. Most of these sections were located in Montana, West Virginia, Virginia, Pennsylvania, California, Maryland, Utah, Alabama, and Colorado.

Number of Through Lanes

For Interstate highways, 88 percent of total mileage was recorded as four-lane divided highways, 3,979 mi of Interstate highways were found to be six-lane divided highways, and 3.11 percent of all Interstate highways (1,294 mi) were constructed to be more than six lanes (Figure 4). Of those Interstate highways with more than six through lanes, more than half were located in California (663 mi). Texas, Maryland, and Georgia were found to have 96, 87, and

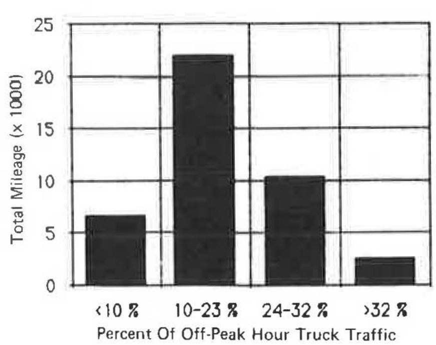

FIGURE 3 Total Interstate highway mileage by percentage of off-peak truck traffic.

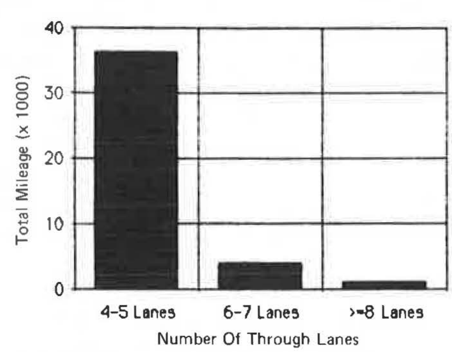

FIGURE 4 Total Interstate highway mileage by number of through lanes.

78 mi with more than six through lanes, respectively. Four locations were recorded as having more than 14 through lanes:

- I-94 between Wheeling, Wisconsin, and Wisconsin border (16 through lanes);
- I-5 between Anaheim, California, and San Diego, California, (15 through lanes);
- I-90 between Park Ridge, Illinois, and Chicago, Illinois, (15 through lanes); and
- I-5 between Everett, Washington, and Lynnwood, Washington, (15 through lanes).

V/C RATIO

V/C ratio and operating speed were computed by the FHWA using the HPMS data submitted by the states. Traffic during the peak-hour period was used to compute V/C ratios. Some of the ratios computed from HPMS records may be greater than 100 percent because a penalty was assigned to those records that had an assigned operating speed below the operating speed where the ratio was given as 1.0. For Interstate highways, 1,388 mi were classified as highly utilized during the peak-hour periods (i.e., V/C >1) (Figure 5). Most of these Interstate highways were located in California, Ohio, and Texas (175, 149, and 141 mi, respectively).

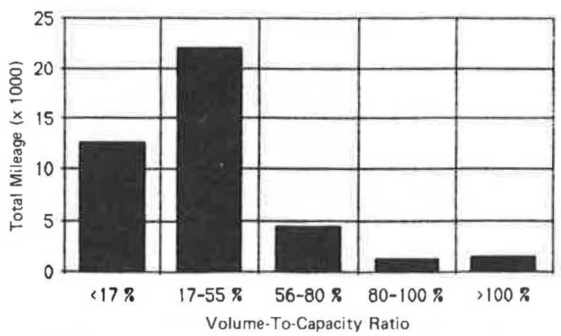

FIGURE 5 Total Interstate highway mileage by V/C Ratio.

The extreme values for the V/C ratios were found to be as high as 437 percent. Some of these extreme values include part of the following four Interstate highways:

- I-95 between Rye, New York, and New York City (437 percent of V/C);
- I-495 between New York City and Harrison, New York, (350 percent of V/C);
- I-95 between Byran, New York, and Rye, New York, (326 percent of V/C); and
- I-87 between Champlain, New York, and Albany, New York, (306 percent of V/C).

Operating Speed

Operating speed was divided into five groups: below 20 mph, 21 to 30 mph, 31 to 45 mph, 46 to 55 mph, and more than 55 mph. About 80 percent of Interstate highway mileage was found to be at operating speeds greater than 55 mph; however, there were 1,363 mi of Interstate highways that had operating speeds of less than 30 mph (Figure 6). Most of these sections were located in California, Ohio, Texas, and Pennsylvania (175, 145, 140, and 98 mi, respectively). California and Texas had more than 100 mi of Interstate highways with operating speeds of less than 20 mph (109 and 105 mi, respectively).

