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Planning-Level Methodology for Freeway Facilities

Ali Hajbabaie, Nagui M. Rouphail, Bastian J. Schroeder, and Richard Dowling

This paper presents a planning-level methodology for the analysis of freeway facilities. The proposed approach is based on and compatible with the operational method of the *Highway Capacity Manual 2010* (HCM 2010). The approach is specifically constructed with the intent to minimize input data requirements. The method covers both under- and oversaturated flow conditions and produces estimates of travel time, speed, density, and level of service. The underlying methodology relies on developing a relationship between a basic freeway segment's delay rate per unit distance and its demand-to-capacity ratio. For weaving segments, the study develops capacity adjustment factors on the basis of volume ratio and segment length. With these factors, demand-to-capacity ratios on weave segments were adjusted and the segment was treated similarly to a basic freeway segment. For merge and diverge segments, a novel methodology is proposed to estimate their capacity on the basis of demand level, free-flow speed, and space mean speed. Subsequently, capacity adjustment factors are calculated on those segments and their demand-to-capacity ratios are adjusted accordingly. The proposed approach is applied to two examples in the HCM 2010 and produced very promising results. For undersaturated flow conditions, facility travel time is at most 3.4% and density was at most 1.1% at variance from the results found by applying the HCM 2010 operational methodology. The corresponding differences for oversaturated conditions are 6.7% and 13.0%, respectively.

This paper introduces a planning-level approach for freeway facility analysis that is compatible with the operational method of the *Highway Capacity Manual 2010* (HCM 2010) (1). The method was developed under the auspices of NCHRP 07-22. The approach was designed in such a way as to minimize input data requirements consistent with planning-level applications and can be implemented for both under- and oversaturated flow conditions. The HCM 2010 defines "planning analyses" as "applications of the HCM that are generally directed toward broad applications, such as initial problem identification, long-range planning analyses, and statewide performance monitoring" (1). The HCM 2010 also cites preliminary engineering analyses to support planning decisions related to roadway design and scope, specifically when alternative treatment analyses are performed.

A. Hajbabaie, Department of Civil and Environmental Engineering, Washington State University, P.O. Box 642910, Pullman, WA 99164-2910. B. J. Schroeder, Highways Group, and N. M. Rouphail, Institute for Transportation Research and Education, North Carolina State University, Centennial Campus, Box 8601, Raleigh, NC 27695-8601. R. Dowling, Kittelson & Associates, Inc., 155 Grand Avenue, Suite 900, Oakland, CA 94613. Corresponding author: A. Hajbabaie, ali.hajbabaie@wsu.edu.

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Both types of analyses typically focus on evaluating future roadway operations in situations in which at least some of the inputs required for an HCM operational analysis must be estimated. These situations include future traffic volumes, signal plans, and any inputs affected by the characteristics of the alternatives to be evaluated. According to the HCM 2010, planning analyses may default nearly all inputs, while preliminary engineering analyses will default some inputs and have specific values available for others. To date, no freeway facilities planning methodology has been documented in any HCM.

This paper develops such a method. It satisfies planning-level analyses in that

1. It uses default values of many operational parameters, as much as practicable;
2. It omits the need to enter detailed data regarding the facility segment description (e.g., acceleration lane length and detailed weaving section geometry);
3. It aggregates the analysis to a coarser spatial representation, reporting at the freeway section level instead of the HCM segment level; and
4. For a single peak hour, the analysis can be performed manually without an extensive amount of effort, but automation of computations is readily feasible for multiperiod or even 24-h analyses.

The remainder of this paper presents a review of relevant studies and details the proposed methodology at the freeway facility planning–preliminary engineering level. Adjustments necessary for weave, merge, and diverge segments are explained, and a discussion of the methodology is followed by example problems and concluding remarks.

LITERATURE REVIEW

The 2000 HCM has three chapters devoted to planning analyses of corridors and areas (2). However, it does not have a specific planning-level method for freeway facilities. The HCM 2010 made several improvements to facilitate planning applications and included useful material for planning applications in the first nine chapters of Volume I (1). In addition, the HCM 2010 introduced the new concept of service volume tables for freeway facilities but fell short of providing a planning-level method for freeways (1). A recent NCHRP synthesis on the *Extent of Highway Capacity Manual Use in Planning* documented the need for improved planning-level methodologies in the HCM, as well as streamlined guidance for incorporating the HCM methods into standard planning practice (3). Two published reports by FHWA in 2010 provided information on how to

create a transportation plan that incorporates operations: *Advancing Metropolitan Planning for Operations: An Objectives-Driven, Performance-Based Approach—A Guidebook* (4) and *Advancing Metropolitan Planning for Operations: The Building Blocks of a Model Transportation Plan Incorporating Operations—A Desk Reference* (5).

Several states have accepted the challenge of estimating freeway facility performance in a planning-level context. For example, North Carolina developed a planning-level interface for the FREEVAL computational engine of the HCM 2010 that allows users to input annual average daily traffic (AADT) data and default values for other inputs (6). However, while the method is applicable in a planning context from a user input perspective, it is not a true planning-level method, as it simply facilitates user input for the more complicated operational method. North Carolina also has NCLOS software, which produces level-of-service (LOS) estimates at a planning level on the basis of HCM methods (7). The method is similar to the HCM 2010 service volume concept. The tool is used for statewide planning and forecasting but does not produce delay or travel time estimates and does not model congested conditions. Another state that has developed planning-level approaches for freeway analysis is Florida, which also produces the FREEPLAN software to conduct a planning-level evaluation for freeway facilities (8). This Florida Department of Transportation method is limited to undersaturated conditions and does not model queuing and congested freeways in a planning context. Broader national guidance on the use of default values from the HCM is provided in NCHRP Report 599, but without specific methodology (9).

