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Replication of Daily and Monthly Freeway Demand Variations for Travel Time Reliability Procedures

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ABSTRACT

The sixth edition of the Highway Capacity Manual incorporates travel time reliability assessment procedure for freeways and urban streets. Several demand adjustment factors, referred to by demand multipliers, are used to capture traffic demand variation across different days and months. These factors are currently produced by referencing the average daily traffic volume of each day-month combination to a base daily volume. Practitioners however usually perform traffic analyses during specific times of day, e.g., peak periods, off-peak periods, or even peak hours, demand multipliers may so replicate demand variation more accurately if they were based on traffic volumes concurred in time intervals narrower than a day. This paper investigates six criteria or periods to derive demand multipliers: full-day, pre AM-peak, AM peak-period, midday, PM peak-period, and post PM-peak. The study explores how these periods impact the scale of demand multipliers and travel time reliability assessment. It was found that the main statistics of demand multipliers, i.e., mean, range, and standard deviation, greatly differ across the different multiplying periods. When analyzing peak periods on oversaturated corridors, the adoption of daily-volume multipliers was found to significantly overestimate the mean Travel Time Index and Planning Time Index during both AM and PM peak periods, the accuracy of travel time reliability estimation was considerably influenced. The study concludes with major findings and recommendations for possible enhancements to the HCM travel time reliability procedure.

INTRODUCTION AND LITERATURE SEARCH

Freeway traffic demand is a key determinant for major Highway Capacity Manual (HCM) (1) procedures such as travel time reliability analysis, level-of-service assessment, and speed estimation. Demand is also a fundamental input for traveler information systems, intelligent transportation systems, ramp metering schemes, work zone management, rerouting plans, congestion pricing, lane use restriction, estimation of accident rates, pavement life analysis, and many other applications. The importance of estimating demand accurately has increased recently because of the growing urban congestion and the tendency to minimize spending on new infrastructure by relying more on active demand management (ADM) strategies. In particular, the increasing use of travel time reliability as a performance measure calls for accurate demand estimation methods that well capture its daily and seasonal variations.

The sixth edition of the HCM (1) incorporates a new travel time reliability assessment procedure. This procedure, explained in chapter eleven, aims at developing the distribution of travel times along a highway corridor so the day-to-day fluctuation in travel time is captured. Several reliability measures are produced by the procedure, e.g., mean Travel Time Index and Planning Time Index. There are essentially two temporal dimensions for any travel time reliability analysis; Reliability Reporting Period (RRP) (i.e., the set of days over which the reliability of the subject freeway is assessed, usually taken as the weekdays over a year) and Study Period (SP) (i.e., the fixed time interval within a day during which the reliability is assessed). The procedure generates multiple scenarios representing the likely traffic conditions (e.g., seasonal demand patterns, inclement weather, work zones, and incidents) in order to replicate travel time variability (1-3). Usually, 240 scenarios are created over a year and this means that each weekday-month combination is given four replications (4 x 5 weekdays x 12 months). In addition to defining the facility basic geometric and traffic features, the analyst needs to use available archived data to define facility-specific inputs pertaining to daily and seasonal demand variations, weather, incidents, and work zones. In the absence of such data, default set of inputs can be used although this may impact the analysis accuracy. Demand multipliers or adjustments are used to capture demand variation across different days and months, 60 multipliers are used so that each weekday-month combination is associated with a distinct multiplier. These multipliers are traditionally produced by dividing the average daily traffic volume of each weekday-month combination by a reference daily volume, the latter has been usually taken as the average daily traffic volume for a base scenario, e.g., Mondays of January or alternatively the average annual daily traffic (AADT). Exhibits 11-18 and 11-19 of the HCM present default daily-volume-driven demand multipliers for urban and rural freeways based on national dataset (1, 3). The provision of these multipliers is considered the only available quantitative method in the HCM that can be used to directly identify seasonal and daily demand variation.

Studies are traditionally more motivated to explore highway capacity characteristics rather than demand, this has narrowed down the demand-driven contributions found in the literature. Few studies were found to particularly explore daily and seasonal variation of freeway demand. Gunawardena et al. (4) investigated the seasonal and daily effects on the K-factor (proportion of the AADT that occurs during the peak-hour) and the D-factor (proportion of the highway volume travelling in the peak-direction). They concluded that season and day-of-the-week have significant influence on these factors. The study also introduced conservative values for the factors, but no guidelines were given to compute factors belonging to each day-month combination. In Connecticut, Ivan et al. (5) analyzed the hourly volume as a proportion of the daily traffic and explored the feasibility of categorizing the influential factors into groups. Results revealed that months, weekdays and hours can be grouped to a considerable level in order to simplify traffic volume models although the resulting grouping was however different across sites. Crevo (6) estimated traffic volumes by purpose and hour-of-the-day as a percentage of ADT using a regional sample size, i.e., the South Atlantic region. Loudon et al. (7) explored the relationship between peak-hour volume and peak three-hour period volume using the volume-to-capacity ratio and facility type, Allen et al. (8) also explored similar relationship but based on congestion level, trip purpose and trip distance.

Only few efforts in the literature targeted the daily and seasonal demand variations. Such studies also did not explore demand variation from the travel time reliability perspective. Albeit the significant importance of freeway demand estimation, the current HCM guidelines set to estimate daily and seasonal demand variations are limited and further improvements and lessons are needed to better capture and explain that variation.

LIMITATIONS OF DAILY-BASED DEMAND MULTIPLIERS

In travel time reliability analysis, traffic conditions within a pre-determined SP are analyzed repetitively over the entire RRP but with varying inputs. The SP usually consists of one or several hours, i.e., not a full-day, because practitioners usually associate traffic analysis with specific periods such as morning-peak, evening-peak, midday, pre morning-peak, and post evening-peak. The HCM currently uses the daily-based demand multipliers to replicate the daily and seasonal demand variations regardless of the time-of-day that is chosen for the SP. This assumes that when the daily traffic volume changes due to changing the month or the weekday, traffic volume during all times of day changes in the same direction and magnitude. This can be actually questionable because of many reasons.

Different Times of Day Have Different Types of Trips

Peak periods are mainly composed of mandatory daily commuting trips, and so their demand can be more repetitive and less sensitive to seasons and days as compared to off-peak periods which are composed of recreational trips. Demand multipliers of peak periods are therefore expected to be of smaller magnitude and narrower range as compared to off-peak periods.

Different Times of Day May Respond Differently to Daily and Seasonal Variations

On Fridays, for example, traffic volume during midday and evening times can be larger as compared to other weekdays because of end-of-the-week recreational activities, but Friday morning traffic may in contrast have a smaller volume. Similarly, summer may have larger midday and evening traffic volumes as compared to other seasons in response to the increasing touristic and recreational activities; however, traffic volume during the summer morning-peaks is not likely to substantially increase because of the school off-season.

Peak Spreading is Not Linear

Because of capacity constraints, traffic volume of the peak-period or the peak-hour does not increase necessarily in the same increasing rate of the daily-volume. When daily traffic volume substantially increases, the proportion of the daily volume that occurs during the peak-period drops because more traffic tends to travel during the shoulder periods (immediately before or after the peak-period) to avoid the resulting congestion.

