IDEA

Innovations Deserving
Exploratory Analysis Programs

SHRP 2 RELIABILITY IDEA PROGRAM

Online Traffic Simulation Service for Highway Incident Management

Final Report for
SHRP 2 Reliability IDEA Project L15C

Prepared by:
Alex Kurzhanskiy
Relteq Systems, Inc.
Albany, CA

February 2013

TRANSPORTATION RESEARCH BOARD
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IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

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IDEA Program Final Report

SHRP 2 L-15(C)

Prepared for the IDEA Program

Transportation Research Board

The National Academies

Alex Kurzhanskiy

Relteq Systems, Inc.

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EXECUTIVE SUMMARY

Incidents are estimated to cause somewhere between 52% and 58% of total delay experienced by motorists in all urban area population groups, according to the 2010 Urban Mobility Report. The delay estimates differ depending on where and what data are collected, and how delay caused by incidents is separated from recurrent congestion delay. More importantly, this delay cannot be predicted, whereas recurrent delay, by definition, is predictable.

Among incidents that cause delay, there exists the so-called 10-90 rule: 10% of incidents account for 90% incident-induced delay[1]. The delay caused by the same type of an incident varies substantially depending on its exact location (e.g. relative to ramps, availability of shoulder) and, more importantly, on the state of traffic. The same incident, when traffic is very light or highly congested, contributes a smaller increase in delay than at other times. Clearance time significantly affects delay, especially when traffic is close to capacity: since queue lengths increase proportionally with clearance time, the freeway section will transition into congestion, and recovery will take longer. In many instances clearance time is prolonged for statutory reasons. For example, the Freeway Service Patrol is not allowed to move a vehicle to the shoulder if there is a serious accident: in case of injury, a Highway Patrol officer must be present before a vehicle can be moved[2]. To reduce response (and hence clearance) time, it may be worth pre-positioning resources (Highway Patrol and tow trucks) to respond to incidents, but this is possible only if reliable statistical data of time and location of incidents are available.

Relteq Systems, Inc. develops software solutions to help traffic engineers and planners achieve superior operational performance on highways and urban arterials – as measured by traffic flows, absence of delays, lower fuel consumption and accident reduction. This Reliability IDEA project improved on technology created at the University of California, Berkeley to provide fast and reliable traffic simulation capabilities to traffic managers as an online service deployed in a cloud.

The resulting product, nicknamed Relteq Harmony, is a Decision Support System (DSS) that transportation network operators can use to determine the best possible response to traffic events. In particular, they can evaluate advanced operational strategies ranging from improved traffic signal timing or freeway ramp metering to variable speed limits, flexible lane assignments and alternative routing. Relteq Harmony functions either as a planning tool, or as a tactical tool that runs in real-time and lets a traffic control center to continuously optimize the application of available tactics, keeping roadways flowing at peak capacity. Relteq Harmony is developed following the paradigm of Active Traffic and Demand Management (ATDM) proposed by Federal Highway Administration (FHWA)[3].

The IDEA project enabled the development of key innovations that are now part of Relteq Harmony. Whereas existing traffic simulation software requires weeks or months of intense engineering work to establish parameters such as travel demand and network capacity, calibration of these parameters is automated in Relteq Harmony, feeding directly off traffic sensors[4]. The solution runs entirely in the Amazon EC2 cloud, requiring no installation or

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[1] P. Varaiya. *Reducing Highway Congestion: Empirical Approach*. European Journal of Control 11(4-5), pp. 301-309, 2005.

[2] These rules exist in California.

[3] *ATDM* is the dynamic management, control, and influence of travel demand and traffic flow on transportation facilities. Under an ATDM approach, the transportation system is continuously monitored, and through the use of available tools and assets, traffic flow is managed and traveler behavior influenced in real time to achieve operational objectives. These objectives include preventing or delaying breakdown conditions, improving safety, reducing emissions, and maximizing system efficiency. Using historical data and predictive methods, actions are performed in real time to achieve or preserve system performance. (Source: http://ops.fhwa.dot.gov/publications/fhwahop12047)

[4] So far, the system was tested with PeMS data (http://pems.dot.ca.gov), most of which come from loop detectors on California freeways.

maintenance on the part of transportation operators. This also means that extensive simulation resources are available on demand – multiple servers in the cloud can run in parallel to deliver faster results. Further, multiple government agencies can now collaborate on the same platform to provide even greater benefits to the traveling public.

Particular enhancements to Relteq Harmony resulting from the current project include:

1. Rich editing capabilities in Google Maps based network and scenario editor, allowing the user to place sensors, controllers and events on the road network;
2. Data handling mechanism for building operational scenarios from the available traffic and event data;
3. User Interface for launching simulations, single deterministic as well as batches of stochastic ones, and generate reports;
4. Software utility for automatic generation of a traffic model based on daily traffic data.

IDEA PRODUCT

Active Transportation and Demand Management (ATDM) [1] is the ability to dynamically manage recurrent and non-recurrent congestion based on prevailing traffic conditions in order to maximize the effectiveness and efficiency of traffic networks. ATDM measures can be primarily categorized as supply side and as demand side. Supply side measures seek to improve traffic network operation by directly changing capacity, speed and/ or signal timing plans. Demand side measures seek to improve traffic conditions by affecting the demand for travel through pricing, traveler information and marketing. ATDM strategies evolve as quickly as the detection, communication, data processing, and actuation technologies they employ.

Relteq Systems is developing Relteq Harmony, a decision support system for active transportation and demand management. Relteq Harmony is currently deployed at http://relteq-staging.heroku.com. The ATDM workflow and the role of the Relteq Harmony service are shown in Figure 1. This workflow consists of three loops. The purpose of the strategic loop is to process the historical traffic data, create travel demand forecasts, and perform cost-benefit analysis of potential ATDM measures, based on which the necessary infrastructure is deployed. It generally takes between 2 and 5 years to complete. Tactical loop refers to the real-time (or near real-time) traffic operations, where the traffic situation for the next day or few hours is modeled under different scenarios, and the best performing out of available ATDM strategies is selected. The third one, dealing only with the supply side measures, is the automation loop, where the traffic controllers are sophisticated enough to properly adjust to the traffic situation without interference of the operator. We envision Relteq Harmony not only as part of strategic and tactical loops of the ATDM workflow, but also as a necessary component of the automation loop, since non-recurrent traffic scenarios cannot be handled without simulation.

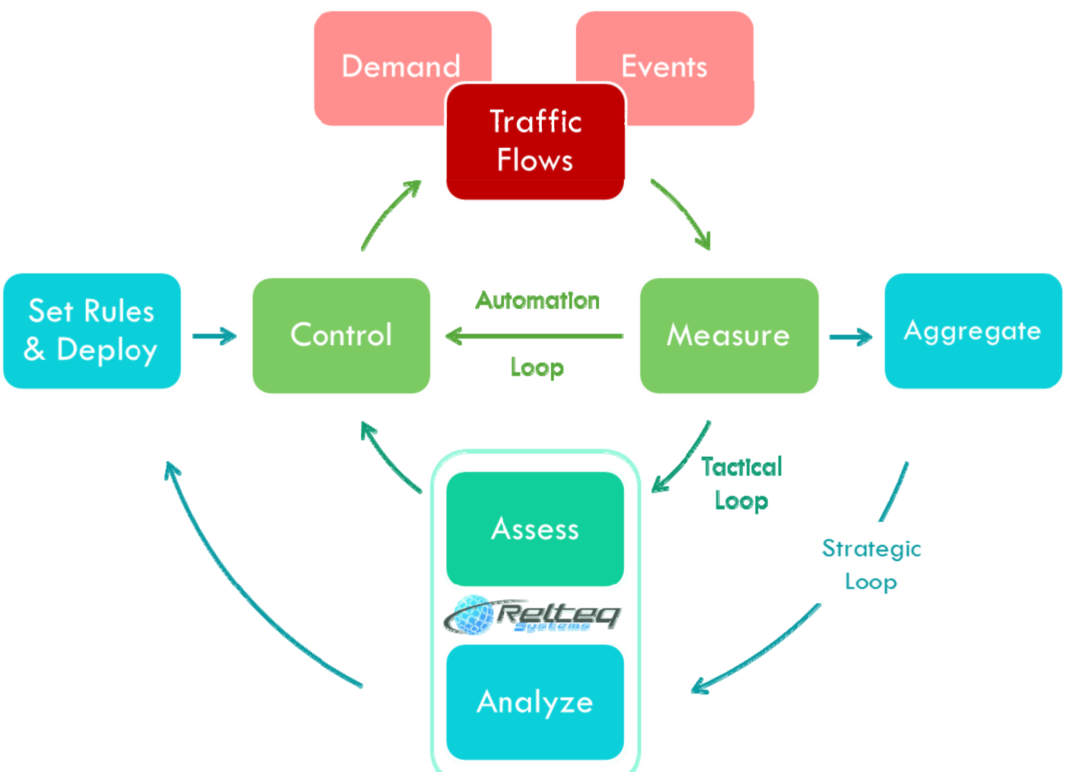


FIGURE 1 ATDM concept and Relteq Harmony's decision support role for either real-time operations or strategic improvements. Traffic measurements are collected from available roadway sensors, and increasingly, from smartphones.

CONCEPT AND INNOVATION

The general concept of real-time traffic management with the Relteq DSS is presented in Figure 2.