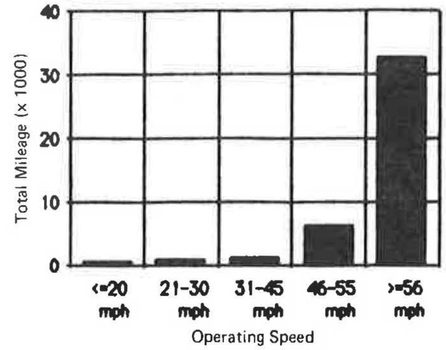

FIGURE 6 Total Interstate highway mileage by operating speed.

DEFAULT VALUES AND AVERAGE TRAFFIC CONDITIONS

The preliminary analysis provided insight into the steps required to correct data inconsistencies, particularly time dimensions of the data. The percentage of truck traffic was reported on an hourly basis for both peak-hour and off-peak-hour periods; and the AADT was expressed as a daily equivalent. The *K*-factor represents the 30th highest hourly traffic volume in a year. To cope with these discrepancies in time units and to obtain the average of traffic conditions corresponding to truck traffic in various time periods, default values were computed based on the 1965 HCM *(3)* and the 1975–1979 National Truck Characteristic Report *(5)*. Two assumptions were made to facilitate the analysis:

- The ratio of the *K*-factor and average peak-hour factor remains constant for reported HPMS data records and
- Computed default values are transferable and remain stable over time.

As illustrated in Figure 7, the 30th highest hourly traffic volumes in a year (*K*-factor) for rural expresssways and urban expressways were 13 percent for the 1985 HCM (or 14 percent for the 1965 HCM) and 11 percent of AADT, respectively. The computed average *K*-factor was 12.8 percent of AADT for Interstate highways. This computed average *K*-factor was comparable to that reported in the Highway Capacity Manuals; therefore, the data used to illustrate the relationship of hourly traffic volumes and AADT in the 1965 HCM were considered transferable.

Some default values were derived from two diagrams reported in the 1965 HCM *(3)* (Figures 8 and 9). The data used to draw the two diagrams were collected at 49 rural stations in Wisconsin's truck highway system in 1961. Reported hourly variations of traffic on rural highways for an average weekday (Figure 8) provided insight into three time periods that could be identified on the basis of percentage of ADT in the peak-hour period (2 p.m. to 6 p.m.), off-peak-hour period (6 a.m. to 2 p.m.), and nighttime period (10 p.m. to 6 a.m.). It was found that traffic volumes varied significantly in different time periods for the two simplified vehicle

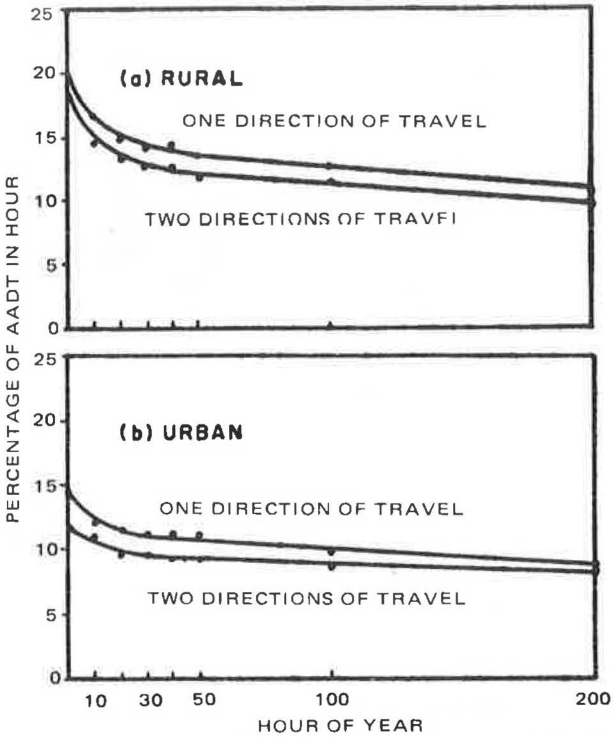

FIGURE 7 Relation of hourly traffic volume and AADT on expressways.

classes, passenger cars and trucks (Figures 10 and 11). The total number of passenger vehicles per hour during the peak-hour period was approximately eight times that observed during the nighttime period. Even during the off-peak period, the total number of vehicles per hour was about five times that of the nighttime period. Therefore, it is assumed that, on average, traffic congestion does not occur during the nighttime period. Averaging the traffic conditions of peak-hour and off-peak-hour periods over a 16-hr rather than a 24-hr period was done to expedite traffic assignment on a daily basis. Two factors were used to expand traffic volume from a 16-hr to a 24-hr period. The two expansion factors were computed as 113 percent and 133 percent of AADT for passenger cars and trucks, respectively.