STUDY CONTRIBUTION

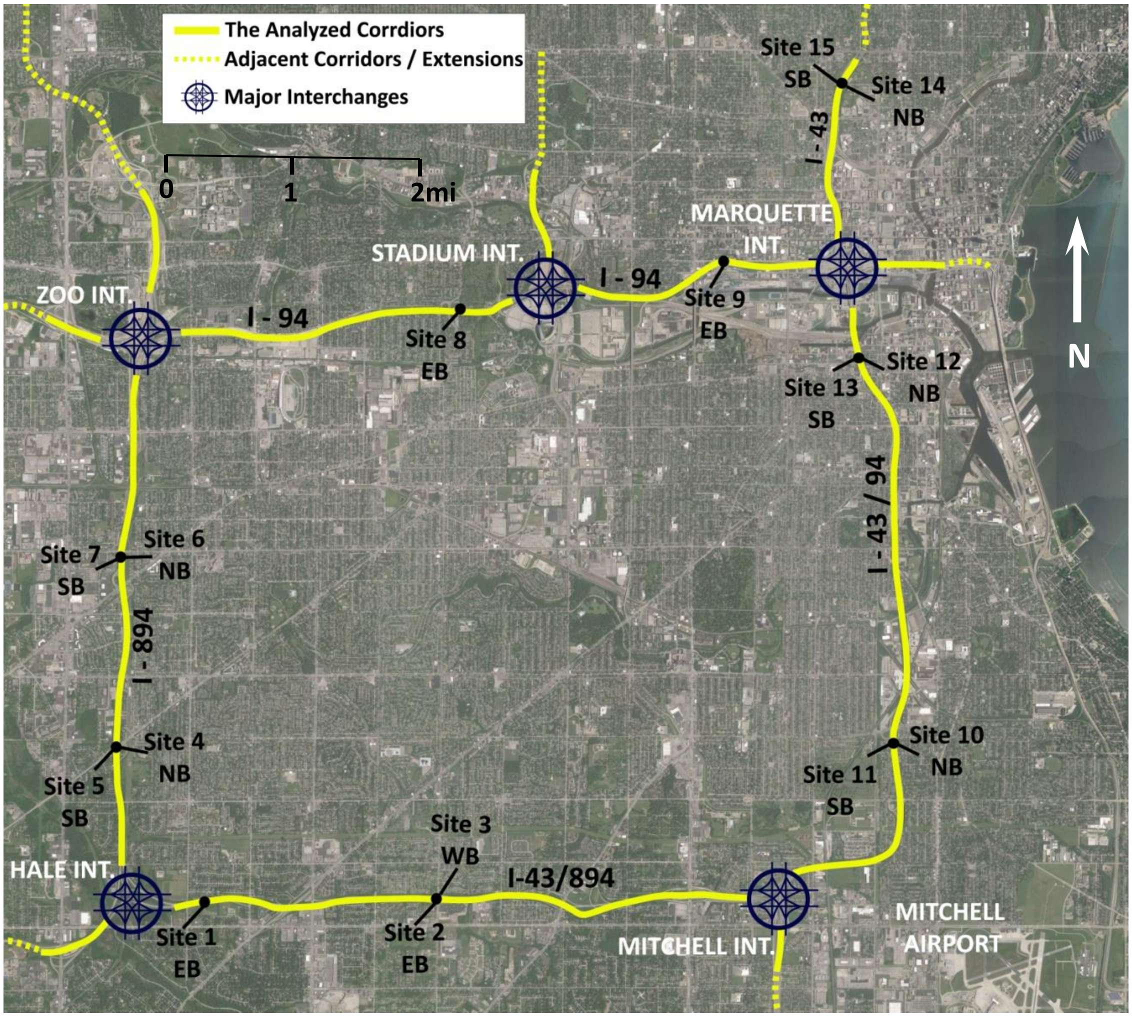
The HCM and previous literature do not provide sufficient guidelines to capture the seasonal and daily variations of traffic demand. Estimating seasonal and daily demand variations accurately is the most important first step in many daily traffic applications and specially in travel time reliability analysis. Generalizing the use of demand multipliers derived by full-day traffic volumes for all times of day merits further investigation and should be carefully assessed. Traffic demand multipliers might replicate traffic volumes more accurately if they were based on time intervals narrower than a day. This paper investigates six criteria or periods that can be used to derive demand multipliers: full-day, pre AM-peak, AM peak-period, midday, PM peak-period, and post PM-peak. The study explores how these criteria impact the scale of demand multipliers and travel time reliability assessment. The HCM reliability methodology is evolving and will be increasingly applied in daily practice, more insights and enhancements to accurately estimate demand levels are thereby urgently needed. Needless to mention that demand estimation techniques are not only useful for travel time reliability analysis but can be used in various daily traffic applications.

DATA AND SITES

Traffic data covered a five-year period extending from January 2011 through December 2015, the data were retrieved from the WisTransPortal data hub which has been developed through an ongoing collaboration between the Wisconsin Traffic Operations and Safety (TOPS) Laboratory at the University of Wisconsin-Madison and the Wisconsin Department of Transportation. The WisTransPortal data hub provided traffic volume, speed, and occupancy at fifteen sites along several corridors in Milwaukee freeway system (Figure 1) covering over 40 miles of directional freeway alignments. All sites had three-lane cross sections except Sites 12, 13, and 15 (four-lane sections) and Site 14 (five-lane section). The selected sites satisfied particular criteria during the study period, specifically they were:

- Spread spatially over major urban freeway corridors in Milwaukee
- Not followed nor preceded directly by active bottlenecks
- Separated by at least three ramp junctions

The study excluded data that showed a deviation from normal traffic behavior which could be the result of malfunctioning detectors, incidents, and work zones. National holidays and days immediately preceding or following holidays were excluded from the analysis. Logical values of flow, speed, and occupancy and logical relationships between these variables were checked. Furthermore, 1min data were checked against one hour data aggregations; data aggregations were found to work accurately. If a single hour data was missing or corrupted the whole day data were subsequently removed. After finishing data screening, a total of 18,649 daily records (447,576 hours) were used in the analysis covering all sites and all years.



Note: roads intersecting the sites are: 92nd St. at Site 1, 60th St. at Sites 2 and 3, Beloit Rd. at Sites 4 and 5, Lincoln Ave. at Sites 6 and 7, Hawley St. at Site 8, 25th St. at Site 9, Holt Ave. at Sites 10 and 11, Virginia St. at Sites 12 and 13, and finally Brown St. at Sites 14 and 15.

Figure 1. The analyzed freeway sites: Milwaukee, WI.

TRAFFIC DEMAND MULTIPLIERS BY DIFFERENT PERIODS

Calculation of Demand Multipliers

Traffic demand multipliers are defined herein as factors or adjustments that aim at estimating the monthly and daily demand variations and they are derived by dividing the average traffic volume corresponding to each weekday-month combination by a reference demand according to the following equation:

$$DM_{ij} = \frac{average\ traffic\ demand\ for\ day\ (i)\ of\ month\ (j)}{base\ or\ reference\ demand} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Where:

DM_{ij}: demand multiplier for day (i) during month (j)
i = one of the five weekdays: Monday to Friday
j = month of the year: January to December

Taking the base demand as the average demand observed in Mondays of January, i.e., similar to the HCM, and considering the site and time-of-day impacts, equation (1) may be rewritten as:

$$DM_{ijkl} = \frac{average\ traffic\ demand\ for\ day\ (i)\ of\ month\ (j)}{average\ demand\ for\ Mondays\ in\ January} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Where:

k = the site where the demand is measured or the network over which the demand is aggregated
l = demand multiplying period, i.e., the time-of-day interval during which the demand is measured

The HCM uses daily traffic demands for equation (2), so the time interval (l) is set to one full day. This research explores six demand multiplying intervals or periods: full-day (over 24 hours), pre AM-peak (0:00-5:59), AM peak-period (6:00-9:59), midday (10:00-13:59), PM peak-period (14:00-17:59), and post PM-peak (18:00-23:59). Those time intervals will be referred to by demand multiplying periods (DMPs). The timing determination of the AM and PM peak periods was carefully made based on time series analysis and previous relevant research experience in Milwaukee (9, 10).

Basic Statistics of Demand Multipliers

Table 1 presents the derived sixty demand multipliers (5 days by 12 months) over all the analyzed network and for the six DMPs. In compliance with equation 2, all volumes were referenced to average volumes recorded in Mondays of January, all multipliers were accordingly equal to 1.00 for the Monday-January combination. Demand multipliers differ greatly and substantially across different DMPs, and this is noticed over all the sixty day-month combinations. Replacing a DMP by another DMP would yield significantly different multiplier and demand estimation would consequently suffer from a considerable inaccuracy. As an example, for Friday-August combination, which had the largest daily demand, demand multipliers were 1.2398, 1.2947, 1.0535, 1.3635, 1.1124, and 1.5567 for the full-day, pre AM-peak, AM-peak, midday, PM-peak and post PM-peak respectively.