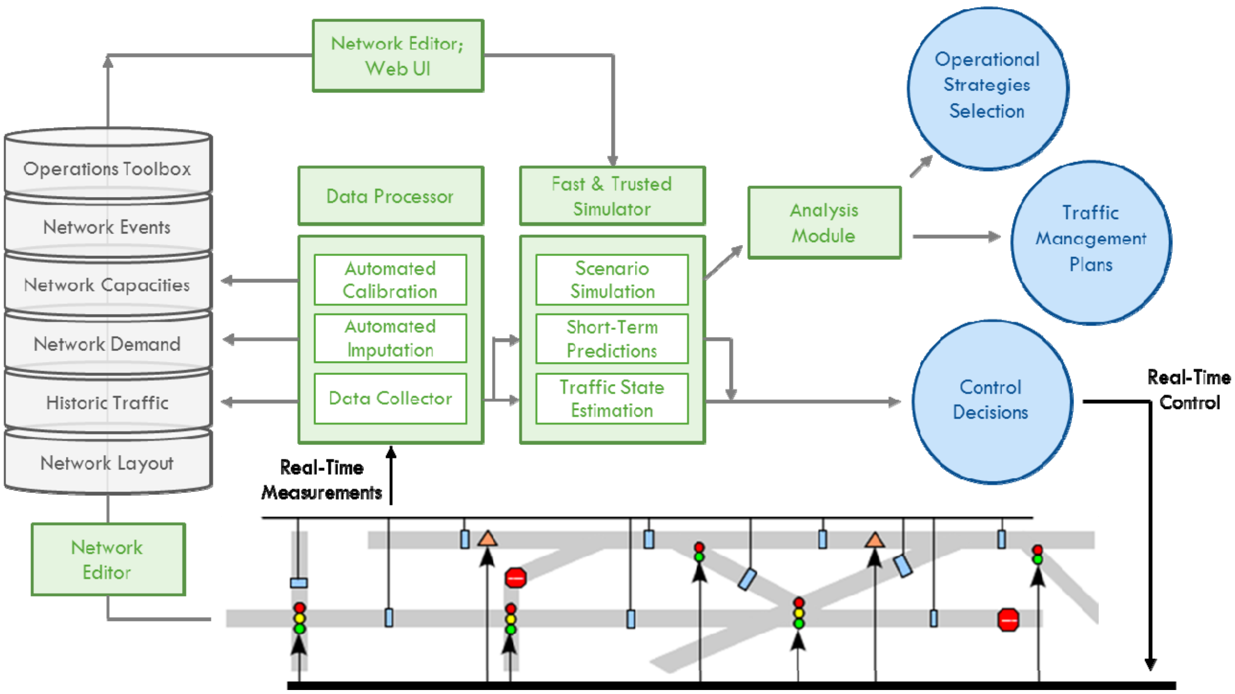


FIGURE 2 General concept of real-time traffic management with Relteq Harmony.

Given the specification, the road network is built with the Network Editor and stored in the Network Layout database. Traffic data needed for model calibration, and data sets for simulation input, are stored in the Historic Traffic repository. Network Demand and Network Capacities databases contain the quantities computed by the Data Processor invoking traffic model calibration and traffic flow imputation routines. The Network Events database stores possible events, such as lane closures, incidents, change of control, traffic re-direction, etc. The Operations Toolbox is a database of controllers that operate on the link, node or network level and can be activated if necessary. All these data can be accessed, modified and used for scenario creation by the traffic operator through the Relteq Harmony Web User Interface (UI) and the Network Editor. Network Editor is especially handy for fast road network modifications, such as creating detours in cases of large incidents.

Fast and trusted simulator is the key component of the DSS. It runs simulation scenarios in off- and on-line modes. A simulation scenario consists of (1) road network with calibrated parameters; (2) demands – vehicle flows at entry points of the road network; (3) capacities at exit points of the road network; (4) turn ratios at diverge points and intersections; (5) set of events; and (6) set of controllers. Item (1) is required, items (5) and (6) are optional, items (2)-(4) are desirable. In the off-line mode, performance measures are computed using statistically forecasted demand for different operational strategies, and the best performing strategy is selected as the default one for the next day. The off-line mode is also used for post factum daily traffic evaluations – determining if there were alternative operational strategies yielding better results. Finally, the off-line mode is used for quick assessment of Traffic Management Plans describing the traffic network operation under expected disruptions, such as a planned construction.

The on-line mode, on the other hand, provides short-term prediction operating continuously, correcting the forecast with the real-time traffic data feeds. In the case of non-recurring and unexpected events, such as large accidents, the on-line prediction is computed for alternative operational strategies, helping the traffic operator to select the best performing one. The other purpose of the on-line simulation mode is to filter the incoming measurements, passing them through the state estimator, before feeding them into field traffic controllers. The on-line simulation mode is the enabler of the real-time DSS.

Figure 3 illustrates the workflow of the real-time DSS operation. To run the on-line simulation, the traffic operator must provide only the road network, the controllers, and the events. The remaining components of the scenario model – the initial traffic state, traffic demand, and routing patterns defined by split ratios – all depend on the measurements, and are computed automatically. The initial state is determined by the traffic state estimation module. Traffic demand forecast is made using the historical data, corrected by the incoming measurements. Dynamic Traffic Assignment (DTA) module computes the split ratios for the traffic flow at diverge points and intersections. These split ratios determine traffic routes. The resulting traffic model is fed into the simulator that predicts traffic behavior for the given time horizon (e.g. 1-2 hours) providing numerical data whose analysis produces the traffic network performance report, presented back to the traffic operator. Then, the traffic operator makes operational decisions about the traffic flow control and traveler information. Operator's decisions are recorded together with original events and prediction reports coming out of the simulation and data analysis engine. Eventually, once enough data about the operator's decisions, prediction quality and daily traffic performance will be recorded, the DSS will provide recommendations suggesting the best performing operational strategy out of those available in the scenario playbook. Certain traffic networks, e.g. travel corridors composed of freeways and parallel city arterials may be managed by different authorities, and thus require sharing of information about the events and operational decisions. The scenario playbook can potentially be shared among multiple agencies, users of Relteq Harmony.

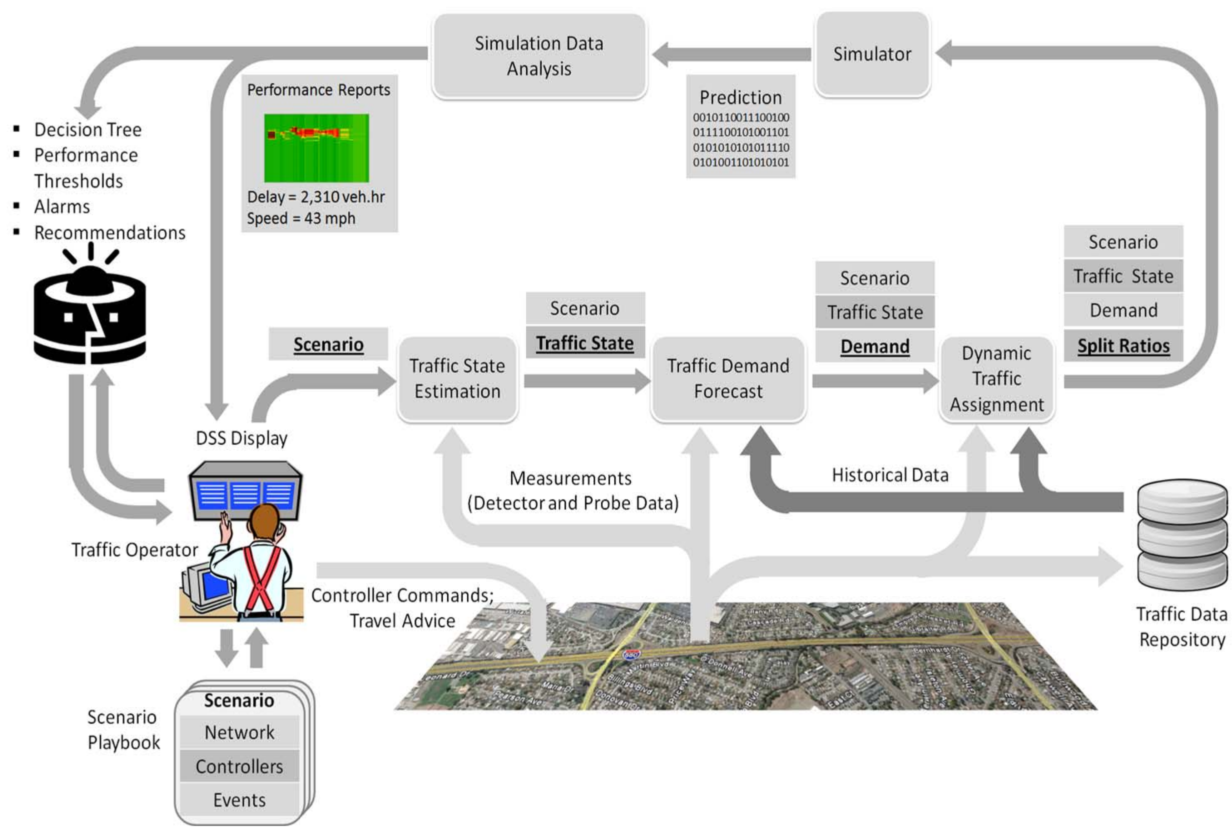


FIGURE 3 Workflow of real-time traffic operation and the role of DSS.

INVESTIGATION

Relteq Harmony consists of the following software components.