In efforts separate from the HCM, the TRB Standing Committee on Transportation Network Modeling recently produced *Dynamic Traffic Assignment: A Primer* (10). Within travel demand models, dynamic traffic assignment attempts to model more accurately the dynamic performance of highway systems and the interaction between highway congestion, route selection, and departure time selection (peak spreading). SHRP 2 Project C05 evaluated the concept of varying capacity in dynamic traffic assignment and applied it to assess the capacity benefits of various operational improvements in a planning context (11). A project conducted for the FHWA's Office of Operations addressed the feasibility of applying HCM methods to long-range transportation planning by introducing operations considerations to the planning process (12). Overall, a clear need exists

for developing a planning-level method for freeway facilities that is true to the HCM but that is compatible with user needs and data availability in planning applications.

METHODOLOGY

The proposed methodology relies on developing a statistical relationship between the delay rate per unit distance and demand-to-capacity ($d:c$) ratio on basic freeway segments in the case of undersaturated flow conditions (Figure 1). For oversaturated flow, the delay rate is approximated on the basis of $d:c$ ratio and assumes uniform arrival and departures at a bottleneck. Under these conditions, all segments are treated identically. After the delay rate is estimated, segment delay is calculated by accounting for segment length, and average travel time is estimated from delay and free-flow travel time.

Weave segment capacity is determined by applying the HCM 2010 methodology for a large combination of input variables. Then, capacity adjustment factors (CAFs) (ratios of capacities of weaving segments to capacities of basic freeway segments) are calculated for each combination, and a model is proposed to estimate CAFs on the basis of input variables. The CAF is used to adjust the $d:c$ ratios, and the weaving segments are subsequently treated similarly to basic freeway segments.

The HCM 2010 assumes that merge and diverge segments have a similar capacity to basic segments. In this paper, a method to derive an equivalent merge-diverge segment capacity on the basis of segment demand level and resulting space mean speed (SMS) is proposed. This practice entails solving the basic freeway segment's speed-flow relationship for segment capacity. Then CAFs are calculated for merge-diverge segments, and their $d:c$ ratio is adjusted accordingly.

The following discussion describes the input requirements. The approach for basic freeway segments is explained in detail for both under- and oversaturated conditions. Necessary adjustments for weave, merge, and diverge segments follow.

Input Requirements

Input variables are characterized into global and section inputs. Rather than having to go through the time-consuming process of

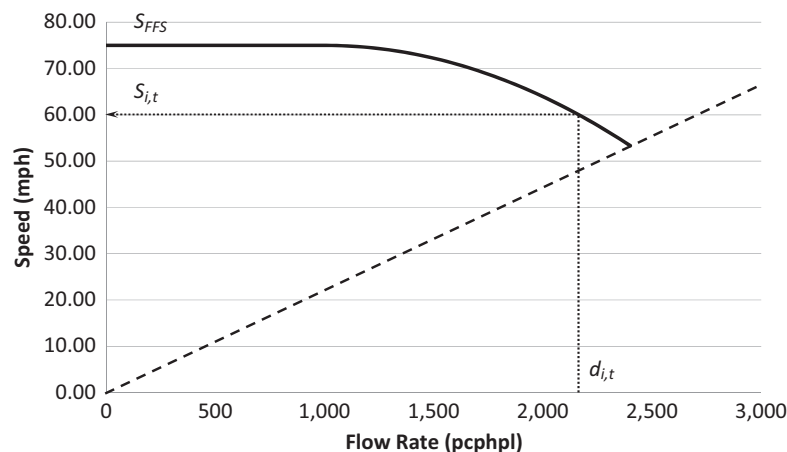


FIGURE 1 Speed-flow curve to estimate delay rate (FFS = 75 mph) (pcphpl = passenger cars per hour per lane).

HCM facility segmentation, the authors defined “sections” as occurring between points at which either demand or capacity changes. For example, if a lane drop exists between an on- and off-ramp, that length will involve two sections. But, for a three-segment sequence of a merge area, a basic segment, and a diverge area, the proposed methodology would define only a single section. This technique facilitates user input and is more compatible with travel demand model links, as well as with modern data sources, such as INRIX.com (13).

Global inputs include information about the facility of interest and are applicable to all sections across all analysis periods. These inputs include free-flow speed (S_{FFS}), peak hour factor (PHF), percentage of heavy vehicles (%HV), k -factor (converts directional AADT to hourly flows), and a traffic growth factor. Free-flow speed and percentage of heavy vehicles are used to calculate section capacity by means of the following equation:

$$c_i = \frac{(2,200 + 10 * (\min(70, S_{FFS}) - 50))}{1 + \frac{\%HV}{100}} \quad (1)$$

Equation 1 is fully consistent with the HCM 2010 speed-flow models. Section inputs include section type (basic, weave, ramp), section length (mi), section number of lanes, and section directional AADT. This information, together with the global inputs, is used to calculate free-flow travel rate (the inverse of free-flow speed), capacity adjustment factors for weave and ramp sections, adjusted lane capacity (the product of base capacity and CAF), and section capacity (the product of adjusted lane capacity and number of lanes).