TABLE 1. Day-Month Demand Multipliers by Different DMPs

Month	DMP	Monday	Tuesday	Wednesday	Thursday	Friday
Jan	**Full-Day**	**1.0000**	**1.0334**	**1.0662**	**1.0568**	**1.1184**
	Pre AM-Peak	1.0000	1.0753	1.1089	1.1382	1.1329
	AM Peak-Period	1.0000	1.0012	1.0144	1.0096	0.9812
	Midday	1.0000	1.0113	1.0344	1.0557	1.1487
	PM Peak-Period	1.0000	1.0220	1.0508	1.0280	1.0856
	Post PM-Peak	1.0000	1.1103	1.1893	1.1454	1.3327
Feb	**Full-Day**	**1.0511**	**1.0646**	**1.0833**	**1.0896**	**1.1380**
	Pre AM-Peak	1.0203	1.1281	1.1218	1.1551	1.1353
	AM Peak-Period	1.0093	1.0356	1.0156	1.0153	0.9878
	Midday	1.0557	1.0556	1.0668	1.0797	1.1628
	PM Peak-Period	1.0503	1.0362	1.0658	1.0567	1.0920
	Post PM-Peak	1.1192	1.1417	1.2171	1.2411	1.4055
Mar	**Full-Day**	**1.0465**	**1.0562**	**1.0901**	**1.1255**	**1.1551**
	Pre AM-Peak	1.0502	1.1273	1.1388	1.1915	1.1825
	AM Peak-Period	1.0060	0.9753	1.0106	1.0334	1.0003
	Midday	1.0461	1.0456	1.0887	1.1230	1.2312
	PM Peak-Period	1.0432	1.0532	1.0649	1.0944	1.0903
	Post PM-Peak	1.1108	1.1676	1.2323	1.2912	1.3895
Apr	**Full-Day**	**1.0693**	**1.1080**	**1.1320**	**1.1330**	**1.1755**
	Pre AM-Peak	1.0707	1.1732	1.1764	1.2049	1.1912
	AM Peak-Period	1.0178	1.0528	1.0526	1.0383	0.9967
	Midday	1.0824	1.1041	1.1223	1.1394	1.2564
	PM Peak-Period	1.0612	1.0725	1.1106	1.0990	1.1308
	Post PM-Peak	1.1423	1.2283	1.2792	1.2949	1.4113
May	**Full-Day**	**1.1089**	**1.1363**	**1.1324**	**1.1531**	**1.2078**
	Pre AM-Peak	1.1360	1.2193	1.2184	1.2375	1.2507
	AM Peak-Period	1.0579	1.0725	1.0510	1.0422	1.0462
	Midday	1.1165	1.1175	1.1312	1.1670	1.2525
	PM Peak-Period	1.0931	1.1052	1.0908	1.1002	1.1363
	Post PM-Peak	1.1912	1.2732	1.2912	1.3562	1.4945
Jun	**Full-Day**	**1.1290**	**1.1648**	**1.1624**	**1.2036**	**1.2283**
	Pre AM-Peak	1.1942	1.3901	1.2791	1.3373	1.3122
	AM Peak-Period	1.0642	1.0761	1.0709	1.0873	1.0453
	Midday	1.1513	1.1998	1.1822	1.2427	1.3156
	PM Peak-Period	1.0891	1.0983	1.0798	1.1011	1.1255
	Post PM-Peak	1.2402	1.2831	1.3669	1.4483	1.5330
Jul	**Full-Day**	**1.1183**	**1.1624**	**1.1806**	**1.1979**	**1.2213**
	Pre AM-Peak	1.4119	1.3573	1.4088	1.3013	1.3007
	AM Peak-Period	1.0309	1.0538	1.0672	1.0720	1.0243
	Midday	1.1843	1.1969	1.2358	1.2523	1.3219
	PM Peak-Period	1.0356	1.0869	1.0810	1.0995	1.1144
	Post PM-Peak	1.2013	1.3359	1.3648	1.4428	1.5390
Aug	**Full-Day**	**1.1243**	**1.1697**	**1.1737**	**1.1999**	**1.2398**
	Pre AM-Peak	1.1869	1.2645	1.2401	1.2903	1.2947
	AM Peak-Period	1.0598	1.0913	1.0787	1.0770	1.0535
	Midday	1.1772	1.1883	1.2112	1.2519	1.3635
	PM Peak-Period	1.0564	1.0948	1.0793	1.0977	1.1124
	Post PM-Peak	1.2455	1.3515	1.3994	1.4540	1.5567

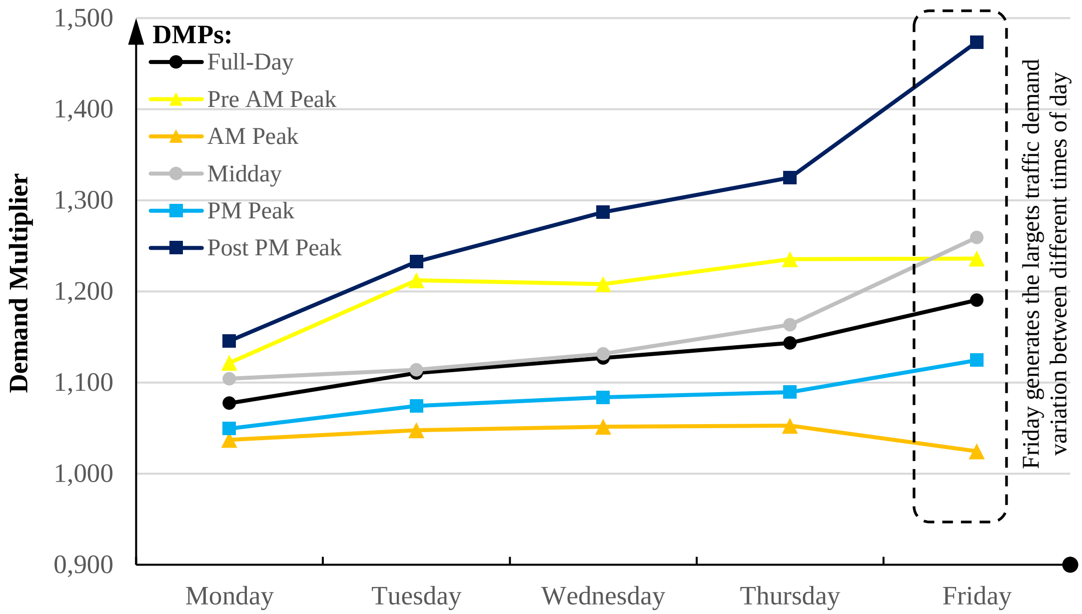
TABLE 1 (Continued). Day-Month Demand Multipliers by Different DMPs

Month	DMP	Monday	Tuesday	Wednesday	Thursday	Friday
Sep	**Full-Day**	**1.1086**	**1.1336**	**1.1479**	**1.1679**	**1.2301**
	Pre AM-Peak	1.1142	1.2351	1.2057	1.2562	1.2695
	AM Peak-Period	1.0793	1.0872	1.0877	1.0934	1.0811
	Midday	1.1381	1.1239	1.1362	1.1903	1.2949
	PM Peak-Period	1.0576	1.0793	1.0930	1.0961	1.1268
	Post PM-Peak	1.1982	1.2654	1.3188	1.3370	1.5276
Oct	**Full-Day**	**1.0895**	**1.1356**	**1.1454**	**1.1663**	**1.2214**
	Pre AM-Peak	1.0964	1.2358	1.2122	1.2316	1.2375
	AM Peak-Period	1.0650	1.0917	1.0874	1.0877	1.0500
	Midday	1.1052	1.1284	1.1468	1.1836	1.2952
	PM Peak-Period	1.0645	1.1004	1.1018	1.1003	1.1434
	Post PM-Peak	1.1451	1.2307	1.2764	1.3457	1.5082
Nov	**Full-Day**	**1.0896**	**1.1150**	**1.1264**	**1.1496**	**1.2053**
	Pre AM-Peak	1.0829	1.2100	1.1968	1.2485	1.2688
	AM Peak-Period	1.0791	1.0804	1.0753	1.0893	1.0840
	Midday	1.1195	1.1258	1.1279	1.1565	1.2481
	PM Peak-Period	1.0686	1.0645	1.0947	1.0960	1.1234
	Post PM-Peak	1.1067	1.2017	1.2267	1.2827	1.4442
Dec	**Full-Day**	**1.0410**	**1.1190**	**1.1434**	**1.1374**	**1.1768**
	Pre AM-Peak	1.0738	1.1837	1.1929	1.2172	1.1745
	AM Peak-Period	0.9889	1.0055	1.0328	1.0308	0.9839
	Midday	1.1128	1.1630	1.1812	1.1886	1.2674
	PM Peak-Period	0.9970	1.0971	1.0972	1.0939	1.1149
	Post PM-Peak	1.0937	1.2476	1.3196	1.2770	1.4559

Notes:
-The table provides the sixty day-month demand multipliers for the six multiplying periods (360 multipliers in total).
-The multipliers provided in the table are computed over all sites and all analysis years, i.e., demand for each day-month combination was the average of all observations recorded at all sites and during all years for that day-month pair.

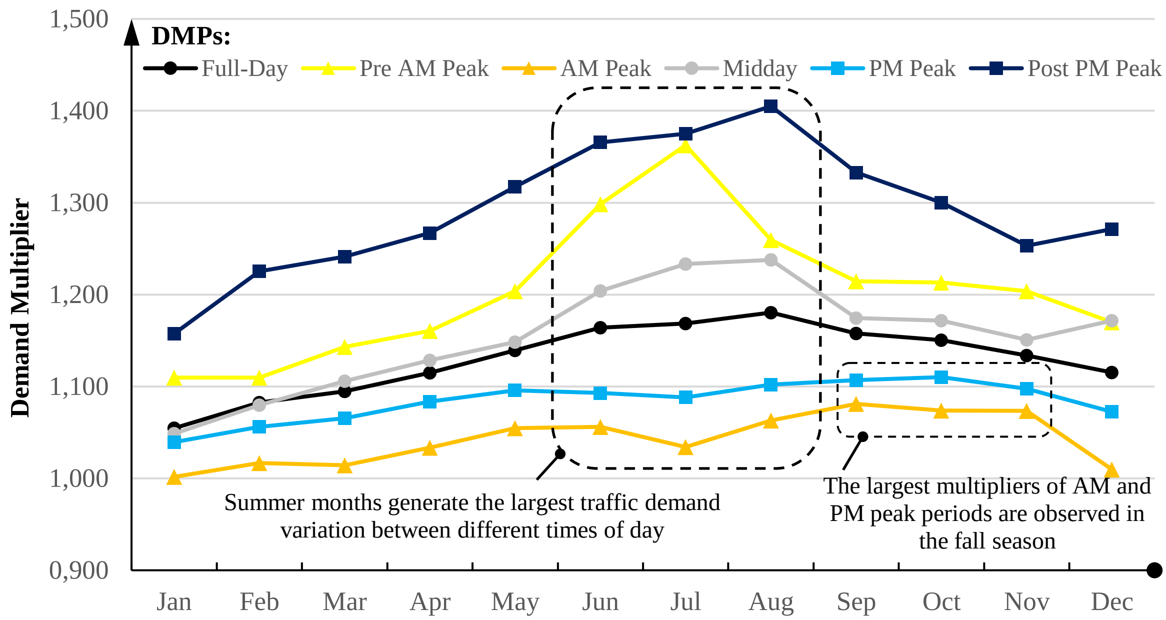
Average Demand Multipliers by Day and Month