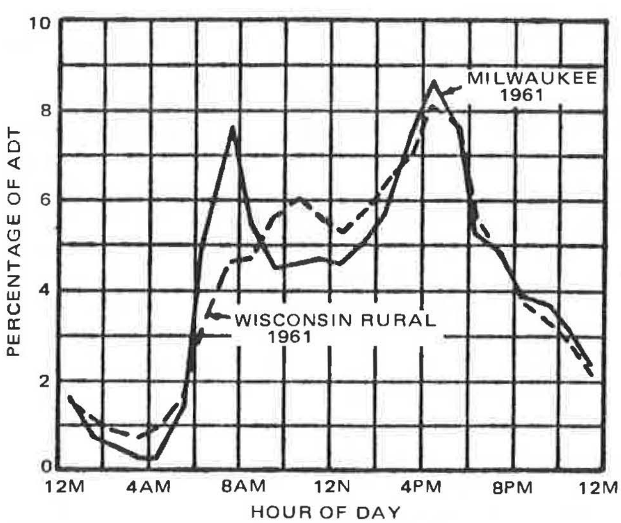

FIGURE 8 Hourly variations of traffic for average weekday.

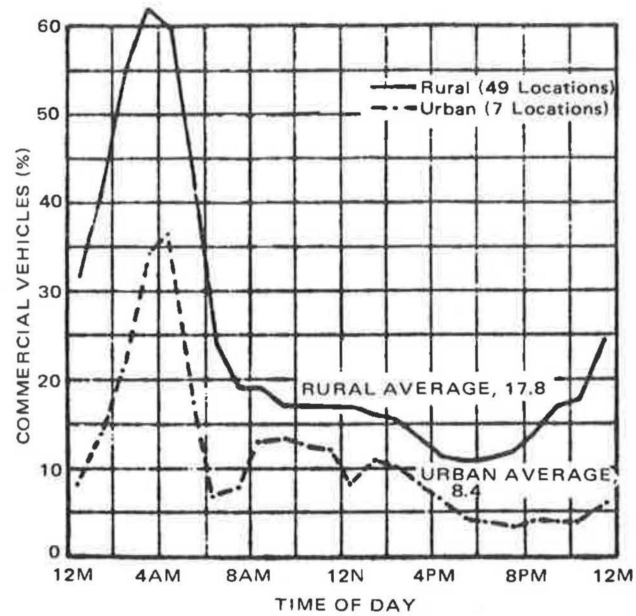

FIGURE 9 Traffic composition by time of day, Wisconsin highways, weekdays, 1961.

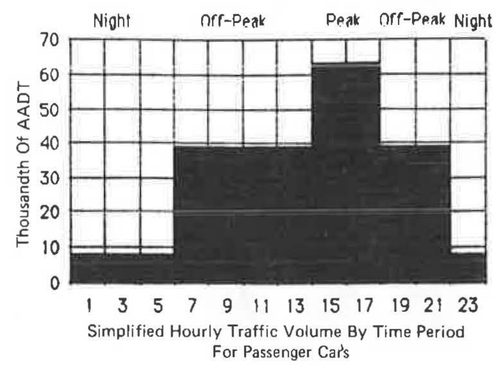

FIGURE 10 Representative hourly traffic volume by time period for passenger cars.

