TO: TRAVEL MODEL ONE DEVELOPMENT FILE
FR: David Ory, Rupinder Singh, MTC

RE: Initial examination of volume delay functions using PeMS data

Travel models attempt to iteratively predict the demand for automobile travel and the resulting travel speed on roadway segments. The estimation of travel demand is complex and, for MTC, described in detail elsewhere. The estimation of travel speed is fairly straightforward and uses so-called “volume delay functions”, which estimate congested travel speed as a function of each roadway’s demand, free flow speed, and effective capacity. During MTC’s most recent model improvement efforts, the legacy volume delay functions were retained.

The purpose of this memorandum is to investigate the reasonableness of the input assumptions which inform the volume delay functions as well as the shape of the volume delay curves themselves. Data from the Caltrans Performance Measurement System (PeMS) database is used in the analysis.

Model validation efforts often focus on comparing observed and estimated volumes and point-to-point average speeds. For the current validation effort MTC has, to date, compared volumes, but not speeds. Here, in lieu of a comparison between observed and estimated point-to-point average speeds, we examine the underlying behavioral assumption embedded in the travel model. By so doing, we ask: if the demand is correct, are the models capable of reliably predicting travel speed? This approach should facilitate a more robust examination of the models ability to replicate travel speed than point-to-point average speed comparisons, which are obscured by differences in estimated and observed flow.

Background

The MTC travel model uses a typical aggregate static user equilibrium assignment method to predict the routing of vehicles in response to congestion. This approach, which is nearly ubiquitous across regional modeling practice in the US, makes several important assumptions, as follows:

- Demand on a roadway segment during a finite time interval can exceed roadway supply/effective capacity. For example, if 4,000 vehicles want to traverse a section of

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1 Please see [http://mtcgis.mtc.ca.gov/foswiki/Main/Development](http://mtcgis.mtc.ca.gov/foswiki/Main/Development) for details.
2 Research into these curves is available here: [http://www.mtc.ca.gov/maps_and_data/datamart/research/boston1.htm](http://www.mtc.ca.gov/maps_and_data/datamart/research/boston1.htm).
roadway that can only handle 3,000 vehicles, the model responds by predicting that travel through the corridor will be very slow, but still possible.

- The delay resulting from high demand on a roadway segment is contained entirely within that segment (i.e. queues do not form at bottlenecks and cause upstream delay; rather, the bottleneck is described entirely on the segment of roadway where the bottleneck occurs).
- An equilibrium condition is found such that no vehicles moving between any single origin/destination pair can achieve a significantly faster travel time by switching routes.

In the MTC application, the demand and congested conditions are described separately for five time periods which, when combined, encompass an entire typical weekday, as follows:

- Early AM, 3 am to 6 am;
- AM peak (also referred to as the “morning commute”), 6 am to 10 am;
- Midday, 10 am to 3 pm;
- PM peak (also referred to as the “evening commute”), 3 pm to 7 pm; and,
- Evening, 7 pm to 3 am.

This approach requires MTC to explicitly assume that congestion is constant within each time period. We know this is not true (e.g., traffic is almost always heavier from 7 am to 8 am than 9 am to 10 am), but we make this, along with numerous other assumptions, as a simplification.

To predict congested speeds on freeways, MTC uses so-called “BPR Curves”, the model form originally developed by the Bureau of Public roads. The shape of the curves are discussed in more detail in a latter section of this memorandum.

The Caltrans PeMS database³ compiles roadway monitoring data collected continuously via loop detectors to support traveler information systems. Historical data can be downloaded from the PeMS website; records for every five- or sixty-minute interval are available. The data includes observed flow, sensor occupancy, and speed for each working detector across the State of California.

**PeMS Data Preparation**

The MTC travel model predicts travel behavior for a typical weekday – when school is in session, the weather is clear, no major accidents occur on the roadway, etc. To extract data that best represents this abstract concept, the following process was used to filter the PeMS data:

- Begin with the hourly PeMS data, which includes estimates of average flow, sensor occupancy, and speed for every hour in the day.
- Only consider data from the following months: March, April, May, September, October, and November for calendar year 2010 (we hope to add data for prior and subsequent years in future analyses).
- Only consider data from the following days of the week: Tuesday, Wednesday, and Thursday.