Figures 2 and 3 illustrate the variation of demand multipliers by day-of-the-week and by month respectively. Mondays produced the smallest differences in demand multipliers across different DMPs, the differences increased throughout the week until reaching Fridays which produced the largest differences. Across months, the summer season produced the largest differences in demand multipliers. The recreational and non-commuting trips are more sensitive to daily and seasonal variations. The large proportion of these trips on Fridays and during the summer season explains why Fridays and summer months yielded the largest scale and variability of demand multipliers across DMPs. Multipliers of the AM and PM peak periods reach their maximum values during the fall months which coincide with the peak season of schools and universities.



Note: demand multipliers are aggregated over the entire network

Figure 2. Average demand multipliers by day-of-the-week and DMPs

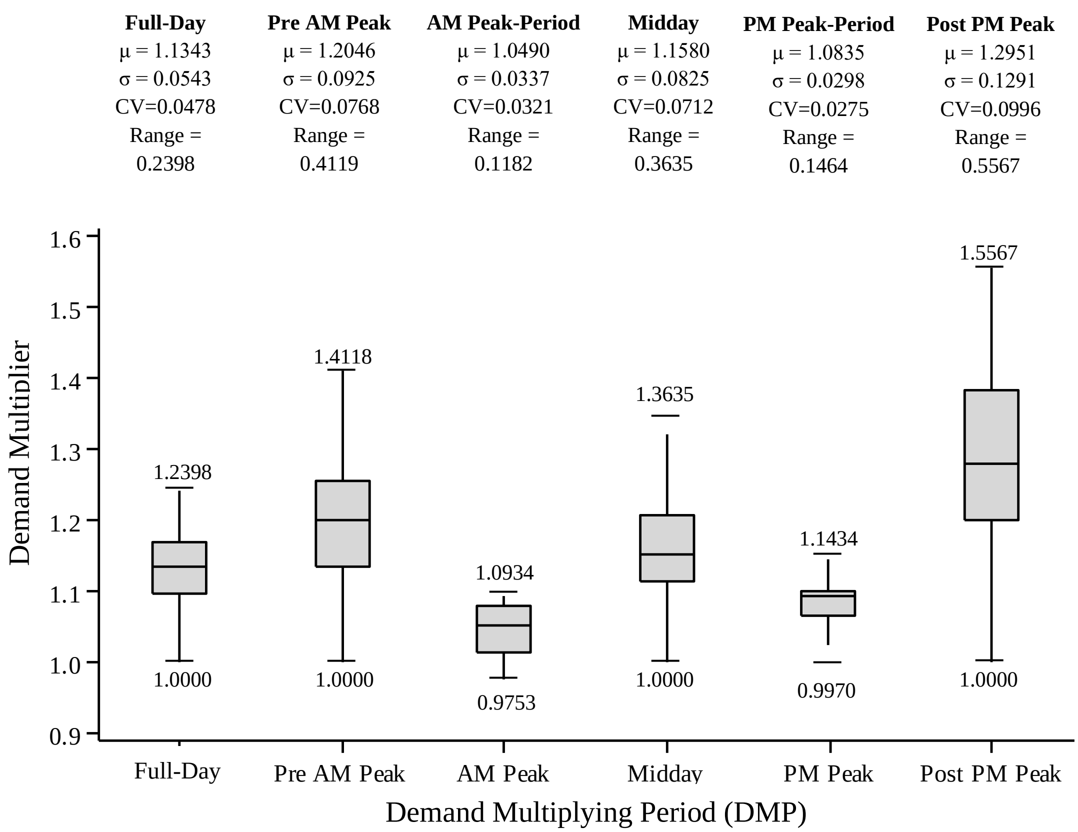


Note: demand multipliers are aggregated over the entire network

Figure 3. Average demand multipliers by month and DMPs

Full-day versus other DMPs

Figure 4 demonstrates box plots and basic descriptive statistics for demand multipliers belonging to each of the six DMPs, the multipliers' variability is clearly different across the DMPs. Demand multipliers that have larger standard deviation reflect a traffic demand that is more changeable by days and months. As mentioned before, peak periods repeat their demand patterns more uniformly across days and seasons because they are mainly composed of the mandatory daily commuting trips. On the other hand, off-peak periods are composed mainly of non-commuting recreational trips (leisure, shopping, etc) which are sensitive to days and seasons (end-of-the-week activities, vacations, etc). Therefore, off-peak periods are likely to undergo larger seasonal and daily demand fluctuations. This explains why the box plots of off-peak periods (pre AM-peak, midday, and post PM-peak) are associated with the widest variability in Figure 4 whereas the box plots of peak periods (AM and PM peaks) are associated with the narrowest variability.



Notes:

- μ = mean, σ = standard deviation, CV = coefficient of variance = σ/μ, Range = max- min
- Sample size for each box plot is sixty points representing the sixty day-month combinations
- The represented multipliers are those provided in Table 1, i.e., computed over all sites and years
- The Tukey boxplot is used herein, i.e., the whiskers extend up to 1.5 of the interquartile range, the maximum and minimum values are provided to the top and bottom of each box plot.

Figure 4. Box plots and basic statistics for demand multipliers by different DMPs

Because full-day multipliers provide a blanket representation of all times of day, the variability of the full-day multipliers result from a combination of all demand variabilities belonging to all times of day. The defined off-peak periods represent temporally two-thirds of the day (16 hrs) whereas peak periods represent one-third (8 hrs). However, the average hourly traffic volume during peak periods is by far larger than the average off-peak hourly volume, i.e., 1259 veh/hr/ln versus 588 veh/hr/ln based on all the study sites. Both the temporal and the volume shares of the peak and off-peak periods will define the overall variability of the full-day demand multipliers. Consequently, the variability of the full-day multipliers in Figure 4 appears significantly wider than the variability of peak periods' multipliers and narrower than the variability of off-peak periods' multipliers. For example, the range of the full-day demand multipliers (max-min) is 0.2398 as compared to 0.1182 for the AM-peak and 0.5567 for the post PM-peak, i.e., the full-day range is almost double the AM-peak range and is less than half the post PM-peak range.

The above discussion highlights that full-day demand multipliers, currently used in the HCM, could not accurately represent the variability and dispersion of multipliers belonging to different times of day. The use of full-day demand multipliers, in a specific time-of-day analysis, will result in the variability and the dispersion of multipliers being either significantly overestimated during peak periods or significantly underestimated during off-peak periods. A further investigation is thereby needed to evaluate the impact of using different DMPs on travel time reliability assessment.

It is also worthwhile to note that the variability may also impact the mean multipliers especially if the reference demand is taken as the Monday-January combination, i.e., a lower-side scale point. Figure 4 indicates that the mean full-day demand multiplier is significantly larger than the respective means of peak periods and smaller than the respective means of off-peak periods, Figures 2 and 3 further confirm that for all twelve months and five days - except for few Midday demand multipliers where the difference becomes slim.

STATISTICAL ANALYSIS

ANOVA Analysis

ANOVA analysis aimed at investigating the sources that explain the variability of demand multipliers. In order to also assess the site factor, ANOVA analysis was not based on the aggregated network level and equation 2 was so used at each site individually. Therefore, a sample size of 5,400 multipliers (points) was used (60 day-month combinations x 6 DMPs x 15 sites). The responses in this ANOVA are demand multipliers. The factor levels are DMP, Day, Month, and Site which are all predictor variables of demand multipliers as indicated by equation 2. These factors generate the main effects. The following interaction effects were also examined: DMP * Day, DMP * Month, and DMP * Site. The Year factor (2011 to 2015) was not considered in the present analysis because of the following reasons: (i) this would have resulted in average multipliers based on extremely low number of observations at each Site, (ii) the ADT aggregated across the study sites only increased by 3.5% over the analyzed five-year period, i.e., year-to-year increase was overall negligible and less than 1%, (iii) traffic volume changes over the years but it does so during all times of day and the change during peak and off-peak periods can be very comparable at uncongested sites which was the case of this study sites, and finally (iv) the traffic volumes used in this study were evenly distributed over the five years. A comprehensive analysis of the Year factor would require conducting the analysis over a sufficiently prolonged time period, e.g., ten years, in order to allow traffic volume to change considerably, and using network-wide demand multipliers aggregated over several sites in order to increase the number of observations of each day-month-year combination.