Referring to Figure 8 and the expansion factors just discussed, the total number of vehicles per hour during the peak hours was estimated as 7.25 percent of AADT. Combined with a default *K*-factor (13 percent of AADT) and the assumption that the ratio of *K*-factor and average peak-hour factor remain constant, the total number of vehicles per hour during the peak-hour period (7.25

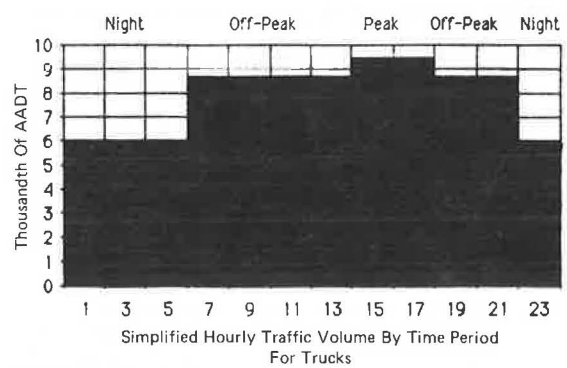

FIGURE 11 Representative hourly traffic volume by time period for trucks.

percent of AADT) was used to find the average peak-hour factor *(PF)* and average off-peak-hour factor *(OPF)* for a given highway section. Equations 1 and 2 illustrate this.

$$PF = 0.5578\,K \quad (1)$$

$$OPF = 0.07378 - (PF/3) \quad (2)$$

where

- K = K-factor of a highway section,
- PF = average number of vehicles in peak-hour period in terms of AADT, and
- OPF = average number of vehicles in off-peak-hour period in terms of AADT.

From these two equations, total annual VMT for trucks (including local and intercity truck traffic) operating on Interstate highways were estimated to be 89 billion in the year 2000. Of these, most were predicted to occur in Texas, Florida, Pennsylvania, California, and Indiana (10.1, 6.1, 5.0, 4.9, and 4.8 billion VMT, respectively).

On a linkwise basis, 76 percent of Interstate highway mileage (31,694 mi) was estimated to have truck traffic of less than 8,000 vpd; 20 percent was between 8,000 and 17,000 vehicles; and 1,538 mi of Interstate highways (3.7 percent) were predicted to have more than 17,000 trucks per day (Figure 12). Florida, Indiana, Texas, and North Carolina were predicted to have more than 100 mi of Interstate highways with daily truck traffic of more than 17,000 vehicles (362, 250, 183, and 132 mi, respectively).

DEVELOPMENT OF HIGHWAY PERFORMANCE FUNCTIONS

A highway performance function was formulated as a function of traffic volume *(V)*, traffic component *(P)*, highway capacity *(C)*, number of through lanes *(N)*, topology *(R)*, average highway speed *(H)*, and speed limit controlled *(L)* at specific time period *(T)*:

$$v \text{ (or } t) = f\,(V, P, C, N, R, H, L, T) \quad (3)$$

The dependent variable could be either average travel speed (or operating speed) *(v)* or average travel time per mile *(t)*. The time period employed was the 16-hr period discussed previously. Highway capacity *(C)* was defined as total number of passenger car equivalents (PCEs) of ideal capacity. For multilane, divided, fully accessed-controlled highways, 2,000 PCEs per lane was used. The categories of topology were simplied to be level, rolling, and mountainous terrain for extended highways. The traffic component was classified into two classes of vehicles, passenger cars and trucks.

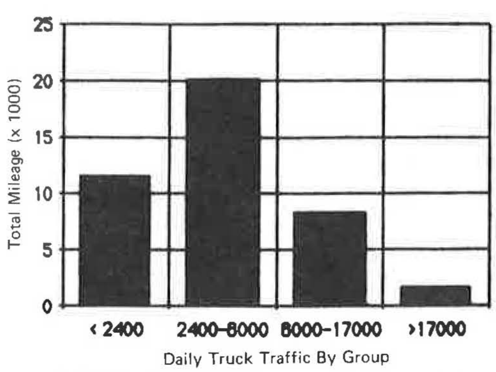

FIGURE 12 Total highway mileage by daily truck traffic volume group for Interstate highways in the year 2000.

The 1985 Highway Capacity Manual reported the relationship between average travel speed (or operating speed in 1965 HCM, see Figure 13) and V/C ratio categorized by total number of through lanes and average highway speed (Figure 14). On the basis of this relationship, a highway performance function could be formulated:

$$v(\text{or } t) = f\,(V, P, C, R \mid H, T, N) \quad (4)$$

subject to v less than L.

