APPLICATION OF ADVANCED ANALYSIS TOOLS FOR FREEWAY PERFORMANCE MEASUREMENT

Pantelis Kopelias
Attikes Diadromes S.A., 41.9 Km of Attiki Odos, GR 19002 Peania, Athens, Greece
Email:pkopelia@attikesdiadromes.gr

Fanis Papadimitriou
Attikes Diadromes S.A., 41.9 Km of Attiki Odos, GR 19002 Peania, Athens, Greece
Email:fapapadim@attikesdiadromes.gr

Alexander Skabardonis
Institute of Transportation Studies, University of California, Berkeley
109 McLaughlin Hall, Berkeley CA 94720-1720
Email:skabardonis@ce.berkeley.edu

Eleni Christofa
Institute of Transportation Studies, University of California, Berkeley
109 McLaughlin Hall, Berkeley CA 94720-1720
Email:christofa@berkeley.edu

ABSTRACT

The paper describes the application of freeway performance measurement system (PeMS) to the Attica Tollway, a 70 Km urban motorway in Athens, Greece to obtain freeway performance measures and provide estimation and prediction of travel times under recurrent and non-recurrent (incident related) congestion. Travel time reliability measures also are estimated from the field data and compared with predictions from recently developed analytical models.

Keywords: freeway performance measurement; archive data user service (ADUS); data warehouse; travel time variability; incidents; mathematical models

INTRODUCTION

There is an increasing emphasis on Active Traffic Management (ATM) for improving the performance of highway facilities through monitoring and control of systems operations. ATM incorporates both demand and supply management strategies. The deployment of ATM and the assessment of their effectiveness should be based on transportation system performance measures that directly relate to the quantity and quality of the traffic stream, based on field data. Such data can be provided by a surveillance system that gathers real-time information from detectors on the state of the system and transmits to transportation management centers (TMCs). This in turn requires an effective and comprehensive data management system for data processing and analysis.

The freeway performance measurement system (PeMS) is a real-time Archive Data Management System (rt-ADMS) [8,12]. PeMS originally was developed for the California Department of Transportation (Caltrans). The California PeMS implementation receives 30 second loop detector data in real time from over 20,000 loop detectors consisting of counts and occupancy (portion of time that a detector is occupied). Over 2 GB of data are received every day. PeMS includes a set of diagnostics to check the incoming loop data for accuracy and reliability, and algorithms for computing freeway performance measures.

The PeMS software architecture is modular and open. It uses commercial-of-the-shelf products for communication and computation. All the data are available on line. Users access PeMS through the Internet; built-in applications are accessed through a Web browser. Custom applications can work directly with the database. There is no need for special access to the agency's TMC data storage, writing scripts to access the database, or requesting off-site archived historical data.

The paper describes the PeMS implementation on the Attica Tollway (AT) in Athens, Greece, and illustrates its use to explore different aspects of performance on the AT freeway system. Emphasis is placed on the features of PeMS in travel time estimation and prediction, and the calculation of travel time reliability measures.

The next section of the paper provides an overview of the AT intelligent transportation systems (ITS) infrastructure and incident management procedures. Next, the PeMS algorithms for travel time estimation and prediction are described. Next, reliability measures for the most heavily trafficked section of the AT are extracted from PeMS and compared with the predictions from recently developed analytical models.

ITS AND OPERATIONS IN ATTICA TOLLWAY

Attica Tollway is 70 centerline kilometers long and includes 29 interchanges. It consists of 373.6 lane-km, of which 268.2 lane-km or 71.8% is on 3-lane sections. About 24.5% is in 2-lane sections and the balance of 3.7% is in 4-lane sections. The 15.4 km spur of Attica Tollway leading to the center of Athens through mountainous terrain has 56 tunnels and cut-and-cover sections, which comprise 12% of its length. Entry to the freeway is through 39 toll plazas with 195 toll lanes. The tollway started being delivered in segments in May 2001 and delivery was concluded in late spring 2004, prior to the 2004 summer Olympics in Athens. In 2009, the average number of weekday vehicle entries through the toll plazas was about 339,000 compared with 332,000 in 2008 and 323,000 in 2007. It is noted that these figures correspond to approximately 6-10% of the total traffic in the Athens metropolitan area.

Attica's Tollway ITS infrastructure comprises of equipment used for event detection and confirmation that are integrated to the traffic management system: 220 Closed Circuit Television (CCTV) cameras placed every 1000 m in open sections and every 125 m in tunnels and covered sections; 11 meteorological stations; 600 inductive loops every 500m in open sections and every 60m in tunnels; 600 Emergency Roadside Telephones (ERT) every 2000m in open sections and every 60m in tunnels (on both sides); 103 Variable Message Signs (VMS) located on the mainline upstream of key decision points and on each access road to the Tollway (AVMS); Lane Control Signs (LCS) and Variable Message Signs (VSLS) every 150m in tunnels and on key gantries in open sections.