ANOVA determines the significance of each factor by testing the following hypothesis:

H_o: factor (or interaction) effect = 0
H_a: factor (or interaction) effect $\neq$ 0

For the significance level ($\alpha = 0.05$), the alternative hypothesis can be accepted if the P-value is less than 0.05 and this provides sufficient evidence to conclude that the factor effect exists. Table 2 summarizes ANOVA results. All the tested factors and interactions are significant (P-value is consistently less than 0.05) and they overall explain 87.03% of the variability of demand multipliers (adjusted R-square = 87.03%). The F-statistic associated with the DMP is by far the largest across all effects indicating that the DMP is the most significant and influential factor. Removing the DMP from the ANOVA resulted in dropping the R-square from 87.03% to only 27.80%. The interaction effects in Table 2 were chosen because they were the most significant ones after conducting several ANOVA trials. Adding other interaction effects, e.g., Month*Site, Day*Site, Day*Month, DMP*Day*Month, etc, only slightly raised the R-square from 87.03% to 93.08%, and so they were not included in the model to avoid undesirable complexity.

TABLE 2. ANOVA Summary Results for Demand Multipliers

ANOVA Results Summary – Original Model			
Source	**DF**	**F-statistics**	**P-value**
Demand Multiplying Period (DMP)	5	3454.23	0.000
Day	4	1182.33	0.000
Month	11	451.91	0.000
Site	14	145.03	0.000
DMP * Day	20	176.67	0.000
DMP * Month	55	33.72	0.000
DMP * Site	70	28.72	0.000

ANOVA Model Statistics:
S = 0.0453089, R-Sq = 87.46%, R-Sq (adj) = 87.03%, Sample Size = 5400 points.

Regression Analysis

ANOVA analysis revealed the factors and interactions that significantly impact the calculation of demand multipliers. The regression analysis aims to develop equations that quantitatively estimate the impact of several factors on demand multipliers. The regression equations, derived herein, estimate demand multipliers corresponding to one of the six DMPs based on Day, Month, and Site, as explained below.

Demand Multiplier (Day, Month, Site) =

$$\sum_{i=2}^{5} B_{DAY_i} * DAY_i + \sum_{j=2}^{12} B_{MONTH_j} * MONTH_j + \sum_{k=2}^{15} B_{SITE_k} * SITE_k + \text{constant} \quad \ldots\ldots (3)$$

Where:

Demand Multiplier (Day, Month, Site): a demand multiplier calculated based on one of the six DMP's and for a combination of the following three variables:
Day: one of the five weekdays,
Month: one of the twelve months of the year,
Site: one of the fifteen study sites.
$\sum_{i=1}^{5} DAY_i$: are dummy variables for the day-of-the-week, *from Monday (DAY_1) to Friday (DAY_5)*. Monday is the reference.
$\sum_{j=1}^{12} MONTH_j$: are dummy variables for the month, *from January ($MONTH_1$) to December ($MONTH_{12}$)*. January is the reference.
$\sum_{k=1}^{15} SITE_k$: are dummy variables for the study sites, *from $SITE_1$ to $SITE_{15}$*. Site 1 is the reference.
B's are the parameters.

Table 3 further demonstrates the regression variables and provides the resulting statistics. The following remarks can be learned from Table 3.

- For all DMPs, all days yielded statistical significant impact in reference to Monday (P-value < 0.05). For the same weekday, the regression parameters change widely across different DMPs. For example, on Fridays, the AM-peak multipliers decreased by -1.2% as compared to the reference whereas the post PM-peak multipliers increased by 32.8%.
- For all DMPs, almost all months yielded statistical significant impact in reference to January except for two cases contiguous with January, one in February and one in December. For the same month, parameters change widely across different DMPs. For example, in August, the AM-peak multipliers increased by 6.1% as compared to the reference whereas the post PM-peak multipliers increased by 24.8%.
- Most sites yielded statistical significant impact in reference to Site 1, this variability can still be observed if another site is made the reference. The differences of the resulting parameters of the SITE dummy variables were also practically significant in many cases. This indicates that that demand multipliers cannot be transferred reliably from one site to another within the same network. However, sites belonging to the same corridor deserve further investigation. Table 4 compares multipliers between sites located on the same corridor where the basic number of lanes remains unchanged. This applies to three pairs of sites: Sites 1 and 2, Sites 4 and 6, and Sites 5 and 7. Table 4 provides the 95% Confidence Interval of the mean difference between multipliers of the subject pairs of sites, differences between multipliers were taken pair-wise for each day-month combination. In most cases, the confidence interval of the mean difference remains slim and practically acceptable. This provides an evidence that demand multipliers may be transferred acceptably between sites located on one corridor that maintains the same basic number of lanes.

TABLE 3. Multiple Regression Analysis (Demand Multipliers by DMPs)

Regression Variable	Regression Parameters by different DMP					
	Full-Day	**Pre AM-Peak**	**AM Peak-Period**	**Midday**	**PM Peak-Period**	**Post PM-Peak**
DAY$_1$ (Monday)	Reference	Reference	Reference	Reference	Reference	Reference
DAY$_2$ (Tuesday)	0.033 (0.001)	0.091 (0.000)	0.011 (0.001)	0.010 (0.008)	0.025 (0.000)	0.087 (0.000)
DAY$_3$ (Wednesday)	0.049 (0.000)	0.086 (0.000)	0.015 (0.000)	0.027 (0.000)	0.034 (0.000)	0.141 (0.000)
DAY$_4$ (Thursday)	0.066 (0.000)	0.114 (0.000)	0.016 (0.000)	0.059 (0.000)	0.040 (0.000)	0.179 (0.000)
DAY$_5$ (Friday)	0.113 (0.000)	0.114 (0.000)	-0.012 (0.000)	0.155 (0.000)	0.075 (0.000)	0.328 (0.000)
MONTH$_1$ (January)	Reference	Reference	Reference	Reference	Reference	Reference
MONTH$_2$ (February)	0.028 (0.000)	*Insig.* *(0.075)*	0.015 (0.004)	0.031 (0.000)	0.017 (0.018)	0.068 (0.000)
MONTH$_3$ (March)	0.040 (0.000)	0.051 (0.000)	0.013 (0.016)	0.057 (0.000)	0.026 (0.000)	0.084 (0.000)
MONTH$_4$ (April)	0.060 (0.000)	0.068 (0.000)	0.032 (0.000)	0.080 (0.000)	0.044 (0.000)	0.110 (0.000)
MONTH$_5$ (May)	0.085 (0.000)	0.112 (0.000)	0.053 (0.000)	0.099 (0.000)	0.056 (0.000)	0.160 (0.000)
MONTH$_6$ (June)	0.109 (0.000)	0.206 (0.000)	0.054 (0.000)	0.155 (0.000)	0.054 (0.000)	0.208 (0.000)
MONTH$_7$ (July)	0.114 (0.000)	0.270 (0.000)	0.032 (0.000)	0.184 (0.000)	0.048 (0.000)	0.218 (0.000)
MONTH$_8$ (August)	0.126 (0.000)	0.167 (0.000)	0.061 (0.000)	0.189 (0.000)	0.063 (0.000)	0.248 (0.000)
MONTH$_9$ (September)	0.103 (0.000)	0.122 (0.000)	0.079 (0.000)	0.126 (0.000)	0.067 (0.000)	0.175 (0.000)
MONTH$_{10}$ (October)	0.096 (0.000)	0.121 (0.000)	0.072 (0.000)	0.123 (0.000)	0.071 (0.000)	0.143 (0.000)
MONTH$_{11}$ (November)	0.079 (0.000)	0.112 (0.000)	0.072 (0.000)	0.102 (0.000)	0.058 (0.000)	0.096 (0.000)
MONTH$_{12}$ (December)	0.061 (0.000)	0.078 (0.000)	*Insig.* *(0.123)*	0.123 (0.000)	0.033 (0.000)	0.114 (0.000)
SITE1	Reference	Reference	Reference	Reference	Reference	Reference
SITE2	*Insig.* *(0.609)*	-0.027 (0.015)	*Insig.* *(0.063)*	*Insig.* *(0.311)*	0.017 (0.034)	*Insig.* *(0.688)*
SITE3	0.013 (0.021)	0.064 (0.000)	0.219 (0.000)	*Insig.* *(0.207)*	-0.018 (0.021)	*Insig.* *(0.848)*
SITE4	0.012 (0.039)	*Insig.* *(0.317)*	*Insig.* *(0.207)*	0.028 (0.000)	*Insig.* *(0.096)*	0.044 (0.000)
SITE5	-0.011 (0.046)	*Insig.* *(0.911)*	0.131 (0.000)	*Insig.* *(0.915)*	-0.056 (0.000)	-0.029 (0.009)
SITE6	*Insig.* *(0.968)*	*Insig.* *(0.134)*	-0.086 (0.001)	0.018 (0.005)	*Insig.* *(0.685)*	0.039 (0.000)