- *Aurora 2.0* core engine is a library of heavy-duty computation tools that include (1) a traffic model calibration utility; (2) imputation of missing flow data; (3) a traffic simulator with scenario assessment, dynamical filter and prediction capabilities; and (4) a simulation data analysis tool, called report generator. Aurora 2.0 core engine is based on Aurora Road Network Modeler [2] and is implemented in Java (http://www.java.com) and MATLAB (http://www.mathworks.com/products/matlab). The calibration utility works with measurement data files in PeMS [3] format. The missing data imputation module is currently in a prototype stage – it is the only module implemented in MATLAB, and will eventually be ported to Java. The report generator uses the following third party libraries:
  - JFreeChart (http://www.jfree.org/jfreechart) – library for generating plots and charts;
  - iText (http://www.itextpdf.com) – library for generating PDF documents;
  - Apache POI (http://poi.apache.org) – library for generating Microsoft Office documents.
- *Simx* service bundle is a set of services for managing (1) user requests for computation jobs that involve Aurora 2.0 functions; (2) CPU instances and processes performing or ready to perform computation jobs; and (3) user data import/export and storage. Simx services are implemented in Ruby (http://ruby-lang.org). They use JRuby (jruby.org) for interfacing Aurora 2.0 modules, and PostgreSQL database (http://www.postgresql.org) for storing all relevant system information. Designed to function in a general networked environment, Simx is currently deployed within the Amazon EC2 and S3 cloud [4].
- *Network Editor* is a web based application for interactive building and editing of road networks and user scenarios on Google Maps using Google Maps API [5].
- *Web Server* is a user-friendly web application that allows the user to manage content (i.e. road networks, scenarios, simulation data and reports) and issue requests to perform certain tasks, such as simulation and report generation. It is developed using Redmine [6], an open-source Ruby on Rails (http://rubyonrails.org) web application for project management and user collaboration.

Figure 4 presents the high-level architecture of the Relteq Harmony system. On the client side there may be individual users accessing the system with their web browsers, or automated Transportation Management Systems (TMS), which can programmatically communicate with Relteq Harmony through its web services API.

The front end of Relteq Harmony is represented by the Web Server, which is built upon the Redmine project management web tool [6]. The Web Server provides a user interface for scenario management that includes importing and exporting user data. It also instantiates a session of the Network Editor with a copy of the user-specified scenario or road network, and handles user requests for launching simulation batches or performing simulation data analysis.

Heavy computation tasks, such as calibration, imputation, simulation and simulation data analysis, are performed by specially dedicated CPU instances shown in Figure 4 as Worker Instances. A Worker Instance is an Amazon EC2 [4] instance with Ubuntu Linux, the Aurora 2.0 library, necessary environment variables, and pre-configured JRuby API used to remotely launch and monitor Aurora 2.0 simulations. In the event of Relteq Harmony software update, an Amazon Machine Image (AMI) [4] containing the latest software version and configuration is created and stored at Relteq's Amazon AWS account. This AMI can be used to clone Worker Instances as many times as required by user demand. The CPU power and memory of a Worker Instance can be chosen from the list of available Amazon EC2 options and largely depend on the user's requirements and willingness to pay for computation speed. In Relteq Harmony, at least one Worker Instance is always active – performing tasks or waiting for new tasks – ensuring that eventually all user requests will be serviced. A Worker Instance does not need to be a part of Amazon EC2 cloud. It can be any computer with Internet connection, properly installed and configured Aurora RNM and JRuby API.

Thus, if the user wishes to run calibration/imputation/simulation/analysis worker processes on his/her own machine, it can be arranged.

When a Worker Instance starts, it automatically registers itself with the Simx component of Relteq Harmony, namely, with the Job Manager. The Job Manager maintains the list of active worker processes keeping track of their status (ready for new task or progress of the current task), and the queue of user requests passed to it by the Web Server. The queued user requests get assigned to Worker Instances as those become available.

The results of simulation and simulation data analysis, user-uploaded measurement data files used in calibration, as well as temporary configuration files created during importing or exporting of user data, are stored in Amazon S3 cloud [4]. The Database contains information about users, projects, road networks, scenarios, pointers to data stored in Amazon S3. User configuration files for road networks and scenarios in the Aurora RNM XML format [2] can be imported into the Relteq Harmony Database with our User Data Import service.

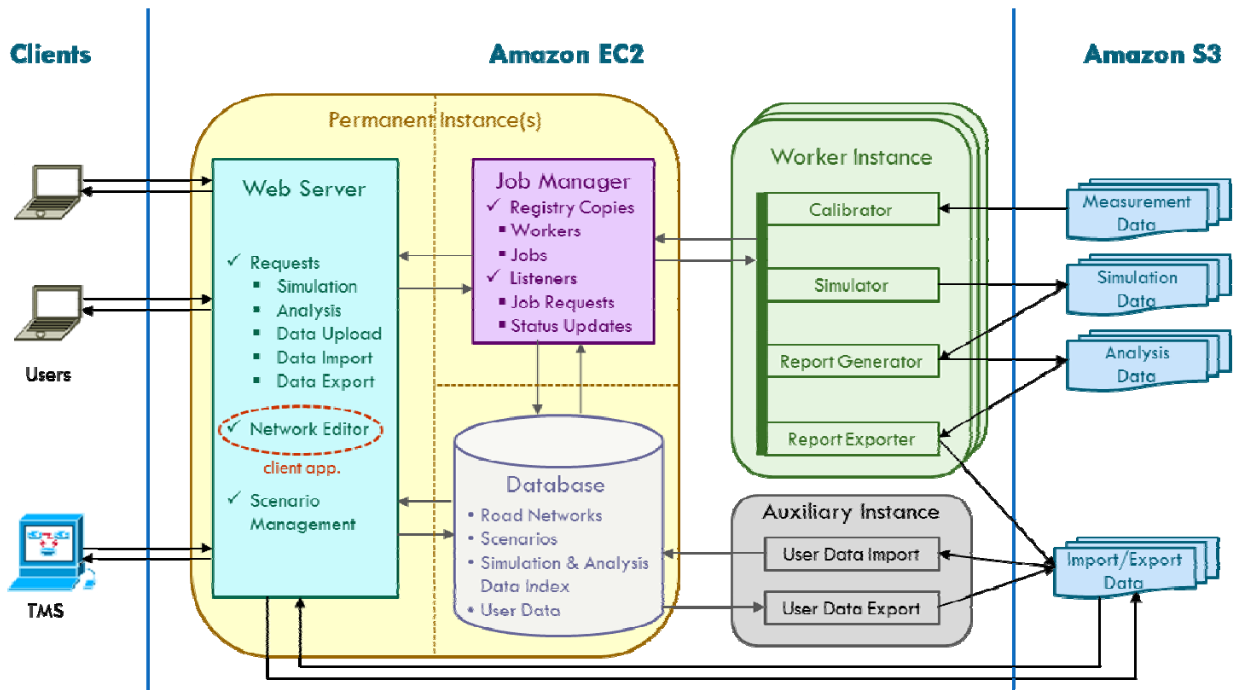


FIGURE 4 Relteq Harmony – high-level architecture.

The R&D focus of the current IDEA project was on developing and testing the following features of Relteq Harmony:

1. User Interface for scenario management and reporting simulation results;
2. Utility for automatic traffic model generation based on daily traffic data (daily model calibration);
3. Playbook incident scenarios for a given California travel corridor (I-80 in San Francisco Bay Area).

USER INTERFACE FOR SCENARIO MANAGEMENT AND REPORTS

One of the handy applications of Relteq Harmony is Network Editor, shown in Figure 5. It runs in a web browser and allows the user to create road networks from scratch as well as to edit existing road network configurations using Google Maps API [5]. While Network Editor is integrated into Relteq Harmony allowing the user to load available road networks from the Relteq database, edit them and save back into the database, it can also be used as a standalone application, which loads and saves road networks in the XML format of Aurora RNM [1] from and to the user's local disk.

By right-clicking on the Google Map the user can create a controller or an event. Special browsers exist in the Network editor for viewing and sorting of controllers and events. Figure 5 shows how these browsers can be launched from the Windows menu. Double-clicking on a controller or an event brings up a corresponding editor window for that scenario element where its parameters can be modified. Currently, we have implemented editors for the ALINEA [7] and Time Of Day (TOD) ramp metering controllers and the event that changes the fundamental diagram in a given link – this event is used to model incidents and lane closures.

Network Editor also allows the user to create detectors by clicking with the mouse at desired locations on the Google map, or by loading a text file in with detector locations provided, for example, by PeMS [3]. Once the detectors are created, they must be associated with road links by dragging and dropping of them onto desired links. In Figure 5, detectors are displayed as green circles. The green detector icon indicates that this detector is attached to a link. Unattached detectors are shown in yellow.

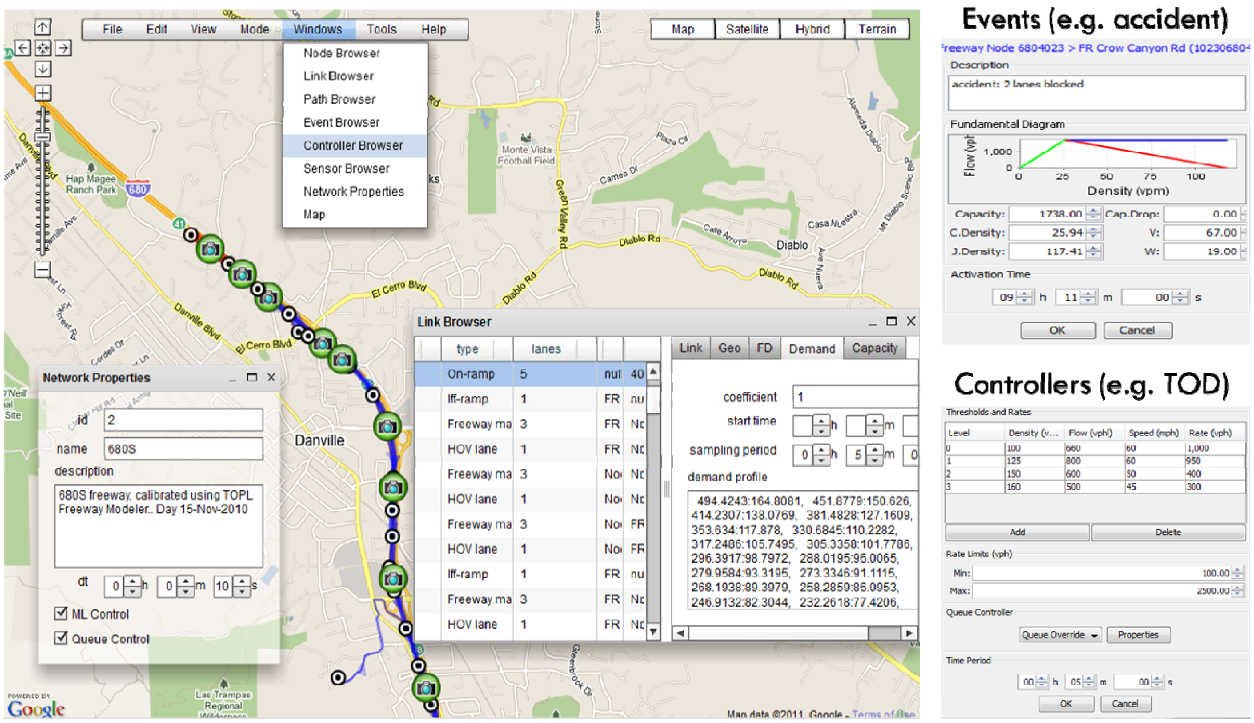


FIGURE 5 Screen shot of Network Editor. On the right are editing panels for events and controllers (TOD stands for "time of day" ramp metering).