Demand Level Calculations

The demand level for each section is determined from entering demand, exiting demand, and carryover demand from a previous analysis period (in the case of oversaturation). From this information, the $d:c$ ratio is calculated, and the delay rate is computed, as discussed later. For each section and period, the method further estimates travel rate, travel time, density per lane, and segment queue length. By using the $AADT_i$ for section i , k -factor, traffic growth factor (f_g), and PHF, inflow and outflow of section i during analysis period (time) t , $q_{i,t}$, are computed as follows:

$$q_{i,t} = \begin{cases} AADT_i * k * f_g t = 1, 3 \\ AADT_i * k * \left(\frac{1}{PHF}\right) * f_g t = 2 \\ AADT_i * k * \left(2 - \frac{1}{PHF}\right) * f_g t = 4 \end{cases} \quad (2)$$

Demand level $d_{i,t}$ in section i at analysis period t is computed as the demand level in section $i - 1$, plus the inflow at section i at analysis period t , subtracted by the outflow at the same section at analysis period t , plus any carryover demand $d'_{i,t-1}$ in section i at the previous analysis period $t - 1$. The relationship is as shown in Equation 3:

$$d_{i,t} = d_{i,t-1} + (q_{i,t})_{in} - (q_{i,t})_{out} + d'_{i,t-1} \quad (3)$$

The carryover demand $d'_{i,t}$ at section i at analysis period t is the difference between the section demand and capacity as follows:

$$d'_{i,t} = \max(d_{i,t} - c_i, 0) \quad (4)$$

The carryover demand is also used as an indication of the presence of a queue on the section. Queues are considered vertical and are not carried to an upstream link. Section queue length is estimated by dividing the difference in lane demand and capacity by its density. It essentially provides an estimate of how far back the queue would spill at the given density if a fixed number of lanes upstream of the bottleneck is assumed.

Delay Rate Estimation

The proposed approach is based on estimating delay rate per unit distance as a function of section $d:c$ ratio. The delay rate is calculated as the difference between actual and free-flow travel time per unit distance. For example, if the SMS on a facility is 60 mph relative to an FFS of 75 mph for a 1/2-mi segment, then the free-flow travel time is 0.4 min and the actual travel time is 0.50 min. The delay rate per mile is the difference of those travel times divided by the segment length, which gives a delay rate of 0.2 min/mi. The delay rate must be calculated separately for undersaturated and oversaturated flow conditions.

Undersaturated Flow Conditions

For undersaturated flow conditions, the HCM 2010 basic segment speed-flow model is used to estimate delay rates. Figure 1 illustrates the speed-flow relationship for a segment with a 75-mph FFS. By using demand level $d_{i,t}$ on segment i in analysis period t , the method first estimates SMS for that demand, $S_{i,t}$, which is then converted to a delay rate as illustrated below. The speed-flow data were generated from the current HCM 2010 model.

The speed estimates $S_{i,t}$ and S_{FFS} are converted to segment travel times by dividing the segment length by these speed estimates. With those segment travel times, the delay rate (hours per mile) on each segment is estimated as follows:

$$\Delta_{U_{i,t}} = T_{i,t} - T_{FFS} \quad (5)$$

$$\Delta_{U_{i,t}} = \frac{L_i}{S_{i,t}} - \frac{L_i}{S_{FFS}} \quad (6)$$

$$\Delta_{RU_{i,t}} = \frac{\text{delay}}{L} = \frac{1}{S_{i,t}} - \frac{1}{S_{FFS}} \quad (7)$$

where

$\Delta_{U_{i,t}}$ = average delay of undersaturated segment i at analysis period t ,

$T_{i,t}$ = predicted travel time for segment i at analysis period t ,

T_{FFS} = travel time under free-flow conditions,

L_i = length of segment i , and

$\Delta_{RU_{i,t}}$ = delay rate for undersaturated segment i at analysis period t .

For a planning-preliminary engineering level analysis, further simplifying the estimation of delay rate as a function of inputs readily

TABLE 1 Values for Parameters of Equation 8

FFS (mph)	A	B	C	D	E
75	68.99	-77.97	34.04	-5.82	0.44
70	71.24	-85.48	35.58	-5.44	0.52
65	92.45	-127.33	56.34	-8.00	0.62
60	121.35	-184.84	83.21	-9.33	0.72
55	156.43	-248.99	99.20	-0.12	0.82

available in a planning context is desirable. Therefore, a relationship for delay rate as a function of segment $d:c$ ratio, is developed.

Travel speed (S_{it}) and consequently, delay rate ($\Delta_{RU_{it}}$), on segment i at analysis period t are functions of the segment demand level (d_{it}) at analysis period t , the free-flow speed (S_{FFS}), and the segment capacity (c_i). As such, for each FFS, a regression model is fitted to estimate the delay rate on the basis of these three parameters. The authors considered the option to unify regression models for all different free-flow speeds; however, that approach yielded larger errors. Therefore, for undersaturated flow conditions, a two-regime model was developed for each free-flow speed as shown in Equation 8 and Table 1:

$$\Delta_{RU_{it}} = \begin{cases} 0 \frac{d_{it}}{c_i} < E \\ A \left(\frac{d_{it}}{c_i} \right)^3 + B \left(\frac{d_{it}}{c_i} \right)^2 + C \left(\frac{d_{it}}{c_i} \right) + DE \leq \frac{d_{it}}{c_i} \leq 1 \end{cases} \quad (8)$$

where the values of parameters A , B , C , D , and E are shown in Table 1 and are based on segment FFS.

For each FFS, the sole input to the regression model is $d:c$. To fit the model for different $d:c$ ratios ranging between 0.42 and 1 in 0.02 increments, the delay rate was calculated by using Equation 7 for the five values of free-flow speed. To avoid a discontinuity with the oversaturated model, the undersaturated model was applied until a $d:c$ ratio of 1.05 was reached. The final regression models returned an adjusted R^2 value greater than .95. Figure 2 shows the data set used to fit the regression model in Equation 8. The figure makes

clear that the proposed model is a reasonable approximation of the estimated delay rates.

Oversaturated Flow Conditions

For oversaturated flow conditions, the delay rate is approximated by assuming uniform arrival and departures at a freeway bottleneck, as depicted in Figure 3. The figure shows cumulative values of vehicle arrival rate, $d_{i,t}$, on segment i at analysis period t , and the departure rate c_i , which is the segment capacity such that $d_{i,t} > c_i$. With demand exceeding capacity, any demand that cannot be served through the bottleneck has to be stored upstream of the bottleneck in a queue. Figure 3 plots the cumulative number of vehicles over time by assuming that the oversaturated conditions last for a period T .