TABLE 3 (Continued). Multiple Regression Analysis (Demand Multipliers by DMPs)

Regression Variable	Regression Parameters by different DMP					
	Full-Day	Pre AM-Peak	AM Peak-Period	Midday	PM Peak-Period	Post PM-Peak
SITE7	-0.034 (0.000)	*Insig. (0.242)*	0.075 (0.004)	-0.022 (0.000)	-0.088 (0.000)	-0.064 (0.000)
SITE8	-0.028 (0.000)	0.029 (0.007)	-0.196 (0.000)	-0.015 (0.021)	-0.051 (0.000)	*Insig. (0.591)*
SITE8	-0.028 (0.000)	0.029 (0.007)	-0.196 (0.000)	-0.015 (0.021)	-0.051 (0.000)	*Insig. (0.591)*
SITE9	*0.010 (0.084)*	0.059 (0.000)	0.082 (0.002)	0.020 (0.002)	-0.036 (0.000)	0.039 (0.000)
SITE10	0.017 (0.002)	*Insig. (0.643)*	-0.240 (0.000)	0.039 (0.000)	0.097 (0.000)	0.117 (0.000)
SITE11	-0.024 (0.000)	*Insig. (0.919)*	0.094 (0.000)	*Insig. (0.433)*	-0.078 (0.000)	-0.042 (0.000)
SITE12	0.076 (0.000)	0.096 (0.000)	0.371 (0.000)	0.053 (0.000)	0.076 (0.000)	0.086 (0.000)
SITE13	0.015 (0.009)	0.082 (0.000)	0.213 (0.000)	0.048 (0.000)	-0.063 (0.000)	*Insig. (0.142)*
SITE14	0.037 (0.000)	0.105 (0.000)	0.248 (0.000)	0.064 (0.000)	-0.025 (0.001)	0.052 (0.000)
SITE15	*Insig. (0.182)*	0.063 (0.000)	0.128 (0.000)	0.021 (0.001)	-0.053 (0.000)	0.056 (0.000)
Constant	0.996 (0.000)	0.980 (0.000)	0.982 (0.000)	0.982 (0.000)	1.023 (0.000)	0.990 (0.000)
Adjusted R^2	**0.782**	**0.713**	**0.671**	**0.847**	**0.659**	**0.835**

Notes:

- The numbers with no brackets refers to the regression parameters, i.e., B's, corresponding to each variable.
- The numbers provided between round brackets refer to the corresponding statistical significance level (P-value).
- Insig. means the corresponding variable is insignificant (P-value > 0.05).
- The sample size for each DMP regression is 900 multipliers, i.e., 60 day-month combinations x 15 sites.

TABLE 4. Difference in Demand Multipliers between Sites on the Same Corridor

Demand Multiplying Period (DMP)	95% CI of the Mean Difference between Multipliers		
	Site 1 vs. Site 2	Site 4 vs. Site 6	Site 5 vs. Site 7
Full-Day	-0.00142 to 0.00719	0.00655 to 0.01723	0.01744 to 0.02850
Pre AM-Peak	0.01777 to 0.03547	-0.00654 to 0.01745	-0.02444 to -0.00356
AM Peak-Period	0.00457 to 0.01741	0.00587 to 0.01796	0.00723 to 0.01821
Midday	0.00212 to 0.01085	0.00371 to 0.01626	0.01711 to 0.02909
PM Peak-Period	-0.02156 to -0.01185	0.01063 to 0.02202	0.02667 to 0.03793
Post PM-Peak	-0.00198 to 0.01084	-0.00376 to 0.01502	0.02515 to 0.04451

DMP IMPACT ON TRAVEL TIME RELIABILITY PROCEDURE

FREEVAL was used in order to explore the impact of using different DMPs on travel time reliability procedure. FREEVAL is a macroscopic freeway analysis tool that deploys the HCM procedures. The user can define the freeway corridor under analysis and insert all geometric and traffic data belonging to each segment, the user then can run several analyses for the freeway core methodology, travel time reliability, and active traffic demand management. For travel time reliability analysis, the user can write all required inputs and assumptions including: demand multipliers, crash history, incidents, work zones, and weather data. Traffic volumes for the seed date are entered in 15-min time intervals.

A virtual FREEVAL corridor was modeled consisting of nine segments of different types. Table 5 illustrates the basic geometric and traffic features of the corridor. The SP of the travel time reliability analysis was set to two hours and the RRP was one full year. Most travel time reliability assessment practices are performed during peak periods which coincide with the highest level of congestion. The analysis herein will focus thereby on the AM and PM peak periods and it aims to answer the question "What would be the consequences on travel time reliability analysis if the full-day derived demand multipliers are generalized and used instead of the multipliers that are based on the AM or the PM peak periods?." Three basic FREEVAL files were created reflecting three sets of demand multipliers, i.e., the full-day, AM peak-period and PM peak-period.

As Table 5 outlines, four traffic demand levels were defined and loaded on the facility, these traffic volumes correspond to the seed date of the first Monday in January. Therefore, replicating the volumes to other days or months would enlarge the volumes because most demand multipliers derived in Table 1, which were referenced to the Monday-January combination, were larger than one. Demand levels one to three represent free-flow conditions and they have fixed traffic volume over the SP, i.e., over eight successive 15-min time intervals. The lowest resulting LOS in any single-segment in the seed date was LOS C, LOS D, and LOS E for demand levels one, two, and three respectively. Lower levels of service maybe observed in other day-month combinations, i.e., with larger demand multipliers, but LOS F was not present even with the largest demand multiplier case of demand level three. The analysis so aimed carefully to avoid any oversaturated conditions in the first three demand levels. Demand level four, on the other hand, represents oversaturated conditions with demand-to-capacity ratio exceeding one. So the resulting queues do not exceed the temporal and spatial boundaries of the facilities, two measures were undertaken. First, traffic demand reaches the peak level early in the second 15-min interval and it starts then to decline gradually so the queues can dissipate. Second, the length of the first segment was increased artificially until insuring that the longest created queue is captured within the facility. In the seed date, only segments 7 and 8 had demand exceeding the capacity (d/c = 1.02) and only during the second 15-min interval. The demand-to-capacity ratio however increased in other day-month combinations resulting in more segments or intervals experiencing oversaturated conditions, the longest queues were observed in the Friday-August combination.

Applying the four defined demand levels to the three basic FREEVAL files (i.e., corresponding to the full-day, AM peak-period and the PM peak-period demand multipliers) yielded twelve FREEVAL analyses. So the impact of DMP can be isolated and well captured, the impacts of weather, incidents, work zones were not accounted for in the analysis.

TABLE 5. Geometric and Traffic Characteristics of the Modeled Freeway Corridor

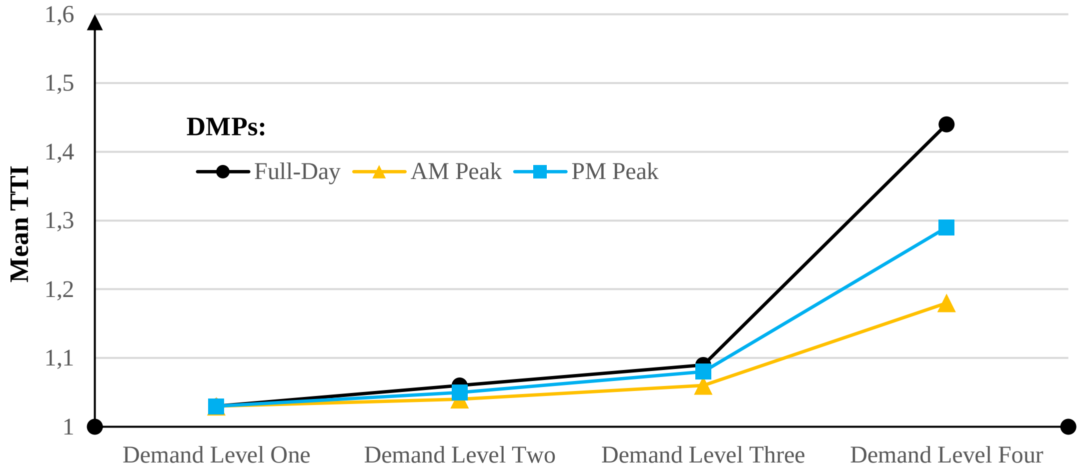
Segment ID	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9
General Features									
Segment Type	Basic	On Ramp	Off Ramp	Basic	Weave	Basic	On Ramp	Off Ramp	Basic
Segment Length (ft)	31,680	2,640	2,640	2,640	1,800	2,640	2,640	2,640	2,640
Number of Mainline Lanes	3	3	3	3	3	3	3	3	3
Free Flow Speed (mph)	70	70	70	70	70	70	70	70	70
Acceleration/Deceleration Lane Length (ft)		500	500				500	500	
Fixed On-Ramp Volume (vph)		500			500		1000		
Fixed Off-Ramp Volume (vph)			500		500			1000	
Tested Mainline Demand Levels (vph)									
Level One: fixed over eight 15-min intervals, lowest LOS in the seed date is LOS C	3,000	3,500	3,500	3,000	3,500	3,000	4,000	4,000	3,000
Level Two: fixed over eight 15-min intervals, lowest LOS in the seed date is LOS D	4,000	4,500	4,500	4,000	4,500	4,000	5,000	5,000	4,000
Level Three: fixed over eight 15-min intervals, lowest LOS in the seed date is LOS E	4,500	5,000	5,000	4,500	5,000	4,500	5,500	5,500	4,500
Level Four: changes over time intervals as shown below, LOS in the seed date reaches LOS F and d/c exceeds 1.0									
First - 15-min interval	4,000	4,500	4,500	4,000	4,500	4,000	5,000	5,000	4,000
Second - 15-min interval	6,000	6,500	6,500	6,000	6,500	6,000	7,000	7,000	6,000
Third - 15-min interval	5,000	5,500	5,500	5,000	5,500	5,000	6,000	6,000	5,000
Fourth - 15-min interval	5,000	5,500	5,500	5,000	5,500	5,000	6,000	6,000	5,000
Fifth - 15-min interval	4,000	4,500	4,500	4,000	4,500	4,000	5,000	5,000	4,000
Sixth - 15-min interval	4,000	4,500	4,500	4,000	4,500	4,000	5,000	5,000	4,000
Seventh - 15-min interval	3,000	3,500	3,500	3,000	3,500	3,000	4,000	4,000	3,000
Eighth - 15-min interval	1,500	2,000	2,000	1,500	2,000	1,500	2,500	2,500	1,500