The two primary goals of the Attica Tollway Traffic Management System (TMS) are to improve safety through the reduction of incidents, and to maximize the capacity of the motorway by managing recurrent and non-recurrent congestion. TMS uses a Response Plan (RP) system that is based on continuous monitoring of traffic at the TMC and on real time information dissemination to motorists driving along the motorway. Attica Tollway TMS response is primarily automatic and based on confirmed data that has been entered into the system. The system uses rules and logic to generate accurate and consistent response. Attica Tollway's response field equipment includes:

- 16 Mainline Variable Message Signs (MVMS) located upstream of key route decision points to provide traffic advisory information to motorists already on the motorway.
- 58 Access Variable Message Signs (AVMS) located at entry points of the motorway to provide limited mainline traffic information that enables motorists to make informed route decisions prior to entering the motorway and prepares them for the traffic conditions they will encounter.
- 29 Single Line Variable Message Signs (SLVMS) are located in some tunnels and on gantries in advance of the tunnels. SLVMS are collocated on gantries with LCS and VSLS and therefore provide supplemental information to motorists on why the lane closures and reduces speeds are in effect.

Concerning the VMS and its use, the system generated RPs have been developed based on the signing policy of the Attica Tollway TMC. For other VMS use, operators follow detailed instructions provided in operation manuals of the company. In any case, the operator either accepts or rejects an alarm given by the system (automatic incident detection) or completes a new incident form as a new incident generation (detected by other source: CCTV, Patrols, Emergency Call Center etc). After completion of the basic features of the incident (position on the motorway, type etc.) the system "proposes" the possible impact on traffic. That means that the system makes a comparison between the demand and the capacity of the road after the incident and the restrictions on the traffic that it has (for example one lane closure).

Response Plans are categorized according to the impact of the incident, i.e., low, medium and high (Table 1). Each category refers both to the scale of implementation (zone within which every VMS must have message) and the "intention" of the message. For example a large scale incident with a long queue has an impact that must be displayed on every upstream VMS with heavy wording [7].

Table1. Types of Incident Response Plans—Attica Tollway

Type/ Level	Impact To Traffic (Queue)	Implementation Zone/ Signing Distance	Type Of Message (Wording)	Example
LOW	No queue-500 m	Last Upstream MVMS	Soft Recommendations	Incident/Accident During Off Peak Hours Or Night – "Right Lane Closed Ahead….."
MEDIUM	500-3000 m	All Upstream MVMS & AVMS Up To 10 km Distance	Medium, Warnings/Info On Delays	Incident/Accident Resulting To Lane Closure During The Day "Delays Due To Road Accident At …"
HIGH	>3000 m	All Upstream MVMS & AVMS	Hard, Warnings/Info On Strong Delays	Incident/Accident During Peak Hours – "Heavy Traffic From …To …Due To …."

PEMS IN ATTICA TOLLWAY

The PeMS system has been deployed for the Attica Tollway since July 1, 2005; it includes freeway detector data every 20 seconds of volume, speed and occupancy from over 1000 loops, incident data and toll data [9]. PeMS checks the data for accuracy, and processes this data every day to compute performance measures. The results are viewed via an extensive set of web pages. Examples include plots of flow, speed over time of day and day of week to see temporal trends. Contour plots of speed or occupancy provide directly the spatial and temporal extend of the congestion, and assist in determining bottleneck locations. PeMS uses the flow and speed data to compute performance measures that can be easily understood by the system manager (e.g., VMT, VHT), and the system user (delay and travel time). Delay is computed as the additional vehicle-hours traveled driving below the free-flow speed, taken to be 100 kph (60 mph).

PeMS is continually enhanced with features to meet special needs of the Attica Tollway operations. Some recent enhancements include a) incident data visualization and statistical analysis, b) origin-destination matrix estimation in AT network, c) automated flow balancing from loop detector and toll data, and d) Route Performance through dashboards and other visualizations.

PeMS travel time estimation and prediction algorithms

PeMS computes travel time for predefined routes and it also has the ability to compute travel time predictions as well. Currently, there are 83 routes defined in the PeMS system, representing common trips along the freeway sections of the Attica Tollway. In PeMS, the travel time on a route is computed by "walking the velocity field". This means that for each route segment we calculate the time it takes to traverse that segment and then get the speed for the next segment at the time that we arrive at that segment. This is in contrast to methods which just sum the travel time of every segment in the route at the starting time.

Walking the velocity field leads to more realistic and accurate travel time estimates than the simple alternative, especially for longer routes since the traffic condition could change during a trip. In empirical studies, this approach produces travel time estimates that are consistent with the true travel times measured with individual vehicles, which we consider to be the ground truth.

The implication of using velocity field travel time is that cannot be computed travel time for the current time period: at best can compute travel time for trips that *end* now. Another implication is that routes need to be predefined, since velocity field travel time cannot be computed via a simple query.