The additional delay, $\Delta_{O_{it}}$, experienced because of oversaturation in period T is the area of the shaded triangle in Figure 3. Therefore,

$$\Delta_{O_{it}} = \left(\frac{1}{2} \right) \left(\frac{Td_{i,t}}{c_i} - T \right) T * d_{i,t} \quad (9)$$

The number of vehicles in T is $Td_{i,t}$. As a result, the additional delay per vehicle in T is

$$\overline{\Delta_{O_{it}}} = \frac{\left(\frac{1}{2} \right) \left(\frac{Td_{i,t}}{c_i} - T \right) Td_{i,t}}{Td_{i,t}} = \left(\frac{1}{2} \right) \frac{Td_{i,t}}{c_i} - \left(\frac{1}{2} \right) T = \frac{1}{2} T \left(\frac{d_{i,t}}{c_i} - 1 \right) \quad (10)$$

where $\overline{\Delta_{O_{it}}}$ is the additional average delay attributable to oversaturation for segment i at analysis period t .

Finally, the additional oversaturation delay rate $\overline{\Delta_{RO_{it}}}$ for segment i at analysis period t , over a 15-min (900-s) analysis period ($T = 900$) is found by

$$\overline{\Delta_{RO_{it}}} = \frac{\overline{\Delta_{O_{it}}}}{L_i} = \frac{450}{L} \left(\frac{d_{i,t}}{c_i} - 1 \right) \quad (11)$$

After the delay rate is determined, the travel rate is determined by summing the value of delay rate and travel rate under free-flow

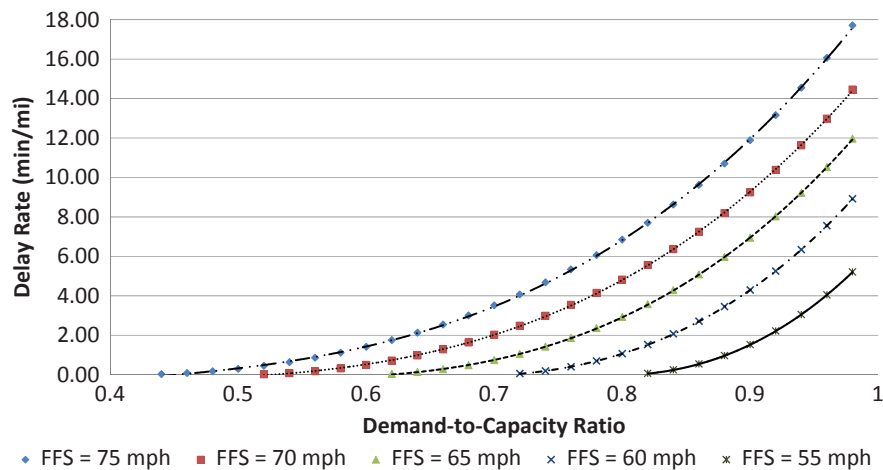


FIGURE 2 Fitted delay rate versus $d:c$ ratio models for undersaturated conditions.

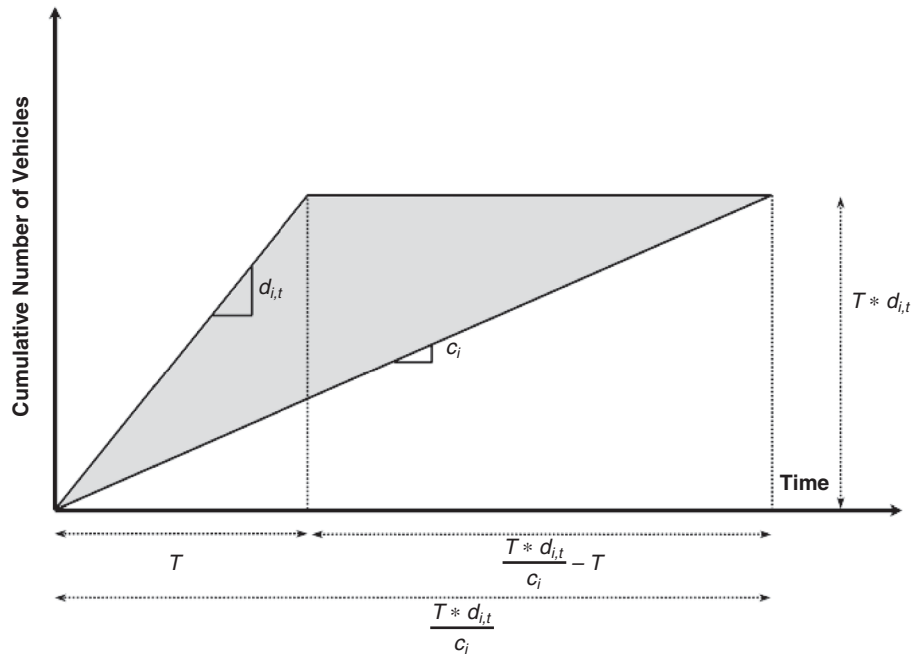


FIGURE 3 Delay rate calculation for oversaturated flow in period T .

conditions. The section travel time is then computed by multiplying the travel rate and segment length. Segment density is found by dividing the segment flow level by the travel speed. From section density, LOS can be estimated if desired. All performance measures can be aggregated to the facility level consistent with the HCM 2010 operational methodology.