Figure 6 presents the Relteq Harmony web user interface for managing scenarios. A full scenario ready for simulation consists of (1) road network with calibrated parameters; (2) demands – vehicle flows at entry points of the road network; (3) capacities at exit points of the road network; (4) turn ratios at diverge points and intersections; (5) set of events; and (6) set of controllers. Item (1) is required, items (5) and (6) are optional, items (2)-(4) are desirable –without them the simulation results are meaningless. Additionally, the user can specify vehicle types (e.g. single-occupancy, high-occupancy, trucks) to be studied, the time range this scenario covers, and the recording period for simulation data (e.g. every 30 seconds, every 5 minutes or every hour of simulated time). The key feature of Relteq Harmony scenario management is that items (1)-(6) described above can be assembled into a scenario in different combinations. For example, if the user wishes to model traffic of a different day but with the same events and control strategy, he/she just needs to replace demands and turn ratios in a scenario with those of the new day. Another example: the same set of events and controllers can be used in combination with several different but overlapping road networks.

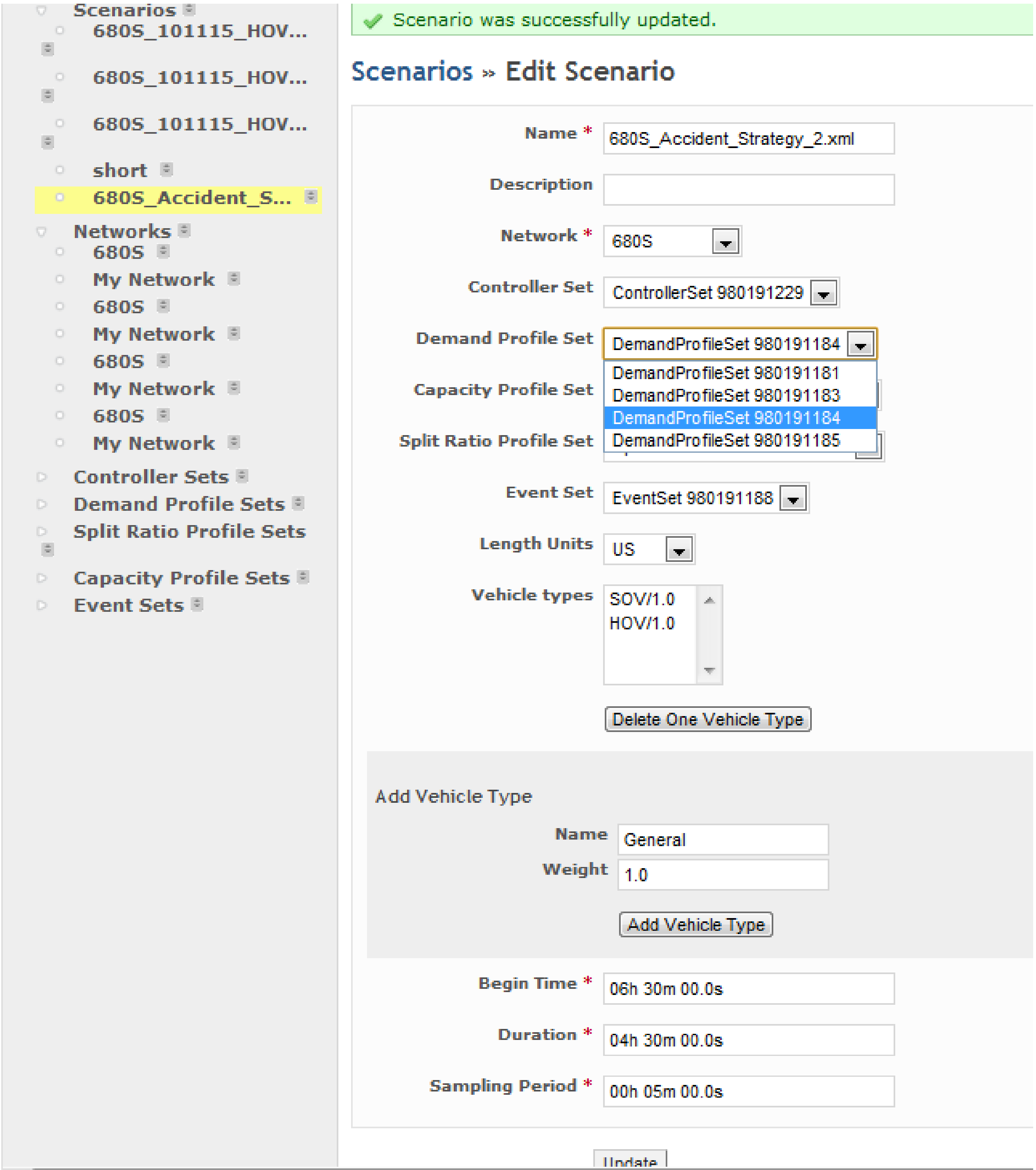


FIGURE 6 Web interface for scenario management.

The web user interface for launching a simulation batch for a given scenario is shown in Figure 7. Here the user can specify the following options.

- Mode of operation – simulation or prediction. The choice of mode makes a difference only in the presence of uncertainty in the road network parameters and/or demands: the simulation mode takes random values from within the uncertainty intervals and produces a stochastic simulation; whereas in prediction mode the best and worst case bounds of the traffic state are computed.
- Number of runs – how many times the simulation should be executed. Multiple runs make sense only for stochastic simulations; otherwise, all of them will produce the same result.
- Time range to be simulated. A scenario may contain enough data to simulate 0 to 24 hours, while the user may be interested in studying just the peak hour interval, say from 6 to 9 AM.
- Other options are enable/disable switches for all the events and all the controllers.

Once the user clicks the "Run" button, the Web Server forwards the simulation batch request to the Job Manager, which assigns it to the available Worker Instance (or, if multiple runs are requested, distributes these runs among available Worker Instances). The simulation output is stored in Amazon S3 [4], and the pointers to the simulation data are recorded in the Database upon completion of the simulation batch (see Figure 4).

The simulation data analysis module of Aurora RNM [2] processes the simulation output files from selected batches, computes and compares the following performance measures for different scenarios (or provides the distribution for multiple stochastic runs of the same scenario): traffic speed; actual travel time along selected routes; vehicle miles traveled (VMT), which is the measure of throughput of a link, route, or road network; vehicle hours traveled (VHT), which the number of vehicles in a link, route or network at given time instance; delay, measured in vehicle-hours; productivity loss, measured in lane-mile-hours, which is the degree of underutilization of road lanes due to congestion. Different operational strategies are compared through performance measures for simulated scenarios corresponding to these strategies.

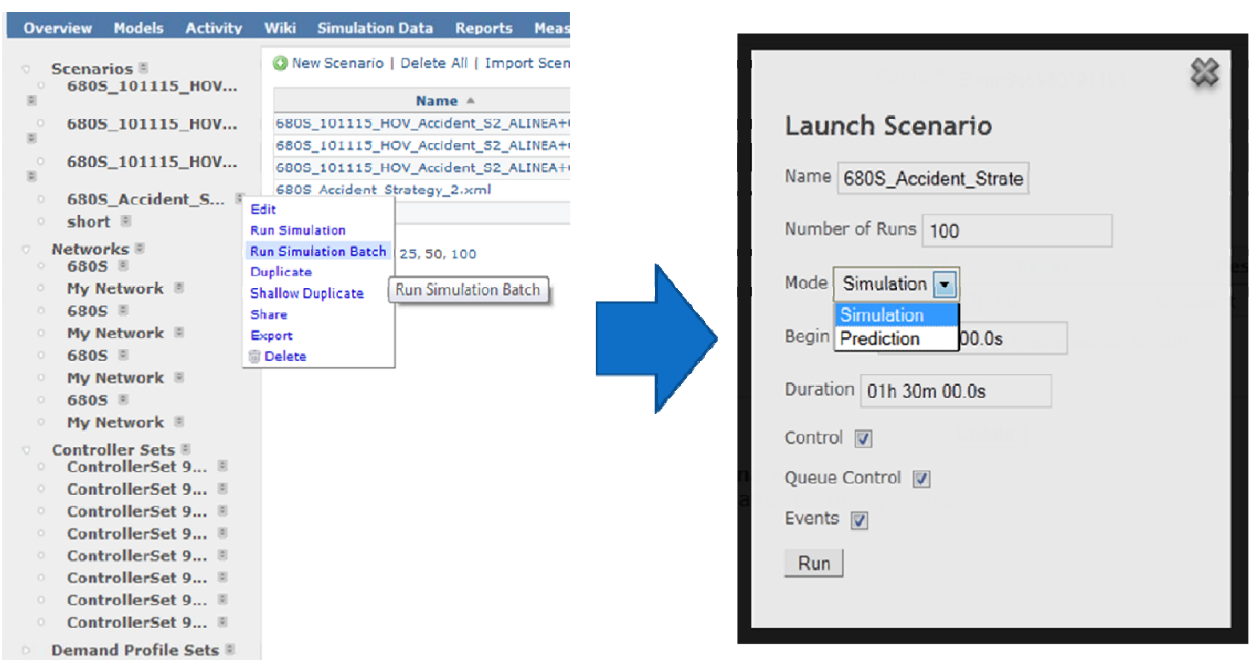


FIGURE 7 Web interface for launching simulation batch.