³ [http://pems.dot.ca.gov/](http://pems.dot.ca.gov/)
Only consider data from functioning detectors – specifically records for which over 90 percent of the observations that make up the computed averages is observed, rather than imputed (Caltrans imputes data when detectors are down or working intermittently).

After extracting hourly data, an average flow for each of the five MTC assignment time periods is computed, as is a time-period-specific flow-weighted average speed. The resulting data is available here⁴ – in an effort to visually separate stations collecting data in opposite directions on a single roadway segment, a small offset was introduced to the station coordinates according to the road mile direction of the freeway (e.g., if the direction was east, the latitude of the station was reduced by 0.001 units) to allow for easier visualizing of the data (in certain cases, such as when an “eastbound” freeway is traveling cardinal north, the offset did not work particularly well).

The MTC roadway network is based on a 1990 Census Tiger line file. The representations of freeways are, as such, a bit dated and less accurate than the X/Y coordinates of the PeMS count stations. For this initial exploration of the volume delay functions, MTC did not locate each of the PeMS count stations onto links in the MTC roadway network. We hope to do this as a next step in this line of inquiry.

Roadway Capacity

MTC uses a simple look up table to estimate each roadway’s effective operating capacity. Specifically, a roadway’s facility type and area type (AT) determine its capacity. A facility’s area type is determined by the use of land immediately adjacent to the roadway using an area type density measure, which is computed as follows:

\[
\text{AT Density} = \frac{(\text{Total Population} + 2.5 \times \text{Total Employment})}{\text{Residential Acres} + \text{Commercial/Industrial Acres}}. 
\]

Each link is then assigned one of the six area types shown in Table 1. It is important to note that we are only examining the capacity assumption made for freeways, which is one of eight facility types used in the MTC travel model (each of the other eight require similar assumptions). Throughout this document we assume that all PeMS data is collected on roadways MTC identifies as freeways – this is generally, but not strictly, true (in the next iteration of this work, we will associate the model link with the count station to eliminate this inconsistency).

The capacities assumed for each freeway in each of the six area types are also shown in Table 1. We know that freeways do not behave in such a uniform manner – each segment, even adjacent segments in the same urban environment, likely has a slightly different effective capacity due to differences in lane widths, shoulder widths, horizontal alignment, vertical alignment, pavement condition, presence of combination trucks, adjacent visual distractions, presence of weaving sections, etc.

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⁴ [http://geocommons.com/maps/84318](http://geocommons.com/maps/84318)
Table 1: Area Type Density Thresholds and Freeway Capacity Assumptions

<table>
<thead>
<tr>
<th>Area type</th>
<th>Area Type Density</th>
<th>Assumed Freeway Capacity (passenger cars per hour per lane)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From</td>
<td>To</td>
</tr>
<tr>
<td>Regional core</td>
<td>300</td>
<td>∞</td>
</tr>
<tr>
<td>Central business district</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>Urban business</td>
<td>55</td>
<td>100</td>
</tr>
<tr>
<td>Urban</td>
<td>30</td>
<td>55</td>
</tr>
<tr>
<td>Suburban</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>Rural</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

The first question in this inquiry is a basic one: in the MTC context, does the PeMS data support segmenting capacity by these area type categories? To answer this question, we first identify the area type of each PeMS count station. Next, we compute the roadway density (vehicles per mile per lane) by taking the ratio of the observed flow (vehicles per hour per lane) and observed speed (miles per hour).

We then make plots for each of the morning one-hour periods when traffic is heaviest (and, as such, has the best chance of revealing an observed maximum flow data point). Figure 1 below plots observed density versus observed flow to reveal the familiar (to traffic engineers) flow/density relationship. This figure suggests that traffic in the Bay Area is generally heaviest between 7 and 8 am. Figure 2 presents flow/density relationships for the 7 to 8 am hour separately for four of the six area types used in the MTC travel model (too few count stations are located in the two most dense area types). This figure reveals the following maximum flow rates:

- Urban business, ~1,750 to 1,850 vehicles per hour per lane;
- Urban, ~1,850 to 1,950 vehicles per hour per lane;
- Suburban, ~1,950 to 2,050 vehicles per hour per lane; and,
- Rural, ~2,000 to 2,100 vehicles per hour per lane.