Note: all ramps have one lane and no ramp-to-ramp volume was assumed for the weaving section.

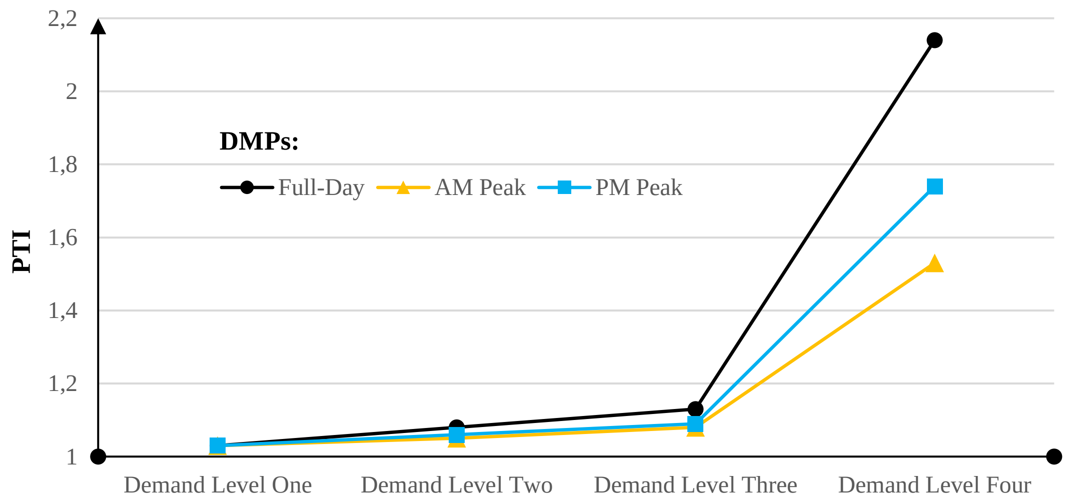
Travel Time Index (TTI) is defined as the ratio of the actual travel time to the free-flow travel time (TTI $\geq$ 1.0). The travel time reliability measures chosen herein for comparison purposes are the mean Travel Time Index (mean TTI) and the Planning Time Index (PTI), the latter denotes the 95th percentile of the TTI distribution. Figure 5 summarizes the impact of using different DMPs on the mean TTI and PTI according to different demand levels. The impact of using different DMPs is slim at low demand levels, but it becomes evident and substantial for demand level four, i.e., the oversaturated conditions. For the fourth demand level, the resulting mean TTI was equal to 1.44, 1.18, and 1.29 for demand multipliers corresponding to full-day, AM peak-period, and PM peak-period respectively; also, the resulting PTI was 2.14, 1.53, and 1.74 for the same periods respectively. These statistics indicate that applying the full-day multipliers instead of the AM-peak or PM-peak multipliers can result in significant overestimation of the mean TTI and PTI. Generally, the mean TTI and PTI increase with demand multipliers having larger magnitude and variability. Recalling Table 1 and Figures 2-4, the full-day multipliers were of larger magnitude and wider variability as compared to multipliers of the AM and PM peak periods, this explains why the full-day multipliers overestimated the travel time indices during peak periods.

Figure 6 shows how the mean TTI and PTI differ by seasons and by the three analyzed DMPs, this analysis only considers the fourth demand level. The summer produced the largest differences in mean TTI and PTI across DMPs whereas the winter produced the smallest differences. The mean TTI in the summer was 1.59, 1.21, and 1.30 for demand multipliers corresponding to full-day, AM peak-period, and PM peak-period respectively; also, the resulting PTI was 2.32, 1.52, and 1.73 for the same periods respectively. These results accord with Figure 3 discussed previously. In the summer, recreational activities increase and intensify especially during off-peak periods, this results in magnifying the daily traffic volume more than the volume of the peak periods. Therefore, the overestimation of travel time variability due to the use of full-day multipliers instead of AM- and PM-peak multipliers becomes more evident and critical in the summer season. The overestimation is also expected to exacerbate on Fridays as compared to other days as Figure 2 implied before.

Conversely, during off-peak periods, i.e., pre AM-peak, midday, post PM-peak, the use of the full-day multipliers can underestimate the travel time variability because these off-peak periods were associated with multipliers of larger magnitude and wider variability. However, off-peak traffic usually operates under free-flow conditions which may lessen any inaccuracy resulting from using the full-day multipliers. Only corridors that serve recreational activities may exceptionally experience high traffic demand during midday and late evening hours.

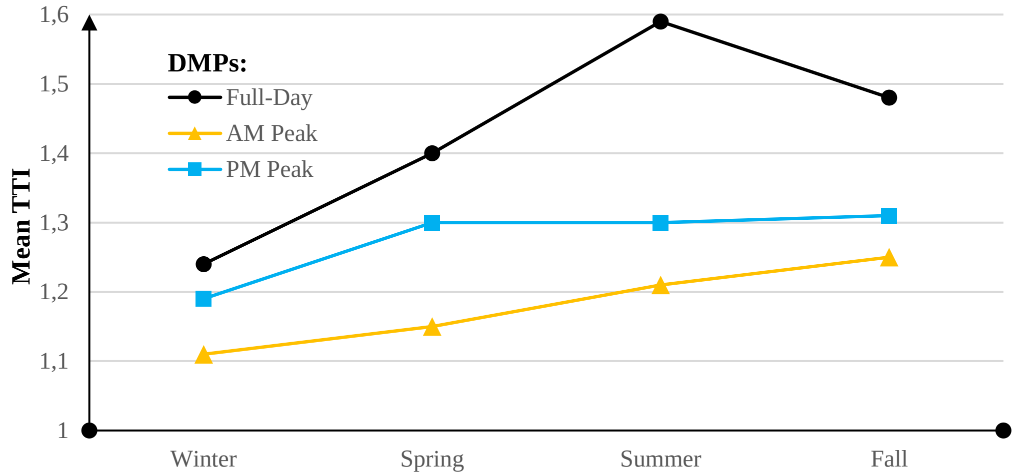


(a) Mean Travel Time Index (TTI) by DMPs and demand levels

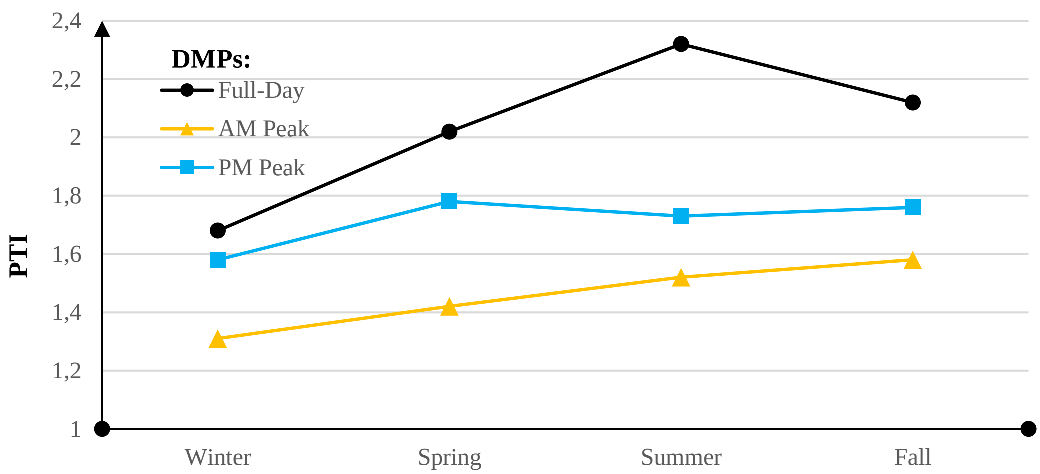


(b) Planning Time Index (PTI) by DMPs and demand levels

Figure 5. Travel time reliability measures by DMPs and demand levels



(a) Mean Travel Time Index (TTI) by DMPs and seasons



(b) Planning Time Index (PTI) by DMPs and seasons

Note: the shown measures correspond to demand level four of Table 5 (oversaturated conditions).