Several algorithms exist for travel time prediction including artificial neural networks [1], linear regression models [2], *k*-nearest neighbour prediction [*3*] and other methodologies. Many studies have also investigated the relationship between incidents and travel time [4, 5]. PeMS predicts the travel time on predefined routes with available real-time data from detectors. The prediction is based on a nearest neighbour approach. This means that PeMS looks at the collection of historical travel times for a particular route and choose the days with the 3 closest travel time profiles. It uses a simple weighted vector over the last few samples to measure distance between travel time profiles. It then forms the prediction by taking the median of these three closest travel time profiles and plots that for the rest of the day.

Mathematically, the process can be represented as follows. Let $x(d,t)$ denote the travel time over the route at time $t = 1, \ldots, T$ and day $d = 1, \ldots, D$. Suppose the current time is t_0 on a new day d_0 and the travel time is available up $t_0 - u$. (Note that the latest travel time available is for the trip that has just *ended*, not the trip that has just *begun*, from the way velocity field travel time is computed.) The nearest travel time prediction for the trip that begins at $t_0 + \Delta$, or Δ time period ahead in the future, is then given by

$$\hat{x}(d_0, t_0 + \Delta) = avg\lfloor x(d_{i_j}, t_0 + \Delta),\ j = 1,2,3 \rfloor, \tag{1}$$

where $d_{i_1}, d_{i_2}, d_{i_3}$ are three days whose travel times up to $t_0 - u$ are “closest” to today’s.

Formally, $d_{i_j} = \delta_{[j]}$ with $\delta_{[1]} \le \delta_{[2]} \le \cdots \le \delta_{[D]}$ for $\delta_d = \sum_{a=1}^{A} w_a \left(x(d_0, t_0 - u - a) - x(d, t_0 - u - a) \right)^2$.

The weights w_1, w_2, and w_3 are fixed at 4, 2, and 1, respectively.

This prediction approach works well with a large amount of data: more “training data” will result in better prediction. On the other hand, using more data slows the process down since the system needs to read more data in the database in order to select the closest days. The nearest neighbour prediction approach will not work well if there is a traffic condition that has never occurred before (or at least has never occurred in the days over which PeMS is trying to pick the closest days) and the resulting traffic pattern and travel times are such that have never been observed before.

Kwon et al [6] evaluated the principles of this method and analyzed the impacts of incidents on route travel times and delays using loop and incident data from 86 weekdays on a 10 mile (16.7 Km) (10.4 mi) route of the Attica Tollway. The observed travel times are shown in Figure 1. The free flow travel time is about 10 minutes, corresponding to an average speed of 60 mph (100 km/hr), and the average peak period travel time is 18 minutes.

Figure 1 shows that there is a high variability in travel times during the peak periods, mostly due to incidents. The analysis shows that each accident increases (biases) the prediction error by about 24 seconds, compared to the average congested travel time of 18 minutes. This suggests that for the route under consideration, the predicted travel times displayed, for example in a CMS could be improved by adding 24 seconds to the predicted travel times when a new accident is reported, thus reducing the bias in travel time prediction.

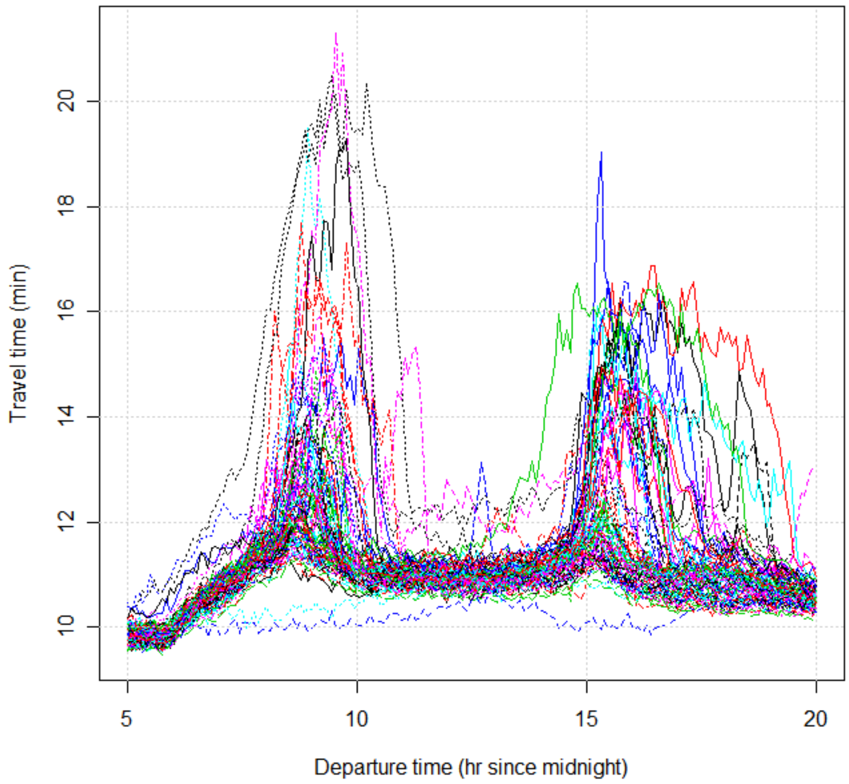

Figure 1. Travel Time for Katechaki-Athinon-Lamias Route Over 86 Weekdays

MEASURING TRAVEL TIME RELIABILITY

Reliability is defined as “the consistency or dependability in travel times, as measured from day-to-day and/or across different times of the day” [10]. In this section, we present the capabilities of PeMS in estimating travel time reliability measures from detector data, and we also compare the PeMS estimates with recently developed analytical models.