Adjustments for Weave Section

As noted earlier, the proposed approach is focused on the basic freeway segment speed-flow model to estimate delay rate and travel speed on a section. When applied to weave sections, a CAF must account for the generally lower capacity in weaving segments than in basic segments. With that adjusted capacity, the basic segment planning method can be applied to weaving segments. To determine the weave section CAF, a large combination (10,000 total) of weave segment lengths, number of lanes, free-flow speeds, and weave segment demand levels was processed in a implementation of a batch run spreadsheet of the HCM weaving method (implemented in a Visual Basic computational engine). Both weave segment capacity and performance (speed) for various inputs were generated as output. The analysis was limited to an assumed representative weaving segment with the following characteristics:

- Minimum number of lane changes (LCs) that must be made by a single weaving vehicle moving from the on-ramp (R) to the freeway (F) is equal to 1: $LC(RF) = 1$;
- Minimum number of lane changes that must be made by a single weaving vehicle moving from the freeway to the off-ramp is equal to 1: $LC(FR) = 1$;
- Minimum number of lane changes that must be made by one ramp-to-ramp vehicle to complete a weaving maneuver is equal to zero: $LC(RR) = 0$; and

- Number of lanes (L) from which a weaving (W) maneuver may be made with one or no lane changes is equal to two: $N(WL) = 2$.

For each combination, the weave segment speed and capacity, as well as the associated basic freeway segment speed and capacity, were determined. From that data set, the capacity and SAFs for weave segments were obtained. A regression model was subsequently fitted to estimate a weave section CAF relative to the basic freeway segment capacity as a function of several independent variables. The proposed model is as follows:

$$CAF_{\text{weave}} = 0.884 - 0.0752V_r + 0.0000243L_s \quad (12)$$

where

- CAF_{weave} = CAF used for a weaving segment ($CAF_{\text{weave}} \leq 1.0$),
- V_r = ratio of weaving demand flow rate to total demand flow rate in weaving segment, and
- L_s = length of weaving segment (ft).

The proposed regression model has an adjusted R^2 value of .54, and all independent variable coefficients are significant at the 5% significance level. In addition, the model has less than 2% error in the prediction of the dependent variable for more than 67% of the input data.

Adjustments for Merge and Diverge Sections

Merge Segments As noted earlier, the approach used in this study generates an equivalent merge or diverge segment capacity that would yield speeds equivalent to a basic segment speed. Rouphail et al. (14) and Aghdashi et al. (15, 16) proposed two generic equations to determine the capacity c_i and speed $S_{i,t}$ for a basic freeway segment

as a function of the free-flow speed S_{FFS} , the breakpoint BP, and the prevailing demand $D_{i,t}$ on segment i in analysis period t :

$$c_i = 2,200 + 10(S_{FFS} - 50) \quad (13)$$

$$S_{i,t} = S_{FFS} - \frac{\left(\frac{S_{FFS} - c_i}{45}\right)}{(c_i - BP)^2} (D_{i,t} - BP)^2 \quad (14)$$

The SMS in merge segments is estimated from the HCM 2010, Chapter 13, and was computed for a large combination of input values. Freeway flow rates (v_F) ranged from 500 passenger cars per hour per lane to segment capacity (of basic freeway segments), while an acceleration lane length (L_A) of 1,000 ft and ramp free-flow speed of 40 mph were assumed. Ramp flow rates (v_r) ranged from zero to ramp capacity, and segment free-flow speed (S_{FFS}) ranged from 55 to 70 mph (in 5-mph increments). Ten thousand random combinations of these variables were created, and for each combination, the merge speed model from the HCM 2010 was used to estimate segment SMS. The equivalent capacity of the merge segment was then calculated by simultaneously solving Equations 13 and 14. The resulting CAFs had a wide range; however, the majority varied from 0.93 to 1.00. A regression approach was attempted to predict the CAF value on the basis of merge segment input variables; however, it produced a very poor fit. Therefore, an average CAF value of 0.95 was used for all merge segments regardless of their configuration. In application of the method, further user-specific calibration of that CAF is possible and is thus recommended for merge segments with known capacity constraints and congestion impacts.

Diverge Segments The same approach used for merge segments was applied to diverge segments, and the input values into the model had identical ranges. For the deceleration lane, the length was identical to that of the acceleration lane. Similarly, a regression model had a very poor fit to the data. Therefore, an average CAF value of 0.97 was used for diverge segments. Again, user-specific calibration of this factor is encouraged, and additional research on the capacity of (congested) diverge and merge segments is strongly recommended.

Ramp Section Capacity Calculation

The overall capacity of ramp sections is determined from a length-weighted average of the capacity of merge, basic, and diverge segments within a given section. The effective lengths of merge and diverge segments are 1,500 ft each in the HCM. If the section is shorter than 3,000 ft, the length of the basic freeway segment is considered zero, and the length of the merge and diverge segments is assumed to be half the section length.

Average Travel Time, Speed, and Density Calculations

The travel rate at section i at analysis period t is calculated by adding the associated travel rate under free-flow conditions TR_{FFS} and delay rate $\overline{\Delta}_{R_{i,t}}$. Then, travel time $TT_{i,t}$ is found by multiplying the travel rate by section length L_i :

$$TR_{i,t} = \overline{\Delta}_{R_{i,t}} + TR_{FFS} \quad (15)$$

$$TT_{i,t} = TR_{i,t} * L_i \quad (16)$$

The average speed $S_{i,t}$ in section i at analysis period t is computed as follows:

$$S_{i,t} = \frac{L_i}{TT_{i,t}} \quad (17)$$

Finally, the density $D_{i,t}$ of section i at analysis period t is found by dividing section demand $d_{i,t} = d_{i,t}$ by its speed $S_{i,t}$ as follows:

$$D_{i,t} = \frac{d_{i,t}}{S_{i,t}} \quad (18)$$

The proposed approach also provides a facility performance summary and reports if the facility is under- or oversaturated, along with the total facility travel time in minutes, SMS in miles per hour, average facility density in vehicles per mile, total queue length in vehicles, and LOS.