The constraint used in Equation 4 has to be replaced by v (operating speed), which is 5 less than L when the speed-flow relationship in Figure 13 is employed. In this formulation, it was assumed that the operating speed could be 5 mph higher than the controlled speed limit. The constraint used in Equation 4 has to be replaced by v (average travel speed) less than L when the speed-flow relationship in Figure 14 is employed. To compute the V/C ratio, it was necessary to convert traffic volume into PCEs. This conversion was the mutual effect of total number of vehicles, traffic component, and topology for extended highways and particular highway sections *(3,4,6,7)*. The output from this conversion was the total number of passenger car equivalents for a highway section or an extended highway (V_{pce}). Equation 4, therefore, could be further simplified to

$$v \text{ (or } t) = f\,(V_{pce}/C \mid V, P, C, N, R, H, T) \quad (5)$$

subject to v less than L (or t greater than $60/L$).

The conversion of traffic volume to PCEs, however, did not consider the effects of vehicle width, vehicle weight, vehicle length, and the like. Therefore the introduction of larger and heavier trucks into the traffic mix of a highway section may change the total number of converted PCEs. Vehicle length was proposed for modifying PCE numbers for large combination vehicles on an extended highway section *(1)*.

From the formulation of highway performance functions and conversion of PCEs, each HPMS highway section could be characterized. This approach could therefore reflect performance characteristics of a highway section more accurately than the approach that calibrated a unique performance function for a global network *(8,9)*.

The relationship of average travel time (or operating speed), travel time per mile, and V/C ratio could be approximated either by a mathematical formulation or by a set of data points. For instance, mathematical formulation of the highway performance functions for four-lane freeways or expressways designed with an average highway speed of 70 mph could be expressed by the speed-flow relationship based on the 1965 HCM:

$$v \text{ (operating speed)} = 25 + [1470 - 14.7\,(V_{pce}/C)]^{1/2} \quad (6)$$

subject to (V_{pce}/C) in percent less than 100 percent and $v - 5$ less than L, or by