Companion plots for the evening commute period are presented in Figure 3 and Figure 4. The evening commute generally has the highest flows from 5 to 6 pm, though the flows from 4 to 5 pm are similar. Figure 4 reveals the following maximum flow rates:

- Urban business, ~1,600 to 1,800 vehicles per hour per lane;
- Urban, ~1,800 to 1,850 vehicles per hour per lane;
- Suburban, ~1,950 to 2,000 vehicles per hour per lane; and,
- Rural, ~1,900 to 1,950 vehicles per hour per lane.
The PeMS data generally support segmenting freeway capacity by the area types identified by MTC. Further, the capacity ranges assumed by MTC (2,050 to 2,150) are in the same range, though a bit higher, as the observed maximum flow (~1,600 to 2,100).

Two areas that may warrant further research are as follows: (1) consider reducing the capacity for the urban, urban business, central business district, and regional core area types (additional data is needed to reach conclusions regarding the latter two area types); and, (2) consider using different capacities for the morning and evening commute, as it appears morning commuters make more efficient use of the roadway than their evening counterparts.
Figure 1: Flow versus Density for All Stations during the Morning Commute
Figure 2: Flow versus Density by Area Type during the Morning Commute
Figure 3: Flow versus Density for All Stations during Evening Commute
Figure 4: Flow versus Density by Area Type during the Evening Commute
Free-flow Speed

MTC uses a simple look up table to determine the free-flow speed on each roadway segment. Similar to capacity, the free-flow speed is determined by a link-specific facility type and area type. For freeways (one of eight facility types used by MTC), the following free-flow speed assumptions are made:

- Regional core, 55 miles per hour (mph);
- Central business district, 55 mph;
- Urban business, 60 mph;
- Urban, 60 mph;
- Suburban, 65 mph; and,
- Rural, 65 mph.

Using the PeMS data, we can ask two interesting questions: (i) is it reasonable to segment free-flow speed by MTC’s area types, and (ii) are the magnitudes of the assumed free-flow speeds reasonable. As with the previous discussion on capacity, it is important to note that we are only examining the assumption made for freeways, which is one of eight facility types used in the MTC travel model (each of the other eight require similar assumptions).

To estimate the free-flow speed of the Bay Area residents traveling in the model, we select the time periods at the beginning of the morning commute and end of the evening commute, as these times likely include resident travelers (as opposed to those passing through the region or making long-distance trips) and have little congestion. Figure 5 plots the observed speed of travelers from 4 to 5 am against sensor occupancy (i.e. the percentage of time the loop detector has a vehicle directly above it), segmented by area type; Figure 6 presents a companion plot for data from 7 to 8 pm. The vast majority of observations in each plot occur at very low sensor occupancy rates, suggesting very low congestion levels.

It is difficult to discern the mean speed from the plots, as the data is tightly bunched; the means are as follows (not enough count stations are present in the more dense area types to compute means):

- Urban business, 63.9 mph from 4 to 5 am, 58.8 mph from 7 to 8 pm;
- Urban, 66.6 from 4 to 5 am, 63.3 mph from 7 to 8 pm;
- Suburban, 65.9 from 4 to 5 am, 65.5 mph from 7 to 8 pm; and,
- Rural, 65.4 from 4 to 5 am, 65.1 from 7 to 8 pm.

The above results suggest that the PeMS data does support segmenting free flow speeds by MTC’s area types, though less definitively than the segmentation of capacity shown in Figure 2 and Figure 4. Further, the speeds assumed by MTC are similar to observed speeds.
Figure 5: Observed Speed by Area Type from 4 am to 5 am
Figure 6: Observed Speed by Area Type from 7 pm to 8 pm
Volume Delay Functions

MTC uses a variation of a BPR curve to compute congestion on freeways. The function is as follows:

\[ T_c = T_0 \cdot \left[ 1 + \alpha \cdot \left(\frac{v}{c} \cdot \frac{4}{3}\right)^\beta \right], \]

where \( T_c \) is the congested travel time estimate, \( T_0 \) is the free flow travel time assumption, \( \alpha \) is a parameter assigned a value of 0.20 in MTC’s application, \( v \) is the estimated vehicle demand, \( c \) is the assumed roadway capacity, and \( \beta \) is a parameter given a value of 6.0 in MTC’s application.5

In order to use a BPR curve, the analyst must: (i) assume a free flow travel time for each roadway segment; (ii) assume roadway capacity for each roadway segment; and, (iii) set the parameters \( \alpha \) and \( \beta \). The previous two sections of this memorandum discussed the assumptions MTC uses for (i) and (ii) and assessed the reasonableness of those assumptions using the PeMS database.