As described in the previous section, PeMS has the ability to define routes consisting of a series of freeway segments with detectors, and then to calculate travel time statistics from the detector data including mean, standard deviation and any percentile value of the travel times. It also calculates the travel time index (TTI), plus the buffer index. The TTI and the buffer index are defined as follows:

TTI = Actual travel time/ideal (or free flow) travel time (1)

Buffer Index = (95th %tile Travel Time – Mean Travel Time)/Mean (2)

The higher the TTI the more congested the route under consideration. The higher the buffer time index the more unreliable the travel conditions are, because the buffer time (the extra amount of time that a user has to plan in order to make this trip 95% of the time) is longer.

Characteristics of the Selected Test Route

The central Section of Attica Tollway, between interchange (i/c) 13 – D.Plakentias and i/c 8 Athinon-Lamias National Road is 8,8 km (5,5 miles) long and connects two major freeways. In an average 2009 weekday, this section carries about 85,000 vehicles per day per direction. During the peak hours, traffic is over 6,500 veh/hr which is close to or exceeds the capacity of the three lane section. Figure 2 shows the hourly distribution of traffic flow on weekdays on the test section in 2009. Figure 3 shows that the average speed in this section drops below 80km/h during the morning peak hours on weekdays.

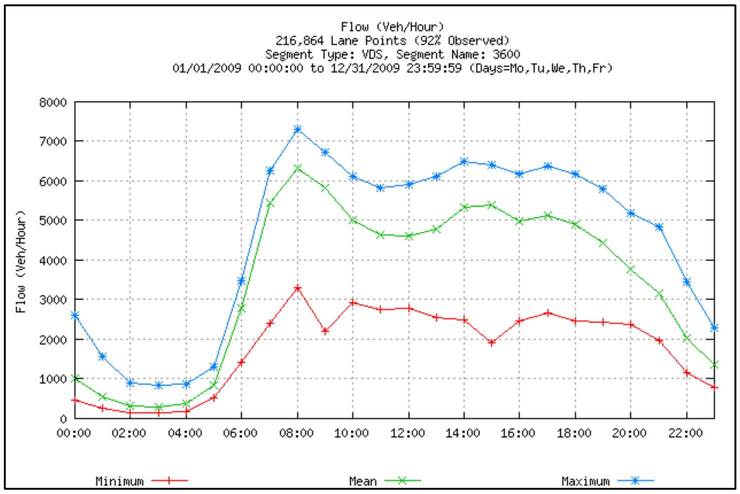

Figure 2. Traffic Flow on the Test Route—I/C 13 to I/C 8

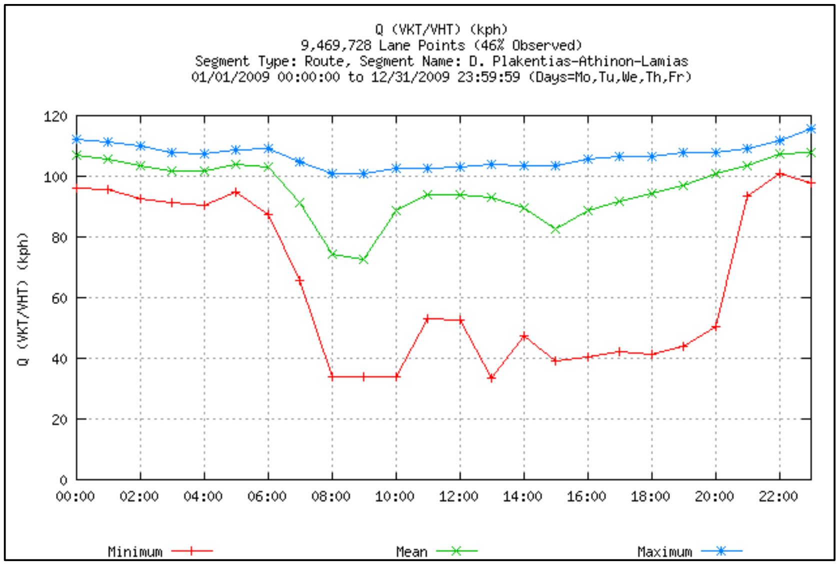

Figure 3. Average Speed on the Attica Tollway Test Section—I/C 13 to I/C 8

Figure 4 shows the veh-km travelled (VKT) in the study section per month for the last five years that PeMS data are available. The results show strong traffic growth (approximately 19% increase in VKT between 2009 and 2005). This has resulted in congestion during the peak periods with increased delays, longer average travel times and higher variability in travel times. This is clearly shown in Figure 5. The mean TTI increased by 25% between 2009 and 2005; the Buffer index also increased by more than 50%.