CASE STUDY

The proposed planning-preliminary engineering approach was applied to Example Problems 1 and 2 from Chapter 10 of the HCM 2010. The first problem represented an undersaturated freeway facility, and the second one applied the approach to an oversaturated case. For both example problems, the approach was applied to the initial four time intervals and the first 10 sections of the facility by using an identical set of input variables. The freeway facility has 11 HCM segments or seven sections (in this case, these represent points at which demand and capacity change), as shown in Figure 4.

The first section was a basic section, identical to HCM segmentation definition. An on-ramp segment was located just downstream of the section that resulted in changes in the demand. As a result, a new section must be defined. A basic freeway segment and an off-ramp segment followed this on-ramp segment. From the on-ramp [(ONR) Segment 2 in Figure 4] to the off-ramp segment [(OFR) Segment 4 in Figure 2], the capacity and demand on the freeway was fixed, and as a result, all three segments were included in a single ramp section. After the off-ramp segment, the demand level in the facility would change and remain fixed until the next on-ramp roadway. As a result, a basic freeway section was defined (Section 3). Sections on the rest of the freeway facility were defined in the same way. Table 2 shows the demand level for Example Problem 1 at the facility entry and exit points. For Example Problem 2, the demand levels are increased by 10% across the facility.

RESULTS

This section presents the results of applying the proposed planning method to the two example problems. In addition, the results are compared to the operational method in the HCM 2010, and the differences are highlighted.

Example Problem 1

The first example problem was designed to include only undersaturated flow conditions. Table 3 shows the $d:c$ ratios for different

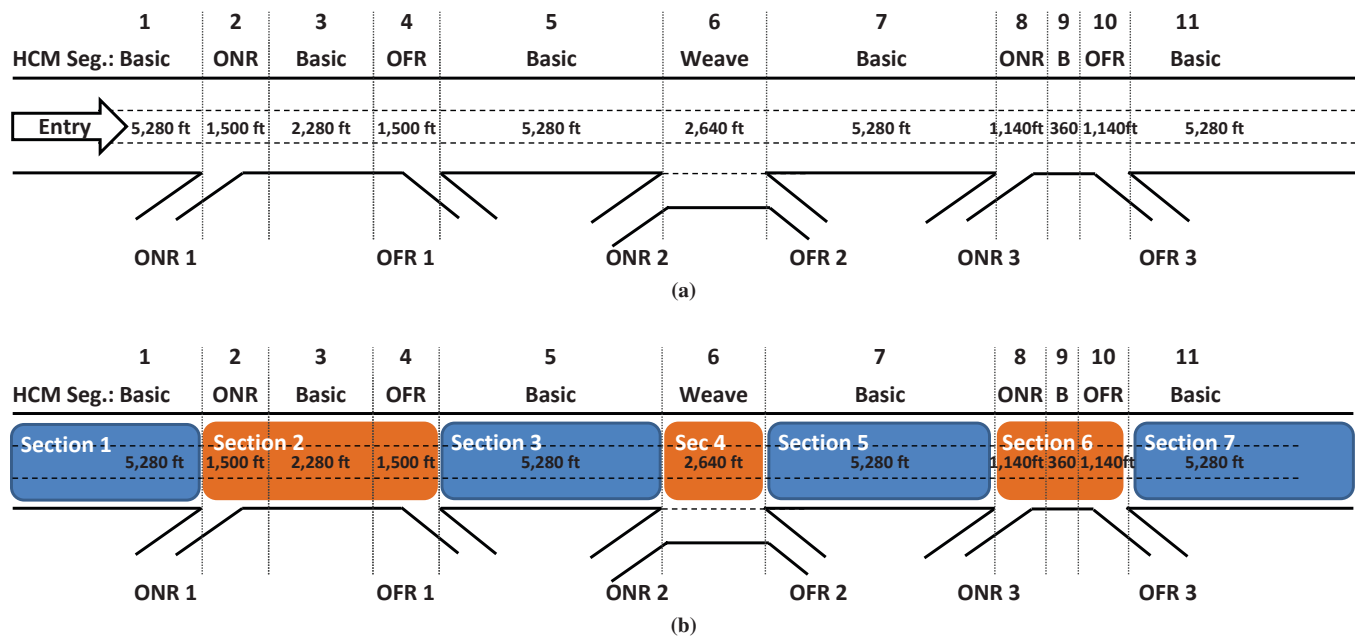


FIGURE 4 Schematic of facility example problem: (a) HCM segmentation and (b) section definition in proposed planning approach (seg. = segment).

sections and segments of this example problem. Section 2 corresponds to HCM Segments 2, 3, and 4, as reflected in Table 3, and Section 6 (HCM Segments 8, 9, and 10). As Table 3 shows, the maximum difference between the $d:c$ calculated by the proposed planning and HCM 2010 operational approach was below 0.06 unit. This is not a practically significant difference and indicates that the proposed approach has great potential to estimate $d:c$ ratios accurately for undersaturated flow conditions.

Table 4 summarizes the average travel time and density calculated by applying the planning-preliminary engineering level and the HCM 2010 operational approaches to Example Problem 1. The travel time in Section 2 should be compared with the sum of travel times on Segments 2, 3, and 4 and the travel time in Section 6 with that of Segments 8, 9, and 10. For density, weighted average value of the three corresponding segments should be compared with their associated section.