Figure 8 shows the web user interface for specifying the report parameters (on the left) and the screen shots of the actual report (on the right). Report parameters include the report type – comparing different scenarios, computing distribution of outcomes for multiple runs of a single scenario, show best/worst case performance; time range of interest; and other options specifying which data to include into the report and how these data should be plotted. Similarly to simulations themselves, the simulation data analysis is performed by the Aurora RNM Report Generator module on a Worker Instance, and the resulting reports are stored in XML format in the Amazon S3 cloud [4], while pointers to these reports are recorded in the Database (see Figure 4). The user can save reports in PDF, Microsoft PowerPoint and Excel formats on the local disk.

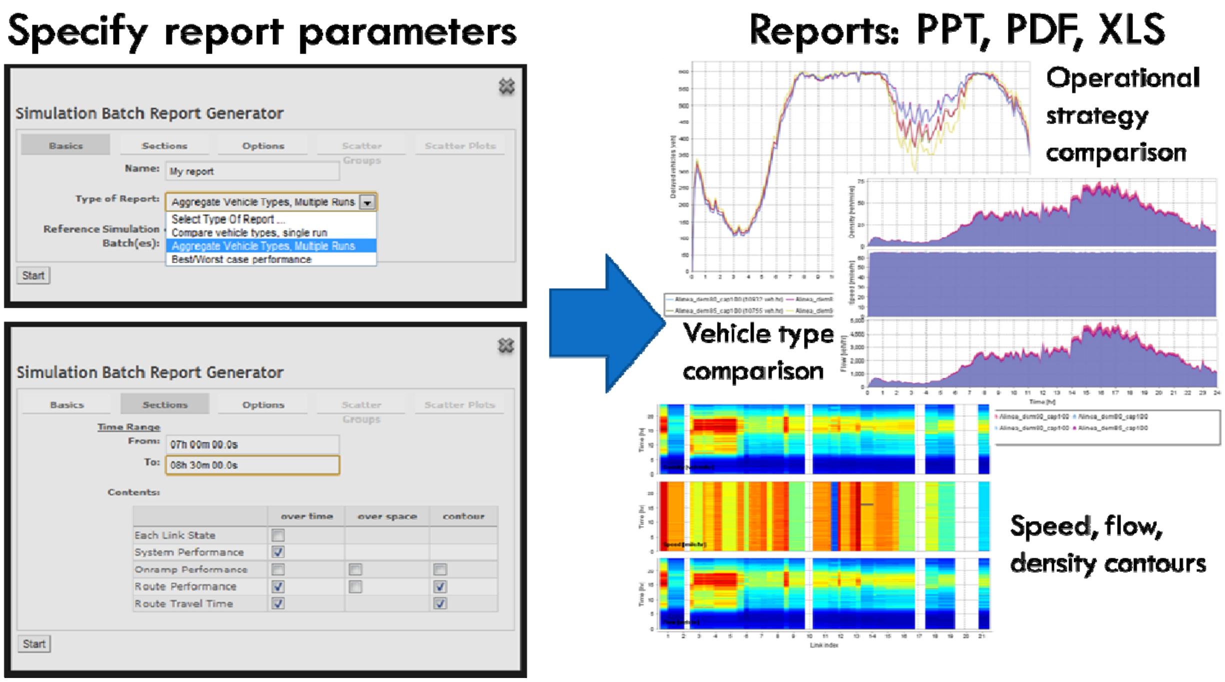


FIGURE 8 Web interface for simulation data analysis and reports.

The Redmine web application [6] serving as a foundation of the Relteq Harmony Web Server provides useful tools for project management and user collaboration. These include user and group management with project permissions and sharing; Wiki; document handling; Gantt charts and issue tracking. Choosing this open source off-the-shelf product with such capabilities allowed the Relteq team to focus on its core technology, and not be distracted by project management infrastructure development.

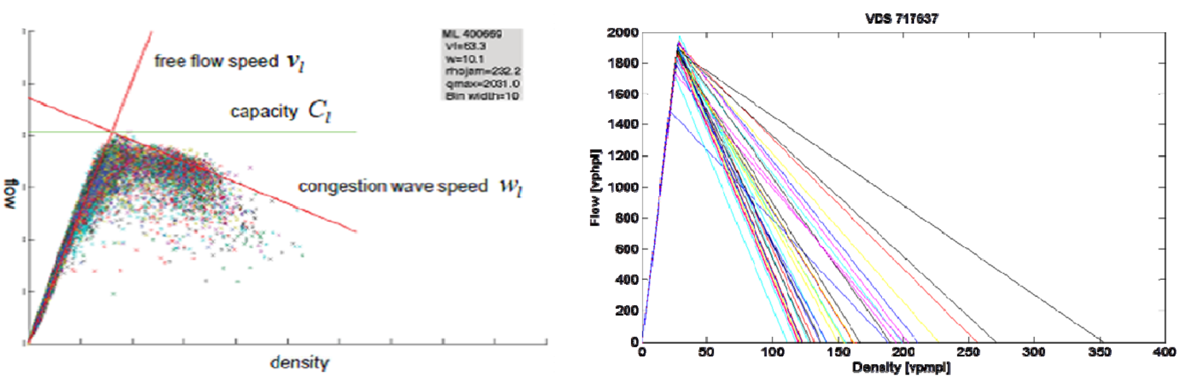
AUTOMATED TRAFFIC MODEL GENERATION FROM DAILY TRAFFIC DATA

One of the main ideas behind the development of Relteq Harmony is to enable automatic creation of dynamical traffic models from available detector measurement data – such that the resulting models would reproduce the traffic state obtained from measurements. PeMS [3] is an excellent source of California freeway data, while data for arterials (major urban streets) are not systematically collected and processed anywhere in the US[5]. For the current

[5] GPS probe data provided by private companies, such as INRIX, TeleNav, Nokia (NAVTEQ), cannot be used for calibration or traffic control yet. Speed data from probes are sufficient and increasingly popular in travel time estimation and travel time reliability assessment. Dynamic model calibration and traffic control, however, require

IDEA project we have built the utility for automatic traffic model generation based on PeMS data, which come from loop detectors.

Using density and flow values from measurement data files assigned to sensors, the calibration utility rapidly estimates the key parameters of road links – capacity, free flow speed and jam density following the methodology of [8, 9]. Since there are usually more links than sensors, those links without sensors get their parameters from the nearest neighbors with sensors. Sometimes, due to large data variability, the resulting fundamental diagrams have uncertainty in capacity and jam density, such as in Figure 9. This uncertainty becomes part of the traffic model used for traffic prediction. For models with uncertainty, the Relteq Harmony user can later request the best and worst case bound assessment or a batch of stochastic simulations. The best and worst case request results in a single run of a simulator, which computes the lower and upper bounds for traffic densities and speeds, as well as performance measures such as route travel time, total network delay, etc. The stochastic batch request results in as many simulator runs as specified by the user, which produce a distribution of possible outcomes for the traffic state and performance measures.



(a) **(b)**

FIGURE 9 (a) Flow vs. density scatter plot and fitted fundamental diagram parameters; (b) Fundamental diagram calibrated for multiple days – each color representing a day.

The next step in building the traffic model is the imputation of flow data that serves as input to the simulation. In the ideal world where all the detectors are present and functioning, this step is unnecessary. Unfortunately, in California it is often the case that detection at freeway on- and off-ramps is missing or malfunctioning, and one has to impute the missing data.

The imputation procedure computes on-ramp flows $r_i(t)$ and off-ramp flows $s_i(t)$ from the measurements of mainline flows $f_{i-1}(t)$, $f_i(t)$ and density $\rho_i(t)$, shown in Figure 10. The implemented imputation technique [10] is based on iterative learning control and linear programming. It is applied sequentially on all the links of the freeway. The selected ramp flows are those, which minimize the error between the simulation and the measurements at the mainline.

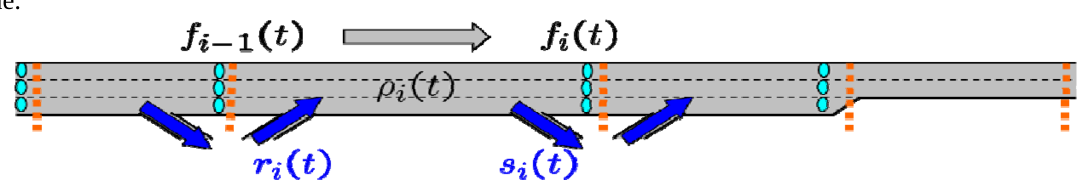


FIGURE 10 Missing ramp flow imputation – find flows r_i, s_i from measurements f_{i-1}, f_i and ρ_i.

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traffic flows and densities, currently obtained only from infrastructure detection. As probe penetration rate grows, and companies come up with methods of estimating traffic volumes from probe data (e.g. INRIX patent EP 1938296 B1), this commercial data source may become dominant, as it is easily accessible and its coverage is nationwide.