$$t = 1.0154 - 0.0052\,(V_{pce}/C) + 0.00015\,(V_{pce}/C)^2 \quad (7)$$

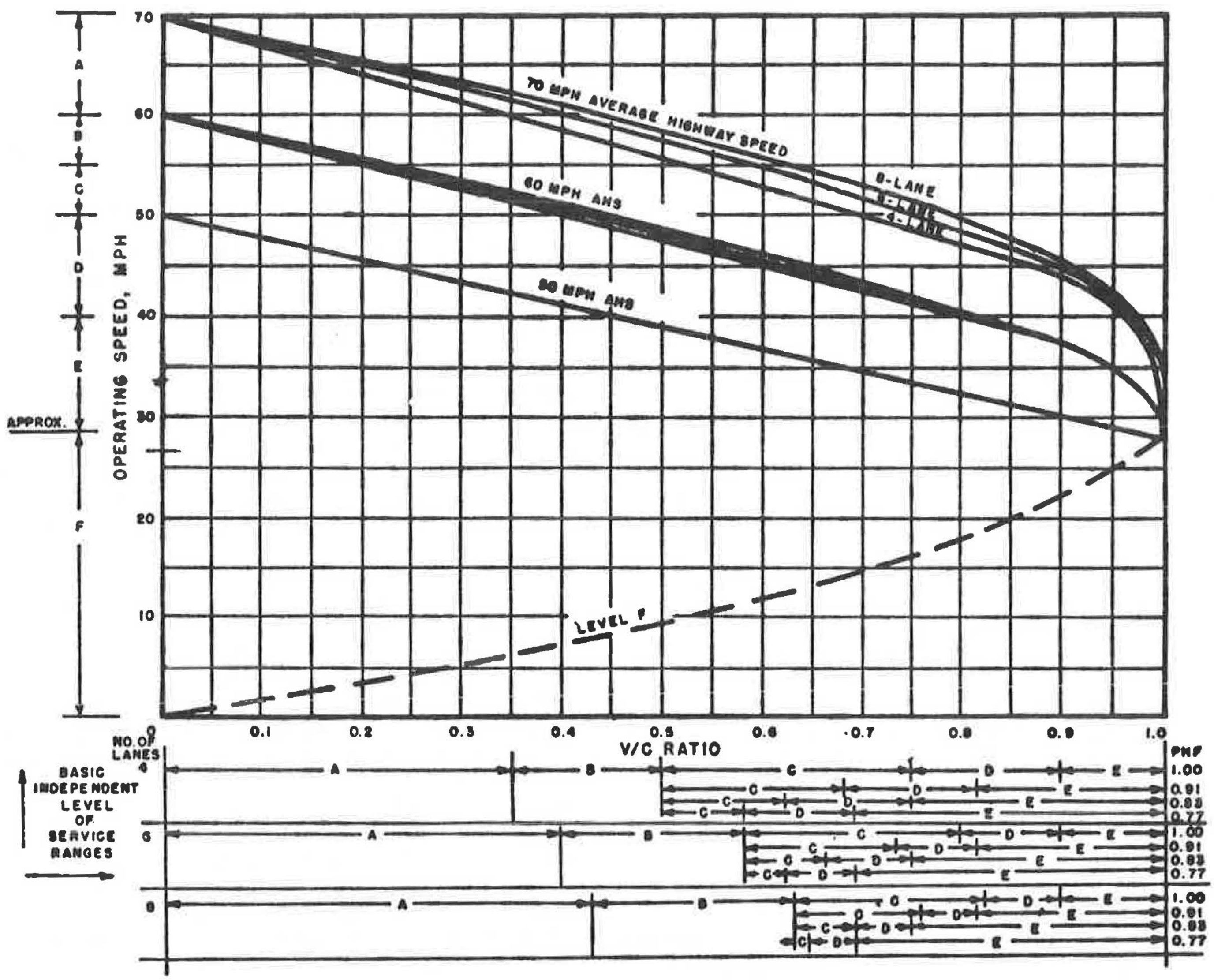

FIGURE 13 Relationships between V/C ratio and operating speed in one direction of travel on freeways and expressways under uninterrupted flow conditions.

subject to t greater than $60/L$ where L is in mph and t is in minutes per mile.

This formulation could also be expressed by the speed-flow relationship based on the 1985 HCM:

$$V_{pce}/C = 1{,}342.71 - 92.15\ v + 2.23\ v^2 - 0.0178\ v^3 \quad (8)$$

subject to v less than L where v is average travel speed in mph, or by

$$t = 0.9514 + 0.01307\ (V_{pce}/C) - 0.00041\ (V_{pce}/C)^2 + 0.0000038\ (V_{pce}/C)^3 \quad (9)$$

The relationship of average travel time versus V/C ratio by number of through lanes and average highway speed, based on the 1985 HCM, is given in Table 2.

All of the formulations were restricted to (V_{pce}/C) not greater than 100 percent. However, for the purpose of an all-or-nothing traffic assignment in an iterative process, the (V_{pce}/C) ratio could be greater than 100 percent. Penalty functions, therefore, were introduced in cases in which the (V_{pce}/C) ratio was greater than 100 percent.

SUMMARY AND CONCLUSIONS

In this paper, collected HPMS data for the Interstate highways were verified, revised where deemed appropriate, and preliminarily analyzed. Some default values were derived on the basis of the investigation of representative hourly traffic flow patterns for both passenger cars and trucks reported in the 1965 and 1985 Highway Capacity Manuals. It was proposed to average traffic conditions of peak-hour and off-peak-hour periods into a 16-hr period. The proposed approach was applied to estimate total annual VMT by truck traffic in the year 2000. It was estimated that there would be 89 billion VMT on the existing Interstate highways in the year 2000. The approach proposed to assess highway performance functions on a section-by-section basis using the HPMS