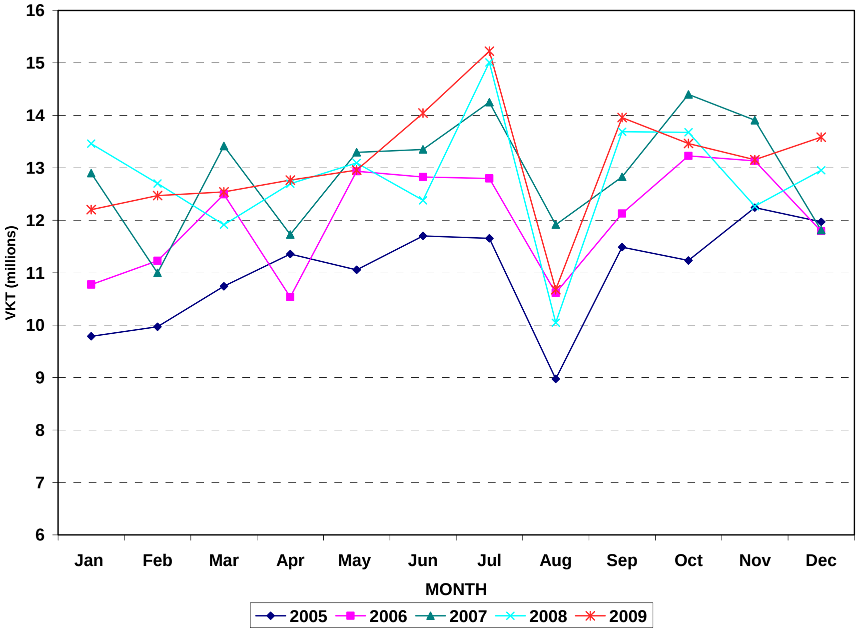

Figure 4. VKT in Attica Tollway Study Section 2005-2009

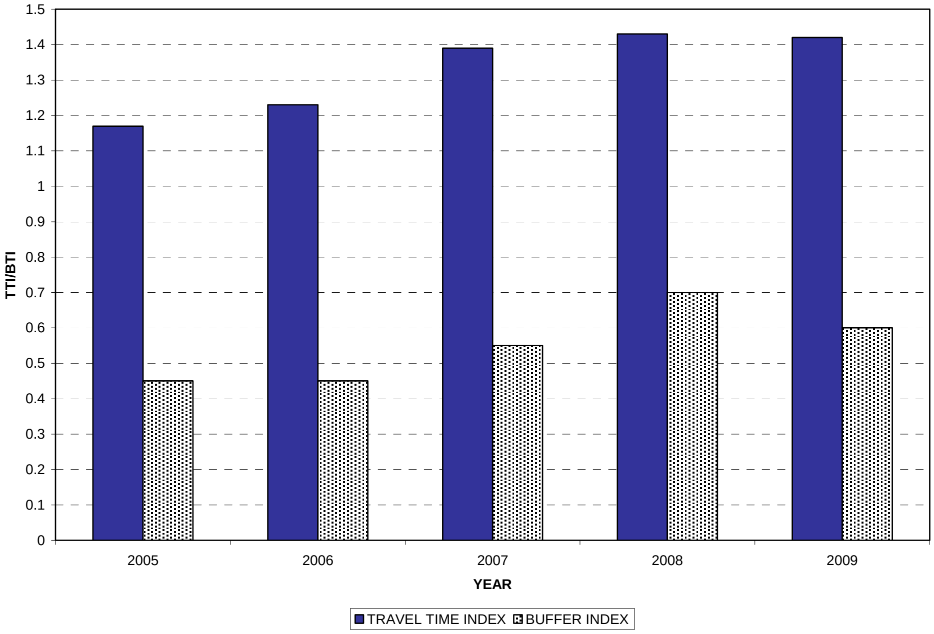

Figure 5. Increase in TTI and BTI in Attica Tollway Study Section 2005-2009

In 2009, the average travel time of a typical 24 hour weekday from i/c 13 to i/c 8 was 5,4 min. During morning peak hours (8-10 am) TT was 7 min or 30% higher. Also the 80th TT was 5,65 min on average and 7,7 min during morning peak hours and 95th TT was 9,48 min on average and 9,2 min during morning peak hours (Figure 6). Travel Time Index reaching on the heaviest day (Friday) values over 1.5 (max) and 1.2 as mean value (Figure 7).