Once the calibration procedure is completed, the resulting traffic model should be validated against the real data. Tests with I-80, I-680 and I-210 networks confirm the reliability of this procedure for generating models that accurately reproduce freeway behavior and meet the requirements imposed on microscopic simulation by the Federal Highway Administration [11]. The example in Figure 4 illustrates how the described procedure was tested with the traffic data from the I-80 freeway. It compares the vehicle miles traveled (VMT), vehicle hours traveled (VHT) and speed contour plots produced by an Aurora 2.0 simulation with actual traffic data obtained from PeMS [3] on February 14, 2012, for the 23-mile long I-80 West freeway segment depicted in the left of Figure 11.

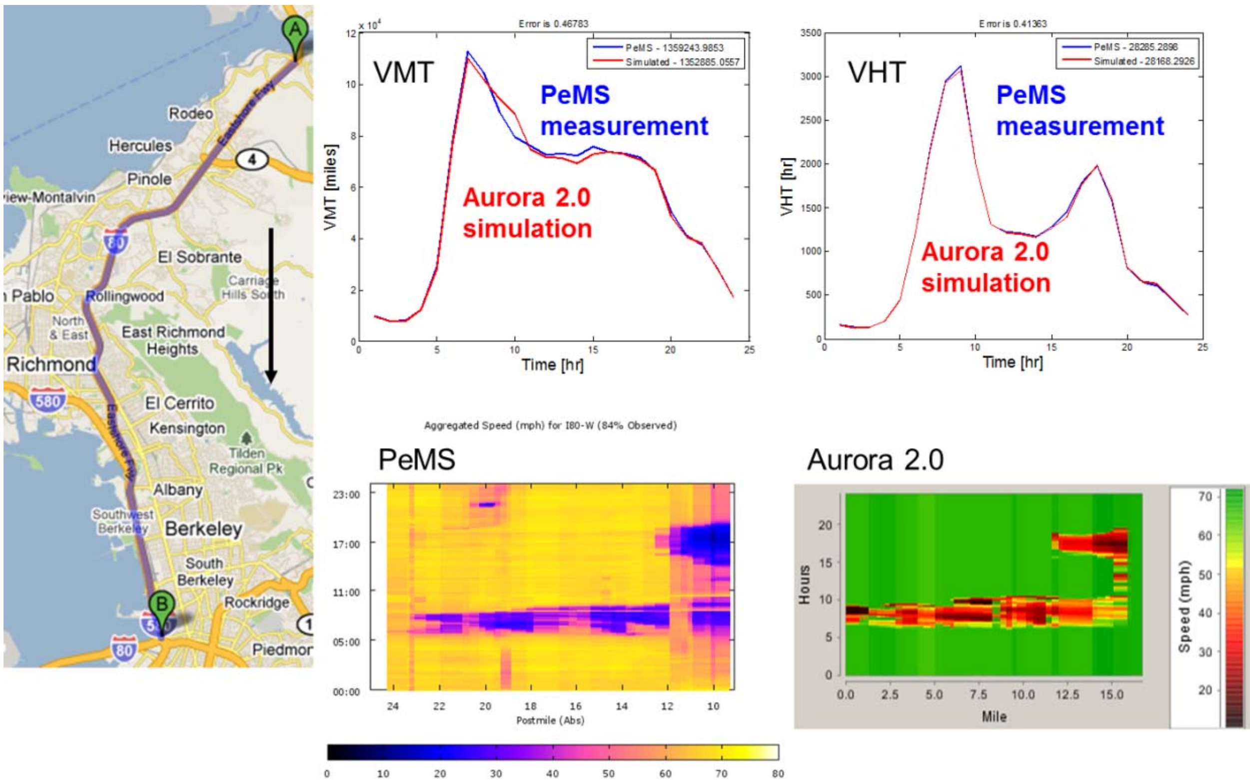

FIGURE 11 Interstate 80 West Bound model – comparing simulation result with measurements.

At the moment, we do not have the tools for automatic model validation and quality assessment, and resort to visual validation of selected models comparing the speed contours and calculating the error for aggregate performance measures, such as VMT and VHT. We work closely with researchers from the University of California PATH Program in establishing the methodology for automatic traffic model validation and its quality assessment.

CASE STUDY: I-80 IN SAN FRANCISCO BAY AREA

For the case study, we chose I-80 freeway corridor, comprising 23 miles of the I-80 freeway from the San Francisco – Oakland Bay Bridge to the Carquinez Bridge (respectively, points A and B in Figure 12), together with the major parallel arterial, San Pablo Avenue (also called State Highway SR-123), and the streets connecting the arterial to the freeway ramps. San Pablo Avenue has two lanes in each direction. The freeway has four or five lanes in each direction (including an HOV lane), 26 on-ramps and off-ramps, and loop detectors that measure occupancy and flow on each lane at 55 locations. This is the most congested corridor in northern California, with 10,000 vehicles/hour on the freeway in the morning and afternoon peak periods, and passes through the cities of Oakland, Emeryville, Berkeley, Albany, El Cerrito, and Richmond. The arterial serves as an alternative to the freeway when the latter is congested. Thirty agencies, including the corridor cities, the Bay Area Metropolitan Transportation Commission (MTC), Caltrans, the California Highway Patrol, and Alameda County have just initiated an $80 million project to design and deploy major ITS (Intelligent Transportation System) upgrades for the corridor within the next five years.

FIGURE 12 I-80 corridor in San Francisco Bay Area.

We have developed models for both directions, East and West, and created hypothetical accident scenarios with possible response strategies for both of them. These models were calibrated using historical 2011 PeMS data for Tuesdays with the corresponding ramp flow imputation, meant to predict I-80 traffic state for February 14, 2012[6].

I-80 East Bound

The I-80 East Bound model was built for prediction of traffic state on February 14, 2012. Congestion on a typical work day starts to form right after 2pm. Hence, we picked the time interval from 2 to 4pm for our study. Accidents occurring at this time have a critical impact on the state of traffic. The estimated uncertainty in the capacity of the links was +/- 1% of the calibrated value. Uncertainty in demand was +/- 2% of the average for Tuesdays. The hypothetical accident occurs at 2.40pm near Buchanan off-ramp shown in Figure 13(a). Two out of five lanes are blocked for 15 minutes, until 2.55pm. Four response strategies are considered:

a. Do nothing;
b. Turn on ALINEA ramp metering [7] with queue override queue control at Powell, Ashby, University and Gilman on-ramps – indicated by stars in Figure 13(b);
c. Add Variable Message Sign (VMS) suggesting a detour to the ALINEA ramp metering – Figure 13(c);
d. Use a combination of Variable Speed Limit (VSL) upstream of the congestion area to reduce incoming flow of vehicles and ALINEA ramp metering at the on-ramps mentioned above – Figure 13(d).

Figure 14 shows the best and the worst case bounds for the predicted delay and speed in each of these four cases. Strategy (c) yields the best results in terms of the total delay. This may be deceiving, however; as the vehicles

[6] Currently, Relteq does not have the infrastructure for processing of large volumes of real-time traffic data. Therefore, in this case study we were using already processed PeMS data.

leaving the freeway will have an adverse impact on neighboring arterials. So, case (c) requires further investigation by extending the traffic network to include arterials, which Relteq Harmony potentially allows to do.

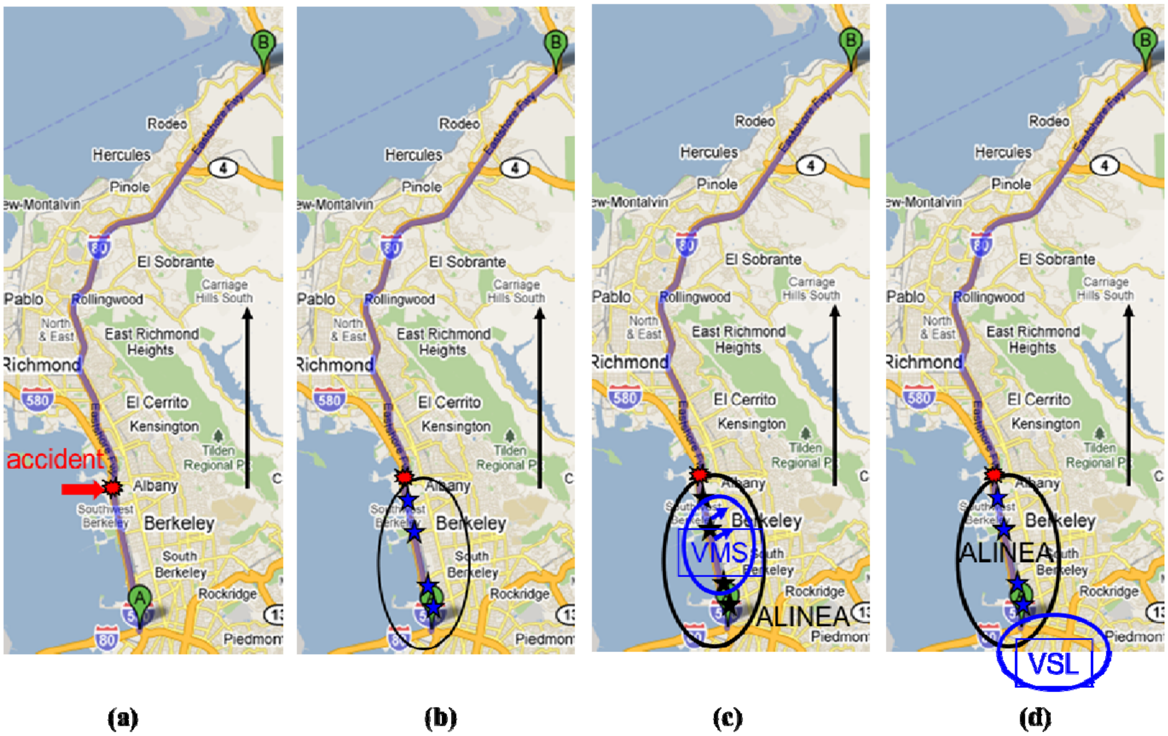

FIGURE 13 I-80 East Bound accident and response strategies: (a) Do nothing; (b) ALINEA ramp metering; (c) ALINEA ramp metering + Variable Message Sign (VMS) with detour suggestion; (d) ALINEA ramp metering with Variable Speed Limit (VSL) strategy upstream.