TABLE 2 Demand Flow Rates on Subject Facility for Example Problem 1

Analysis Period	Entry Demand Flow Rate	On-Ramp 1	Off-Ramp 1	On-Ramp 2	Off-Ramp 2	On-Ramp 3	Off-Ramp 3
1	4,505	450	270	540	360	450	270
2	4,955	540	360	720	360	540	270
3	5,225	630	270	810	360	630	450
4	4,685	360	270	360	360	450	270

TABLE 3 $d:c$ Ratio on Sections and HCM Segments for Example Problem 1

Analysis Period	Method	Sec. 1	Sec. 2				Sec. 3	Sec. 4	Sec. 5	Sec. 6			Sec. 7
		Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11	Seg. 12
1	Operational Planning	0.67	0.74	0.74	0.74	0.70	0.63	0.72	0.79	0.79	0.79	0.75	0.75
		0.67		0.75		0.70	0.62	0.72		0.82			
2	Operational Planning	0.74	0.82	0.82	0.82	0.76	0.71	0.82	0.90	0.90	0.90	0.86	0.86
		0.74		0.84		0.76	0.70	0.82		0.93			
3	Operational Planning	0.78	0.87	0.87	0.87	0.83	0.77	0.90	0.99	0.99	0.99	0.92	0.92
		0.78		0.89		0.83	0.76	0.90		1.03			
4	Operational Planning	0.70	0.75	0.75	0.75	0.71	0.61	0.71	0.78	0.78	0.78	0.74	0.74
		0.70		0.77		0.71	0.61	0.71		0.84			

NOTE: Sec. = section.

TABLE 4 Travel Time and Density Results for Example Problem 1

Time Period	Method	Sec. 1	Sec. 2		Sec. 3	Sec. 4	Sec. 5	Sec. 6			Sec. 7	Facility	
		Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10		Seg. 11
Travel Time on Sections or HCM Segments for Example Problem 1 (s)													
1	Operational Planning	60.00	18.97	26.04	18.23	60.00	37.50	60.10	14.56	4.60	13.88	60.30	374.18
		60.00		60.30		60.00	30.00	60.10		30.80		60.30	361.50
2	Operational Planning	60.20	19.22	26.53	18.33	60.40	38.54	61.43	14.89	4.70	13.98	62.61	380.84
		60.20		61.90		60.40	30.00	61.40		33.00		62.60	369.50
3	Operational Planning	60.61	19.48	27.22	18.36	61.75	39.05	64.17	15.36	4.85	14.08	65.45	390.39
		60.60		63.90		61.80	30.20	64.10		36.50		65.40	382.50
4	Operational Planning	60.00	19.01	26.04	18.23	60.00	36.22	60.00	14.53	4.59	13.88	60.20	372.69
		60.00		60.50		60.00	30.00	60.00		31.00		60.50	362.00
Density on Sections or HCM Segments for Example Problem 1 (vphpm)													
1	Operational Planning	25.00	30.70	27.70	29.40	26.00	27.20	27.10	33.20	33.20	31.70	28.20	27.50
		25.00		27.70		26.00	21.80	27.10		30.30		28.20	27.20
2	Operational Planning	27.60	34.50	31.30	32.80	28.70	31.30	31.30	38.50	38.50	36.20	33.40	31.30
		27.60		34.51		28.74	24.40	31.25		36.88		33.40	31.10
3	Operational Planning	29.30	37.20	34.20	35.00	31.90	34.60	35.80	43.90	43.90	40.30	37.70	34.80
		29.30		34.62		31.94	26.83	35.84		43.68		37.65	34.80
4	Operational Planning	26.00	31.30	28.20	30.00	26.50	25.80	26.50	32.50	32.50	31.10	27.60	27.50
		26.03		28.26		26.53	21.40	26.53		31.18		28.88	27.60

NOTE: vphpm = vehicles per hour per mile.

As Table 4 clearly shows, the proposed approach produced travel times across the facility that were very close to the operational approach values of the HCM 2010 in each time interval. In fact, the maximum difference between the two approaches for undersaturated flow conditions was no more than 3.4%, indicating an accurate estimate of average travel time at the facility level. The difference between the two approaches was attributable mostly to merge (~6.8%) and weaving segments (~22.7%). This result was not surprising, as the planning–preliminary engineering method greatly simplifies the way in which those two types of segments are treated. The same trend was observed for density estimation. The maximum observed difference in facility density was limited to 1.1%, indicating a very high accuracy level. The difference again was lowest for basic sections (0.16%) and was followed by merge–diverge sections (~5.35%) and weaves (22.46%). These results seemed to indicate the need for application of an additional adjustment in free-flow speed—and in capacity—to weaving sections if the differences are to be further reduced.

Example Problem 2

Example Problem 2 was designed to include some oversaturated periods during the study. Table 5 summarizes the $d:c$ ratios for all sections of the facility for both the proposed and the HCM 2010 operational approaches. The proposed planning approach generated $d:c$ ratios that were close to those of the HCM chapter, at least for the first five sections. In Section 6, however, the differences became larger as soon as oversaturation started (Analysis Periods 2 through 4). The HCM 2010 assumed no change in capacity of merge and diverge segments. In contrast, the proposed approach estimated an equivalent capacity for merge and diverge segments that was lower than the capacity of basic freeway segments. This feature of the proposed approach contributed to the difference between $d:c$ ratios on Section 6 at Analysis Periods 2 through 4. In addition, the proposed approach added the unserved demand from a previous analysis period to the next, yielding higher $d:c$ ratios. In the operational method of the

TABLE 5 $d:c$ Ratio on Sections and HCM Segments for Example Problem 2

Time Period	Method	Sec. 1	Sec. 2				Sec. 3	Sec. 4	Sec. 5	Sec. 6			Sec. 7
		Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11	
1	Operational Planning	0.74	0.82	0.82	0.82	0.77	0.70	0.80	0.88	0.88	0.88	0.83	
		0.74		0.84		0.73	0.65	0.76		0.87		0.79	
2	Operational Planning	0.82	0.91	0.91	0.91	0.85	0.79	0.91	1.00	1.00	1.00	0.95	
		0.82		0.93		0.85	0.77	0.91		1.04		0.95	
3	Operational Planning	0.86	0.97	0.97	0.97	0.92	0.85	1.00	1.10	1.10	1.10	1.02	
		0.86		0.99		0.92	0.84	0.99		1.18		1.06	
4	Operational Planning	0.77	0.83	0.83	0.83	0.79	0.68	0.79	0.86	0.86	0.86	0.82	
		0.77		0.85		0.79	0.68	0.79		1.08		1.05	