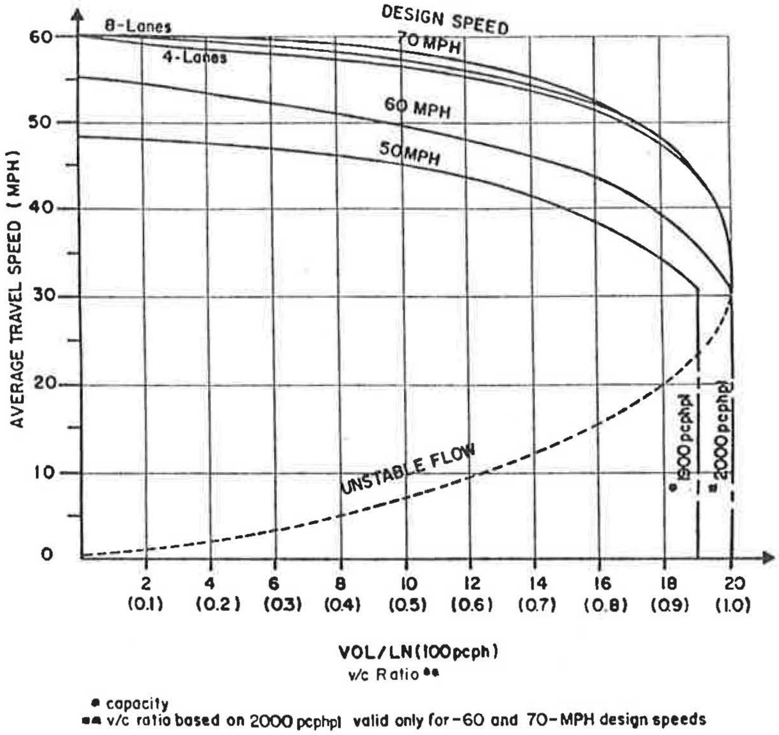

FIGURE 14 Average travel speed-flow relationships under ideal conditions for freeways.

TABLE 2 RELATIONSHIP OF AVERAGE TRAVEL TIME VERSUS *V/C* RATIO BY NUMBER OF THROUGH LANES AND AVERAGE HIGHWAY SPEED

Category	Relationship of Average Travel Time Versus *V/C* [t in minutes per mile and (V_{pce}/C) in percent]
70 mph, four lane	$t = 0.95140 + 0.01307\ (V_{pce}/C) - 0.00041\ (V_{pce}/C)^2 + 0.00000348\ (V_{pce}/C)^3$
70 mph, six lane	$t = 0.94228 + 0.01379\ (V_{pce}/C) - 0.00045\ (V_{pce}/C)^2 + 0.00000384\ (V_{pce}/C)^3$
70 mph, eight lane	$t = 0.94501 + 0.01312\ (V_{pce}/C) - 0.00044\ (V_{pce}/C)^2 + 0.00000387\ (V_{pce}/C)^3$
60 mph	$t = 1.05589 + 0.00938\ (V_{pce}/C) - 0.00027\ (V_{pce}/C)^2 + 0.00000253\ (V_{pce}/C)^3$
50 mph	$t = 1.2274 + 0.00481\ (V_{pce}/C) - 0.00016\ (V_{pce}/C)^2 + 0.00000175\ (V_{pce}/C)^3$

data was based on the relationship of average travel time (or average travel speed) versus V/C ratio reported in the 1985 Highway Capacity Manual (or the relationship of operating speed versus V/C ratio reported in the 1965 HCM). It is hoped that the proposed approach would foster the understanding and use of developing highway performance functions from collected HPMS data.

The following points are recommended for further improvement and research:

1. A reliable data base is the foundation for generating plausible results. It is recommended that the quality of HPMS data be improved. Missing data or coding errors, or both, in HPMS data records should be avoided. A uniform sample and identification scheme and systematic arrangement of data records are important for applying collected HPMS data to practice.
2. Understanding of the interaction between various vehicle classes and different highway infrastructure, traffic conditions, and the like has not been well developed. The introduction of large combination vehicles (Rocky Mountain double trailers, turnpike double trailers, and triple trailers) makes this interaction more complicated. An understanding of this interaction would provide a basis for reliable assessment of highway performance.
3. Most traffic assignment algorithms use an iterative process to assign traffic by an all-or-nothing method. The justification of a penalty function for highway performance on overcapacity highways may be worthy of further research.

REFERENCES

1. C. M. Walton et al. *Feasibility of a National Intercity Truck Route Network.* Center for Transportation Research, the University of Texas at Austin, 1986.
2. *Highway Performance Monitoring System Field Manual.* FHWA, U.S. Department of Transportation, Sept. 1980.
3. *Special Report 87: 1965 Highway Capacity Manual.* HRB, National Research Council, Washington, D.C., 1965, 397 pp.
4. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.

5. *1975–1979 National Truck Characteristics Report*. Highway Statistics Division, FHWA, U.S. Department of Transportation, June 1981.
6. *Transportation Research Circular 212: Interim Materials on Highway Capacity*. TRB, National Research Council, Washington, D.C., Jan. 1980, 272 pp.
7. R. Roess et al. *Passenger Car Equivalents for Uninterrupted Flow: Revision of the Circular 212 Values*. Transportation Training and Research Center, Polytechnic Institute of New York, Brooklyn, Nov. 1983.
8. K.B. Davidson. "A Flow Travel Time Relationship for Use in Transportation Planning". *Proc., Australian Road Research Board*, Melbourne, Vol. 3, 1966, pp. 183–194.
9. D. Branston. Link Capacity Function: A Review. *Transportion Research*, Vol. 10, 1976, pp. 223–230.