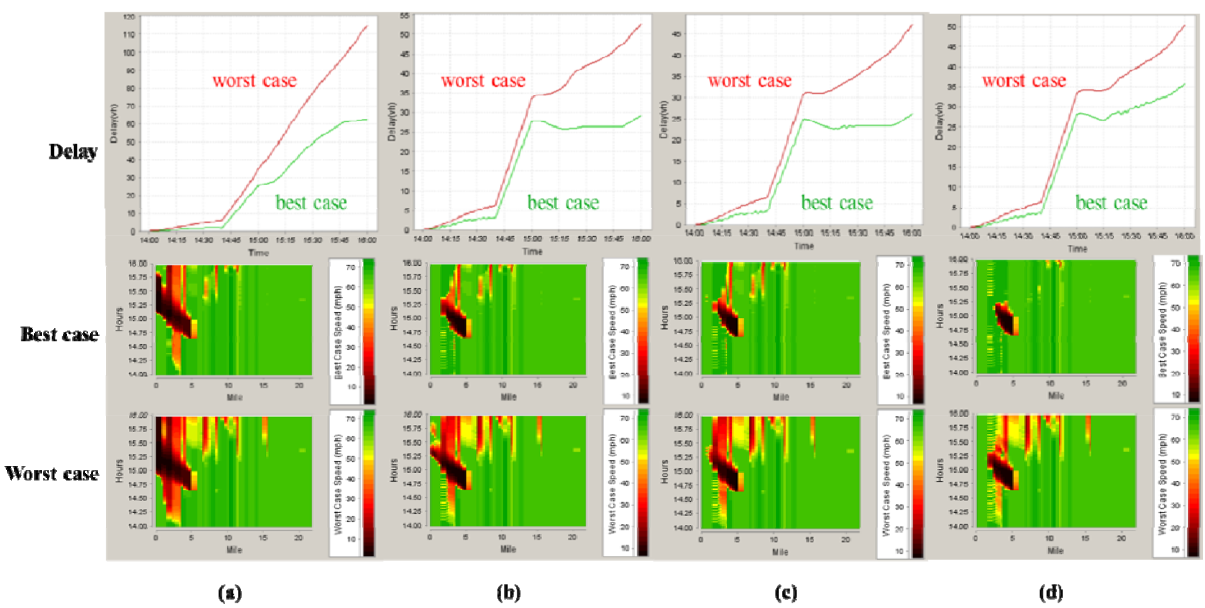

FIGURE 14 I-80 East Bound response strategy evaluation: the best and the worst case delay curves and speed contours.

I-80 West Bound

The I-80 West Bound model was built for prediction of traffic state on February 14, 2012. Congestion on a typical work day starts to form right after 6am. Hence, we picked the time interval from 6 to 8am for our study. Accidents occurring at this time have a critical impact on the state of traffic. The estimated uncertainty in the capacity of the links was +/- 0.8% of the calibrated value. Uncertainty in demand was +/- 2% of the average for Tuesdays. The hypothetical accident occurs at 6.35am right before the merge with I-580 East, shown in Figure 15(a) – according to PeMS [3], this place is an accident hot spot. Two out of five lanes are blocked for 15 minutes, until 6.50am. Five response strategies are considered:

a. Do nothing;
b. Turn on HERO coordinated ramp metering [12] with queue override queue control at John Muir, Appian, Hilltop, San Pablo Dam, Cutting, Potrero, Carlson and Central on-ramps – indicated by stars in Figure 15(b);
c. Turn on ALINEA ramp metering [7] with queue override queue control at the same on-ramps – Figure 15(c);
d. Use a combination of VSL upstream of the congestion area to reduce incoming flow of vehicles and ALINEA ramp metering at the on-ramps mentioned above – Figure 15(d);
e. Use parallel I-580 East freeway to re-route vehicles off of I-80 West through Carlson Boulevard and Central Avenue; after bypassing the accident, vehicles merge back to I-80 West at I-580 E and I-80 W merge point and continue toward Bay Bridge – Figure 15(e).

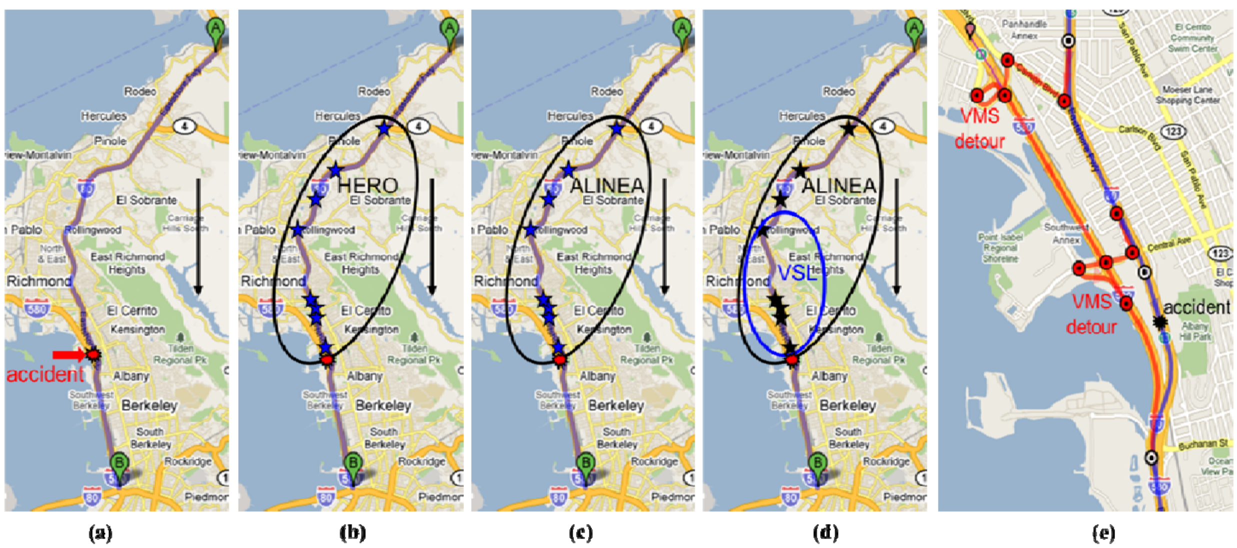

FIGURE 15 I-80 West Bound accident and response strategies: (a) Do nothing; (b) HERO ramp metering; (c) ALINEA ramp metering; (d) ALINEA ramp metering with VSL strategy upstream; (e) Use parallel freeway for detour.

Figure 16 shows the best and the worst case bounds for the predicted delay and speed in each of the first four cases. Strategy (c) – ALINEA ramp metering – yields the best results in terms of the total delay.

The most interesting case, however, is case (e), in which we model the detour using two alternative routes – through Carlson Boulevard and through Central Avenue. At both exits, Carlson and Central, we force 10% of traffic off of I-80 West toward I-580 East. Figure 17 shows the best/worst case prediction for response strategy (e), as well as the total traffic delay for that strategy. It turns out that strategy (e) is the best response for the given accident scenario.

This I-80 West accident scenario and the response strategy (e) provide a good example and use case of the Network Editor, which enables quick modifications of the road network and reassigning of traffic.

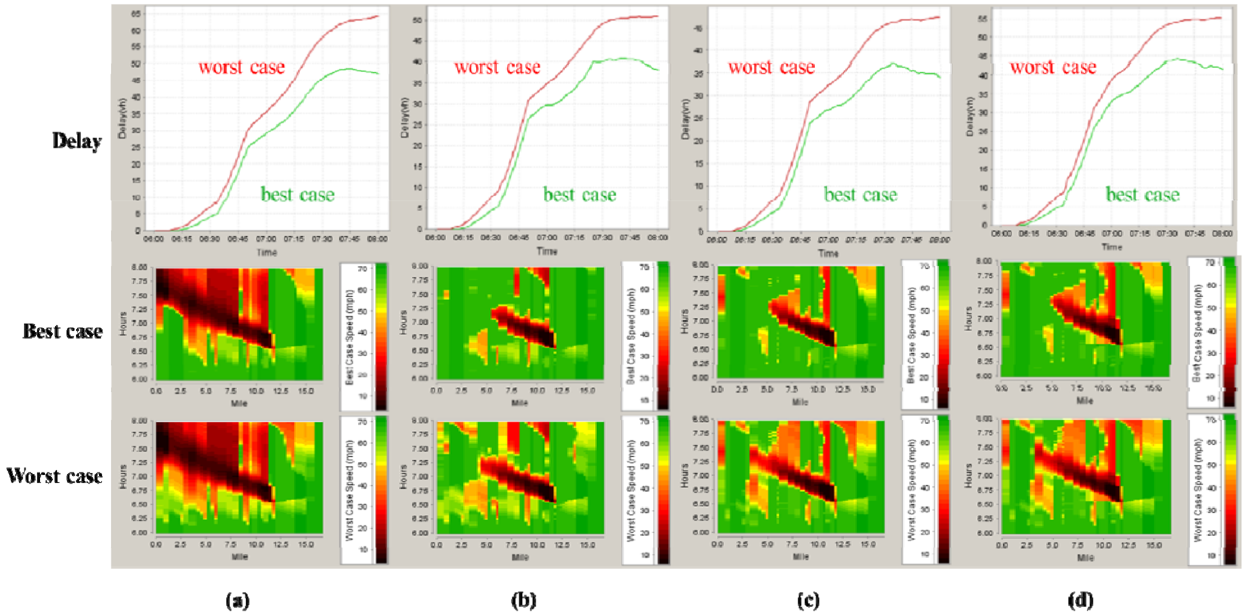

FIGURE 16 I-80 West Bound response strategy evaluation: the best and the worst case delay curves and speed contours.