TABLE 6 Travel Time and Density Results for Example Problem 2

Time Period	Method	Sec. 1	Sec. 2				Sec. 3	Sec. 4	Sec. 5	Sec. 6			Sec. 7	Facility
		Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11		
Travel Time on Section or HCM Segments for Example Problem 2 (s)														
1	Operational Planning	60.20	19.26	26.53	18.30	60.61	38.46	61.12	14.81	4.68	13.95	61.86	379.76	
		60.20		61.90		60.10	30.00	60.40		31.50		60.80	364.90	
2	Operational Planning	61.43	19.63	27.91	18.43	62.28	39.65	64.63	15.39	4.86	14.06	66.91	395.19	
		61.40		65.60		62.30	30.30	64.60		36.70		66.90	387.80	
3	Operational Planning	62.72	20.05	29.33	18.46	67.16	63.83	103.45	15.48	4.89	14.11	65.93	465.42	
		62.80		69.50		65.30	31.10	70.00		111.30		86.70	496.70	
4	Operational Planning	60.61	19.30	26.71	18.33	72.14	45.92	66.79	15.18	4.79	14.06	64.75	408.57	
		60.60		62.40		60.80	30.00	60.80		77.99		45.56	398.15	
Density on Section or HCM Segments for Example Problem 2 (vphpm)														
1	Operational Planning	27.90	34.50	31.30	32.80	29.20	31.00	30.60	37.50	37.50	35.30	32.10	31.00	
		27.90		31.60		27.30	22.90	28.50		32.60		29.80	29.40	
2	Operational Planning	31.30	39.00	36.50	36.70	32.90	35.80	36.50	44.20	44.20	40.40	39.70	36.10	
		31.29		37.06		32.85	27.34	36.45		43.94		39.66	36.20	
3	Operational Planning	33.70	42.50	40.90	39.10	38.00	58.80	57.70	44.70	44.70	40.70	38.30	43.70	
		33.70		41.80		37.48	30.66	43.41		133.24		54.03	49.40	
4	Operational Planning	29.20	35.20	32.10	33.40	36.00	39.40	36.90	42.10	42.10	38.90	36.70	35.50	
		29.17		32.36		29.85	23.75	29.85		77.99		46.56	37.00	

HCM, this concept was applied as well, but the “adjusted $d:c$ ” after congestion was never reported in the method. Thus, the authors also expected the difference to continue to increase as long as the oversaturated conditions remained, as more vehicles were stored on the section because of lower capacity, which increased demand level in the next analysis period.

The proposed approach generated facility travel times that were at most 6.7% different from the values predicted by the operational method (Table 6). Both approaches estimated comparable section values for travel time and density before the onset of oversaturation; however, some significant differences occurred afterward because of lower estimated capacities on ramp sections. This difference was expected to increase if oversaturated conditions persisted, as a higher number of vehicles would be stored on the facility.

Similar trends were observed for facility density, as expected. The maximum difference between facility densities calculated by the proposed and the HCM 2010 operational approaches was 13.4%. Density values were very comparable before the start of the oversaturated periods; however, the difference became more significant during oversaturated periods.

CONCLUSIONS

This paper presented a methodology at the planning–preliminary engineering level compatible with the HCM 2010 to analyze freeway facilities. The approach minimizes input data requirements and uses the hourly k -factor and AADT values to generate a demand profile for a 1-h study period. In addition, the approach proposes a new definition for freeway sections that significantly simplifies the segmentation process. By using the planning-level approach, these practices yielded a significant reduction in the time and effort required to analyze a freeway facility. Compared with the operational method

in the HCM 2010, the proposed approach requires about 10% of the time and effort to analyze a freeway facility.

The methodology first estimates $d:c$ adjustment factors for each section. In oversaturated flow conditions, the number of vehicles queued on a section in one analysis period is added to its demand in the next analysis period, and $d:c$ ratios are adjusted accordingly.

The underlying methodology relies on developing a relationship between the delay rate on a basic freeway section and its $d:c$ ratio. For weaving sections, the study proposes CAFs that are based on the volume ratio and the length of the section. By using these factors, $d:c$ ratios on weaving sections are adjusted, and then the segment is treated similarly to a basic freeway segment. For merge and diverge sections, a novel methodology is proposed to estimate their equivalent capacity on the bases of demand level, free-flow speed, and SMS by solving the basic freeway segment speed–flow relationship to estimate section capacity. Then capacity adjustment factors are calculated for merge and diverge segments, their $d:c$ ratio is adjusted accordingly, and they are treated as basic freeway segments.

The proposed approach was implemented in the two example problems adopted from the HCM 2010 and produced very promising results. The facility travel time was at most 3.4%, and facility density was at most 1.1%, different from those found by the HCM 2010 operational methodology for undersaturated flow conditions. These differences were 6.7% and 13.0% in oversaturated conditions, respectively.

Developing speed adjustment factors for weaving sections can bring the estimated average travel times under the proposed approach closer to those found by the HCM 2010 operational approach. In addition, the user is encouraged to scrutinize capacity closely in merge and diverge segments on the bases of local defaults and experience and to calibrate capacities for other known bottlenecks in the study area. Finally, while estimates of travel time and density at the facility level are within reasonable ranges, travel times and density values

at the section level should be interpreted cautiously in oversaturated flow conditions.

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