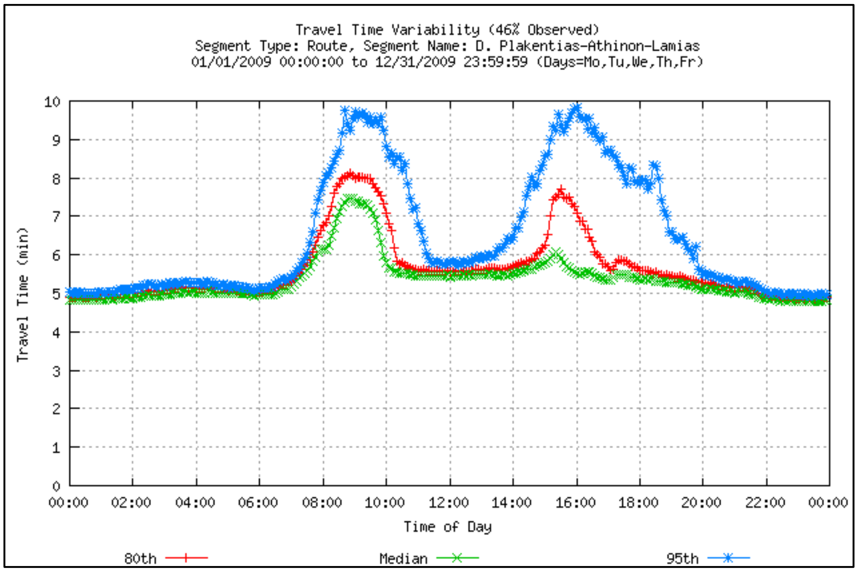

Figure 6. Travel Time Variability --Attica Tollway Study Section, 2009

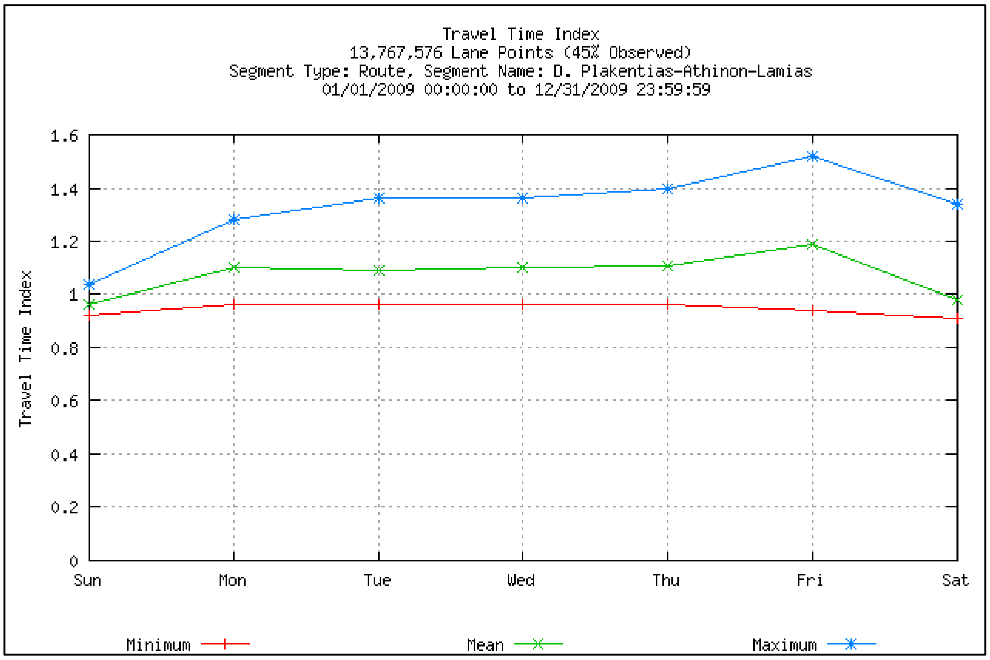

Figure 7. Travel Time Index (TTI) in Attica Tollway Study Section, 2009

Comparisons of PeMS Reliability Metrics with the SHRP2 L03 Methodology

The recently completed Strategic Highway Research Program 2 (SHRP2) L03 project in the US [11] was a major step in the development of methods for predicting travel time reliability and how reliability can be mitigated. SHRP2-L03 gathered a year's worth of travel time data for 292 directional miles of urban freeways in seven metropolitan areas of the United States. Incident, work zone, and weather data were gathered for each study section.