Comfortable that our assumptions for free flow speed and capacity are, while not perfect, reasonable, we can use the estimates of observed flow from the PeMS database as a surrogate for demand and then compute estimates of congested travel time (and therefore speed). These congested speed estimates can be compared to the observed speeds in the PeMS database. Such an examination should help us assess the reasonableness of the shape assumed for the BPR curves used in the MTC travel model.

The PeMS database reveals only flow estimates, meaning the number of cars that traverse the roadway in each observed hourly period. This flow is a revealed expression of an unobserved demand, meaning the number of cars that wish to traverse the roadway in each observed hourly period. Flow cannot exceed capacity; demand can exceed capacity. The travel model predicts demand, not flow. This limitation requires care when exploring the performance of the volume delay curves, because the PeMS data will reveal the same flow rate at two very different speeds (i.e. low flow when traffic is light and speeds are high, and similarly low flow when traffic is heavy and speeds are low).

The performance of the volume delay curves is explored in two ways. First, observed \( v/c \) ratio versus observed travel speed plots are made. These charts are shown, by time period, in Figure 7, Figure 8, Figure 9, Figure 10, and Figure 11. Important notes regarding these plots are as follows:

- The capacity of each link is not directly observed in the hourly PeMS data. As such, each plot presents the \( v/c \) ratio (both flow and demand are referred to as volume in the figures below) as computed two separate ways by making two separate assumptions about the roadway capacity as follows: (i) the capacity is 2,200 passenger cars per hour per lane (a typical maximum flow rate used by traffic engineers), or (ii) the capacity is segmented by area type per the MTC travel model (see Table 1). Relative to the broad fit of these simple curves, the differences between the results of these two sets of assumptions are not great.

5 Please see the following link for a detailed discussion of the parameters selected for these curves: http://mtc.ca.gov/maps_and_data/datamart/research/boston1.htm.
As noted above, the flow, rather than the demand, for each link is not directly observed in the PeMS data. As such, when demand exceeds supply and speeds degrade, the volume delay curve is no longer relevant for the PeMS estimated flow-to-capacity ratio (it is still relevant for the demand-to-capacity ratio). Links with very low speeds are still presented in Figure 7 through Figure 11, but should be ignored in these charts when assessing the fit of the volume delay functions.

Two BPR curves are shown on each of the charts, one reflecting an input free flow travel speed of 60 mph and the other an input free flow travel speed of 65 mph. As discussed in the previous section, one of these two free flow speeds are assumed for the majority of roadway segments described in the data.

The plots generally show the curves fit the data well when flow is less than capacity. For the non-commute time periods, this reflects only the accuracy of the input free flow speed assumption.
Figure 7: BPR Curve Comparison, Volume to Capacity Ratio against Speed, Early AM Period
Figure 8: BPR Curve Comparison, Volume to Capacity Ratio against Speed, AM Peak Period
Figure 9: BPR Curve Comparison, Volume to Capacity Ratio against Speed, Midday Period
Figure 10: BPR Curve Comparison, Volume to Capacity Ratio against Speed, PM Peak Period
Figure 11: BPR Curve Comparison, Volume to Capacity Ratio against Speed, Evening Period
The second method of assessing the accuracy of the volume delay functions focuses on the performance of the curves when demand exceeds capacity. Here, density (the quantity hourly flow by lane divided by speed) is plotted against speed. These plots reveal observed travel speeds when densities exceed the critical threshold at which speed begins to degrade (around 30 vehicles per mile, as shown in Figure 1, Figure 2, Figure 3, and Figure 4). Figure 12 shows the speed/density relationship for the morning commute; Figure 13 shows the relationship for the evening commute. As in Figure 7 through Figure 11, two separate BPR curves are shown, one with an assumed free flow speed of 65 mph and other 60 mph. Both plots show the curves perform okay at high densities, though tend to overestimate speeds at heavy congestion levels. One area of future inquiry is to explore the fit of steeper curves against these and additional PeMS data.

In sum, this initial investigation reveals that the MTC volume delay functions replicate travel speeds fairly well.
Figure 12: BPR Curve Comparison, Density against Speed, AM Peak Period
Figure 13: BPR Curve Comparison, Density against Speed, PM Peak Period