Figure 6. Travel time reliability measures by DMPs and seasons

PEAK-PERIOD VERSUS PEAK-HOUR MULTIPLIERS

Peak periods usually last several hours, but practitioners may need to analyze traffic operations during the heaviest single hour. Table 6 evaluates how demand multipliers differ if the multiplying criterion is tightened to the traffic volume observed during the peak-hour rather than the whole peak-period. Time intervals of peak periods were fixed as explained earlier whereas the peak hours were observed at each site and on each day distinctly, the aim was to well capture the day-to-day movements of peak-hour timing in 15-min time intervals. Results indicate a significant mean difference between peak-hour and peak-period multipliers (P-value < 0.05), the mean demand multiplier is lower for peak hours as compared to peak periods. Albeit the statistical test, peak hours and peak periods produced very tight 95% CI mean multiplier difference and the difference is practically tolerable and insignificant. The 95% CI of the mean difference in demand multipliers between peak-hour and peak-period was tighter in the case of PM-peak as compared to AM-peak. This is attributed to the fact that both shoulders of the PM peak-hour (hours immediately before and after) usually experience high traffic volumes making the demand more homogeneous throughout the whole period whereas the preceding-shoulder of the AM peak-hour is usually influenced by some of the early-morning moderate traffic volumes. Peak hours produced slightly smaller deviation in demand multipliers as compared to peak periods, the difference between the two variances was however neither statistically nor practically significant.

TABLE 6. Comparison between Peak-Hour and Peak-Period Demand Multipliers

Statistic	Demand Multiplying Period (DMP)			
	AM Peak-Period	**AM Peak-Hour**	**PM Peak-Period**	**PM Peak-Hour**
Mean	1.0490	1.0263	1.0835	1.0777
ST Dev	0.0337	0.0292	0.0298	0.0247
COV	0.0321	0.0284	0.0275	0.0229
Min	0.9753	0.9571	0.9970	0.9982
Max	1.0934	1.0676	1.1434	1.1198
Range	0.1182	0.1105	0.1464	0.1216
95% CI Mean Difference (pair-wise)	(0.01937, 0.02663)		(0.00368, 0.00868)	
Mean Difference Test (Paired T-test)	H_o: $\mu_{\text{AM peak-hour multipliers}} = \mu_{\text{AM peak-period multipliers}}$ H_a: $\mu_{\text{AM peak-hour multipliers}} < \mu_{\text{AM peak-period multipliers}}$		H_o: $\mu_{\text{PM peak-hour multipliers}} = \mu_{\text{PM peak-period multipliers}}$ H_a: $\mu_{\text{PM peak-hour multipliers}} < \mu_{\text{PM peak-period multipliers}}$	
	T-Value = 12.69	P-Value = 0.000	T-Value = 4.95	P-Value = 0.000
Variance Difference Test (Levene test)	H_o: $\sigma^2_{\text{AM peak-hour multipliers}} = \sigma^2_{\text{AM peak-period multipliers}}$ H_a: $\sigma^2_{\text{AM peak-hour multipliers}} \neq \sigma^2_{\text{AM peak-period multipliers}}$		H_o: $\sigma^2_{\text{PM peak-hour multipliers}} = \sigma^2_{\text{PM peak-period multipliers}}$ H_a: $\sigma^2_{\text{PM peak-hour multipliers}} \neq \sigma^2_{\text{PM peak-period multipliers}}$	
	T-Value = 1.11	P-Value = 0.295	T-Value = 1.22	P-Value = 0.272

Notes: Statistics are based on the sixty day-month multipliers aggregated over the network (all-sites)

RESULTS ADAPTABILITY AND TRANSFERABILITY

This study provides evidence that demand multipliers can considerably differ from site to site within the same city-wide highway system, only those sites located on one corridor that maintains the same basic number of lanes produced practically similar multipliers. Demand multipliers are so not flexibly transferrable from one jurisdiction to another, and when introducing default values for specific time periods in the HCM, this should be derived from plentiful number of sites. Moreover, a recommendation should clearly stress that practitioners must, whenever possible, derive the local demand multipliers pertaining to each corridor traffic data. The impact of different times of day must be carefully considered when short traffic data intervals are available. If daily traffic volumes are the only available data and finer interval resolution cannot be obtained, then practitioners must be aware of the following two cases.

First, for corridors operating at LOS F during the analysis period, practitioners must take note that the use of full-day demand multipliers will overestimate travel time reliability indices (e.g., TTI and PTI) for peak periods and will underestimate these indices for off-peak periods. The actual size of such overestimation and underestimation depends mainly on the level and duration of traffic congestion. When congestion intensifies, travel time becomes more and non-linearly related to traffic demand and a tiny miscalculation in traffic demand will generate a large error in the calculated travel time indices. This is especially important for peak periods which experience LOS F more commonly as compared to off-peak periods.

Second, for corridors operating at LOS E or higher during the analysis period, using the full-day demand multipliers to estimate travel time reliability measures should be practically acceptable with tolerable inaccuracy. Practitioners should however be aware of conditions that may deteriorate the operations below LOS E, e.g., work zones, incidents, and weather.

CONCLUSIONS

This paper aimed at improving how seasonal and daily traffic demand multipliers are replicated. This is especially important for the HCM travel time reliability procedure, lessons learned however can still be useful for the various daily applications that need traffic demand. This paper investigated six criteria or periods to derive demand multipliers: full-day, pre AM-peak, AM peak-period, midday, PM peak-period, and post PM-peak. These periods were referred to by Demand Multiplying Periods (DMPs). Below are the main study findings.

- Different DMPs produced substantially different demand multipliers, differences were observed in all major descriptive statistics (i.e., mean, standard deviation, and range) and this reveals different sensitivity towards seasonal and daily variations. The full-day-based multipliers, currently used in the HCM, do not accurately capture or represent seasonal or daily demand variations for all times of day.

- ANOVA results revealed an important effect of DMP, day, month, and site on the calculation of demand multipliers, the DMP was however the strongest factor among all the examined main effects.

- Recalling the HCM travel time reliability procedure, the recommendation is critically made herein to use demand multipliers that are based on traffic volumes associated with a period that coincides with the analyzed study period. The HCM should highlight the importance of using different sets of multipliers representing different times of day. The six periods examined in this study are recommended to be adopted as bases to replicate demand multipliers.

- In the absence of traffic data during fine time intervals, the use of full-day-based multipliers should be done with careful attention. During oversaturated conditions, the adoption of full-day multipliers may significantly overestimate travel time reliability indices during peak periods and underestimate them during off-peak periods. During free-flow conditions, travel time becomes less sensitive to accurate demand levels and the full-day multipliers can be used with tolerable inaccuracy. However, attention must be paid towards scenarios that have incidents, work zones, and inclement weather which may transfer free-flow corridors into the constrained-flow conditions.

- The study sites produced different demand multipliers, differences were practically significant in some cases. However, the difference in demand multipliers between sites remains practically moderate and acceptable when they were located on one corridor that continuously maintains the same basic number of lanes. When introducing default values for specific time periods in the HCM, this should be derived from plentiful number of sites.

- Demand multipliers computed by several-hour periods may be applied acceptably for peak-hour analysis, this can be even slightly conservative because peak-hour volumes would produce smaller multipliers with less variability.

FUTURE REEARCH DIRECTIONS

The present research focused on improving the calculation of traffic demand multipliers and FREEVAL was used to estimate the corridor travel time reliability indices. Two main recommendations are made to further supplement this research thread. The first recommendation is to calibrate this research findings by using ground freeway travel time data. Such empirical analysis however needs data different than those used in the present study. The data would include, for example, speeds of all sections along a corridor so travel times can be derived. Alternatively and more accurately, license-plate recognition systems or vehicle detection using smart-phone sensing and WiFi localization can be used at two stations on the examined corridor, i.e., entry and exit, to record the time stamps of each vehicle and derive the actual travel time. Encryption protocols must insure protecting private information. Field-driven travel times can be then compared with the HCM-driven travel times and the impact of using different DMPs can be accurately assessed. The second recommendation is to explore how different demand multipliers impact travel time reliability using mathematical models other than those used in FREEVAL, for example, by using volume-delay functions customized and calibrated for specific cases or corridors. The analysis may also consider other reliability factors such as incidents, work zones, and inclement weather conditions.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: all authors; data collection: A. Drakopoulos, A. Dehman; analysis and interpretation of results: A. Dehman, T. Brijs; draft manuscript preparation: A. Dehman. All authors reviewed the results and approved the final version of the manuscript.

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