Based on this data, SHRP2-L03 developed two types of predictive models for urban freeways: (1) simple models that predict reliability measures as a function of the mean Travel Time Index (TTI) and (2) more complex models that predict the mean and reliability measures as a function of demand, capacity, incident characteristics, and rainfall. The simple reliability predictive models for urban freeways were developed for both links and sections. A link is defined as a short segment of highway between interchanges, and a "section" is an extended freeway segment typically 4-6 miles long, comprised of multiple links that are relatively homogenous in terms of traffic and geometric characteristics. The simple relationships for freeway sections are shown below:

$95^{th}\ \%ile\ TTI = TTI^{1.8834}$ (RMSE=15.7%; alpha level of coefficient < 0.0001) (3)

$80^{th}\%ile\ TTI = TTI^{1.365}$ (RMSE=4.5%; alpha level of coefficient < 0.0001) (4)

$Median\ TTI = TTI^{0.8601}$ (RMSE=6.3%; alpha level of coefficient < 0.0001) (5)

Where:
MeanTTI = mean travel time index (ratio of the mean travel time to the free-flow travel time)
95%TTI = 95 percentile highest travel time index (ratio of 95% highest time to free-flow time)
80%TTI = 95 percentile highest travel time index (ratio of 95% highest time to free-flow time)

Note that the MeanTTI used as the independent variable in the above equations is the overall mean that may include conditions with incidents and other events that can occur over the course of a year on a section. The L03 procedures provide for adjustments to the TTI obtained based on data only from periods of recurrent congestion.

We obtained four months of data on travel time reliability metrics from the PeMS system for the study section for all weekdays from January 1 through April 30, 2010. We compared the field data from PeMS on the median and 80% values of TTI with the predictions using Equations (4) and (5).

A remarkable consistency of values is shown at the results of equation (4) and (5). The maximum deviation is lower than 7.5% and on average the difference of the values is only about 3%. It is also noted that the minimum differences can be found during the most critical period of the day, the morning peak hours. The average difference between field and predicted 80% TTI is less than 1,7% on average between 7 and 11 am (Figure 8). The differences are even smaller for the Median TTI; the maximum deviation is less than 6% and on average is 1.8% (Figure 9).

These results clearly show that it is possible to predict the impact of ATM measures on the travel time reliability for a facility using the surveillance data and the SHRP L03 equations. The surveillance data through PeMS provide the performance under existing conditions. The impacts on the mean travel times for a proposed ATM strategy can be obtained with analytical or simulation tools. The SHRP2-L03 models will be used to estimate the 80th percentile and 95th percentile highest travel time index based on an estimate of the mean travel time index.

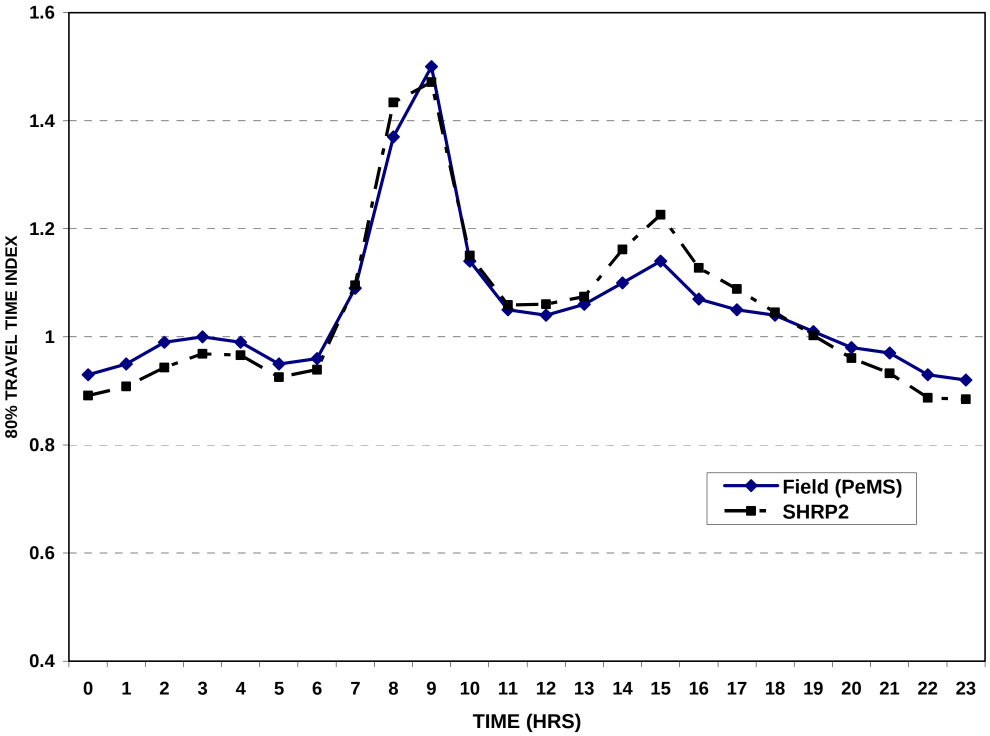

Figure 8. 80% TTI on Attica Tollway Test Section--Comparison of SHRP2 Model & Field Data

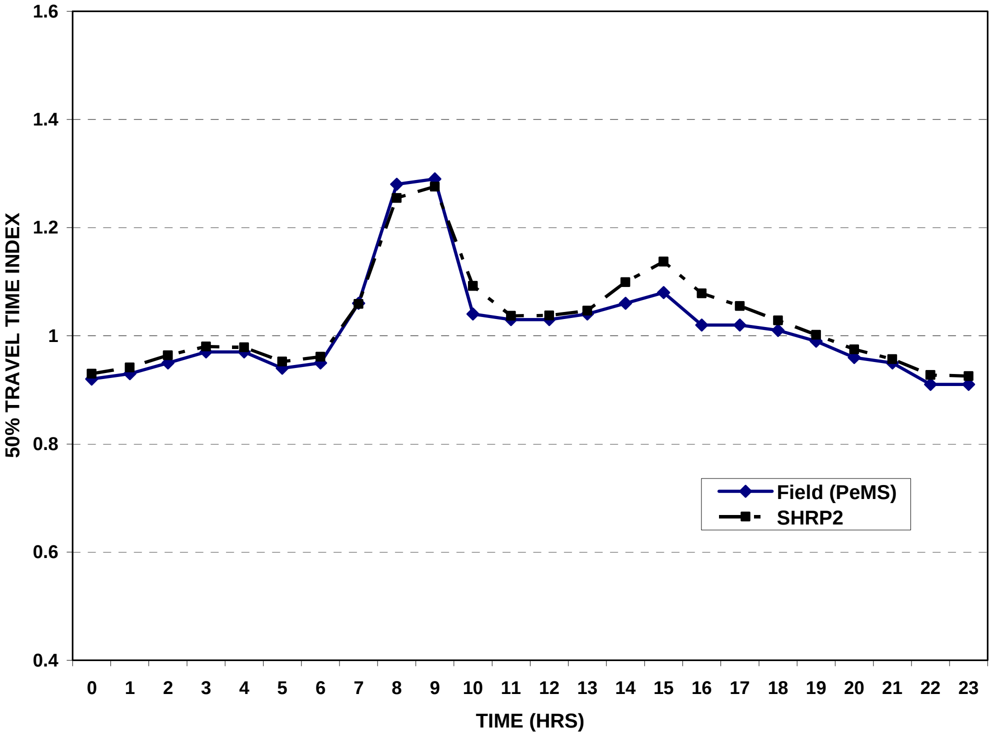

Figure 9. 50% TTI on Attica Tollway Test Section--Comparison of SHRP2 Model & Field Data

REFERENCES

1. Tao, Y., Yang, F., Qiu, Z.J., and Ran, B. (2005), “Travel Time Prediction in Presence of Traffic Incidents Using Different Types of Neural Networks,” *Transportation Research Board 85th Annual Meeting*, CD-ROM, Washington DC, USA.
2. Kwon, J., B. Coifman, and P. Bickel. (2000), “Day-to-day travel time trends and travel time prediction from loop detector data,” *Transportation Research Record: Journal of the Transportation Research Board, No. 1717*, pp. 120-129.
3. Nikovski, D., N. Nishiuma, Y. Goto, and H. Kumazawa (2005), "Univariate Short-Term Prediction of Road Travel Times", *IEEE Conference on Intelligent Transport Systems (ITSC)*, pp. 1074-1079.
4. Petty, K., M. Ostland, J. Kwon, J., Rice, and P. Bickel, (2002) "A New Methodology for Evaluating Incident Detection Algorithms," *Transportation Research, Part C (*10), pp.189-204.
5. Kwon, J., Mauch, M. and Varaiya, P. (2006) "Components of Congestion: Delay from Incidents, Special Events, Lane Closures, Weather, Potential Ramp Metering Gain, and Excess Demand," *Transportation Research Record* no. 1959, pp. 84-91.
6. Kwon, J., K. Petty, and P. Kopelias (2008), “Empirical Modeling of the Effect of Incidents on Congestion and Travel Time Prediction: Case Study of Attiki Odos Motorway,” 87thAnnual Meeting Transportation Research Board, January 2008, Washington, D.C.
7. Kopelias P., K. Papandreou, M. Bullock, and D. Theochari (2008), “Event and Queue Response in Urban Motorway: Implementation and Evaluation,” 10th International Conference on Applications of Advanced Technologies in Transportation, ASCE, Athens, Greece.
8. Freeway Performance Measurement System (PeMS). http://pems.eecs.berkeley.edu
9. Attica Tollway Freeway Performance Measurement System (PeMS), 2010, http://aom.bt-systems.com:4000, Accessed May 2010.
10. Texas Transportation Institute & Cambridge Systematics, (2005), “Travel Time Reliability: Making It There on Time, All the Time,” Federal Highway Administration, Washington, DC.
11. Cambridge Systematics, et al, (2009) “Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies,” Final Report, SHRP2-L03 project, NCHRP, Washington DC.
12. Choe, T., A. Skabardonis, and P. Varaiya, (2002), “Freeway Performance Measurement System (PeMS): an Operational Analysis Tool,” Transportation Research Record No.1811.