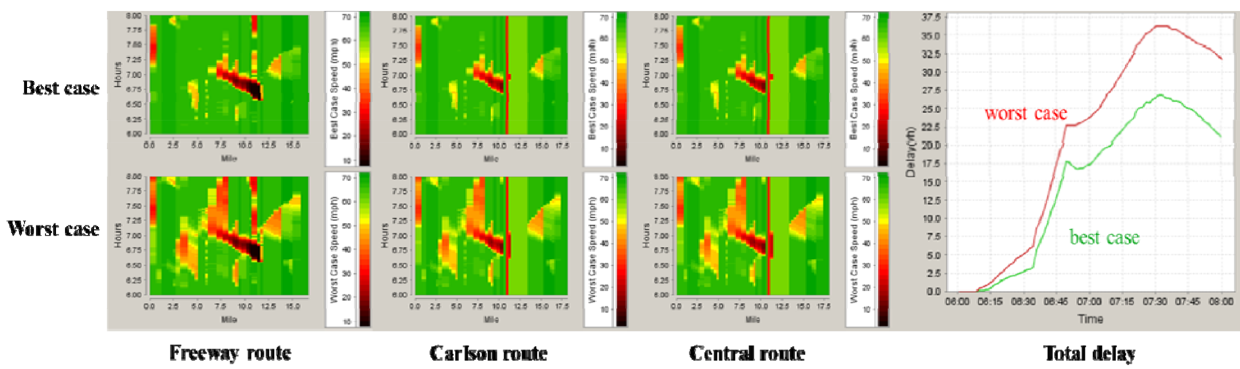

FIGURE 17 Response strategy (e): comparison of alternate routes and total delay bounds.

PLANS FOR IMPLEMENTATION

Currently, Relteq Harmony is at its Alpha phase. The steps toward making it a full scale product include production testing, proper documentation and providing interfaces for the third party Traffic Management Systems, such as Delcan Intelligent NETworks (http://delcantechnologies.com/technologies/intelligent-networks), IRIS (http://en.wikipedia.org/wiki/IRIS_(transportation_software)) developed by Minnesota DOT, and SunGuide (http://www.sunguidesoftware.com).

Being a service, Relteq Harmony is easy to deploy. The deployment in a Transportation Management Center (TMC) can happen in three stages. First stage does not require any interaction between Relteq Harmony and any TMC software: on a separate computer screen a traffic operator may develop scenarios and test response strategies.

Second stage requires real-time data channeled into Relteq Harmony from the Traffic Management System. These data include:

- Traffic measurements from detectors and, if available, probes;
- Data quality assessment;
- Incident reports from Highway Patrol;
- Road work schedules;
- Transit schedules;
- Weather data, which serves as classifier for historical traffic data used in model calibration – sun, fog, rain, snow, ice affect a lot free flow speed and capacity of road links.

In the third stage of deployment Relteq Harmony becomes an integral part of the TMC software setup, when the chosen strategies are automatically propagated to the field controllers through a TMS.

Relteq's market fits into so-called Advanced Traffic Management Systems (ATMS), which broadly encompass traffic detection devices and control systems that regulate signals and digital billboards, as well as software products such as ours. In 2006, Frost and Sullivan analyzed the Western European market for ATMS and found that it amounted to €660 million (about $900 million), providing a lower bound figure for the slightly larger U.S. market [13]. A 2010 report by Global Industry Analysts projected the worldwide market for Intelligent Transportation Systems to reach $18.5 billion by 2015, with ATMS the largest individual segment [14] and the U.S. still representing 40% of the total. Back in the 1990's, the Intelligent Transportation Systems Society of Canada (ITS Canada) estimated that the North American ATMS market represented about 30% of ITS expenditures [15]. Extrapolating that figure forward suggests a $5.5 billion global ATMS market in 2015, whereas the 2010 U.S. domestic market for ITS amounts to $4.8 billion, including $1.5 billion for ATMS products and services – in line with what can be inferred from the Frost and Sullivan study [13].

Further, an IDC study of the Chinese transportation market estimated that software spending amounted to about 7% of total IT expenditures [16]. Because software revenues are comparatively lower in China, we assume the U.S. figure to be closer to 10%. This means that the total market size that Relteq will be competing in is currently $150 million in the U.S. and $350 million worldwide. Infrastructure development in emerging economies, and increased emphasis on system operations and management in mature countries also mean that the segment is bound to experience vigorous growth, creating opportunities for new entrants such as Relteq.

Relteq's initial focus will be on the U.S. domestic market. Our product is applicable to the 50 largest metropolitan areas, and our assumptions regarding demand and pricing would establish potential receipts between $200,000 and $2,000,000 per year and per area, depending on size. In other words, we estimate our total addressable market to represent $25 to $35 million annually in present dollars. International expansion will come under consideration after we have successfully established a commercial track record in the U.S. Current providers of traffic simulation software tend to have a worldwide presence. On the other hand, traffic management software found in operations centers varies across geographies.

While we intend to sell to both transportation agencies and private engineering firms, the market ultimately hinges on government contracts. This creates two specific challenges for Relteq. First, government agencies are naturally conservative. While they rhetorically encourage innovation, their buying behavior can tell otherwise. We feel very confident that our product will solve a clear and present need with few alternatives, which should mitigate the novelty factor. The second challenge is the long sales cycles in government contracting. We reflect this challenge in our financial models by front-loading selling expenses.

CONCLUSIONS

Relteq Systems has developed Relteq Harmony, a decision support system for ATDM. Relteq Harmony aims to help traffic engineers and planners achieve superior operational performance on highways and urban arterials – as measured by traffic flows, absence of delays, lower fuel consumption and accident reduction. Relteq Harmony can operate as a real-time tactical tool, or support strategic decisions such as deploying new traffic systems or fine-tuning existing ones.

The primary engine of Relteq Harmony is its roadway traffic simulator. The simulator is based on flow modeling, meaning that each roadway segment is described by a few state variables, and these variables are updated at each simulation step according to dynamic equations. This approach allows for quick and efficient model-building and simulation runs several orders of magnitude faster than real-time events, making it possible to support traffic control decisions in an operational environment.

A key innovation of Relteq Harmony is its ability to directly assimilate traffic data collected from roadway detectors into simulation models whose parameters are automatically calibrated from this empirical information. Similarly, Relteq Harmony features automated routines to impute missing traffic demand information at the edges of network – a good example is the ability to assign traffic flows to freeway ramps even if they are not instrumented. As a result, Relteq Harmony enables a wide range of applications with minimal effort from end users: a trusted planning tool; a continuous, live model that allows engineers to apply "what-if" scenarios to yesterday's traffic conditions; and a real-time prediction engine that helps operators assess the consequences of actions before decisions are made –a truly robust decision support system.

Relteq Harmony may be instantiated through cloud computing services, enabling multiple, parallel runs to accelerate the delivery of results even further. Engineers can now run dozens of scenarios in batch as opposed to a single "typical day". The web-based delivery method also simplifies setup and collaboration across operations teams or between an agency and its consultants.

Our customer development initiatives to date have highlighted the lack of available tools supporting the operational decision-making in regions that implement ATDM strategies. Historically, ATDM deployments have been limited in both extent and scope, which explains this scarcity. However, the situation is changing rapidly: the performance and affordability of ITS technologies, combined with the impossibility to add lanes in densely populated corridors, have contributed to a flurry of projects such as toll lanes and regionally-integrated corridor management systems. Together, these projects will impact over 700 miles of highways in the U.S. alone over the next three to five years.

TABLE 1 Transportation Agencies' Pain Points and Solution Benefits.

Acknowledged pain points	**Relteq's benefits**
Existing microscopic traffic simulation models are hard to calibrate – in fact they typically do not represent reality.	Flow-based simulation model that is self- calibrating and tractable.
The typical traffic day is hard to define, let alone model. It yields dubious results.	Automated data interfaces and runtime performance allow dozens of scenarios.
In spite of hundreds of millions of dollars spent on transportation management centers across the U.S., operations are still "reactive".	Relteq Harmony is designed to support proactive traffic management planning and operations.
Leading traffic management software products lag far behind the IT curve and offer no real-time decision support mechanisms.	Relteq Harmony uses the latest web technologies to offer a compelling real-time decision toolbox.
Coordinating operations across jurisdictions in large metropolitan areas is a struggle, in part because there is no software application to meet that need.	Software as a Service delivery can readily support multi-agency collaboration.

For the most part, roadway operators use a combination of traffic control software with no built-in intelligence, and traffic simulation software for planning purposes. The vast majority of traffic simulation software is 'microscopic', in that it models the interactions of individual vehicles. The corresponding models are very heavy and their application is thereby limited to a handful of scenarios at best. By contrast, Relteq Harmony uses flow-based simulation in which the roadway network is chopped up into individual segments and described by state variables – which translates into much faster runtime and the very neat ability to self-calibrate from field data. Relteq accelerates runtime even further by operating in the Amazon cloud, which provides the possibility to run multiple software instances in parallel when needed.

Table 1 lists pain points that were explicitly acknowledged by potential customers, as well as the corresponding benefits offered by Relteq Harmony. Moreover, we also collected the following elements of positive feedback during our prospective customer interviews:

- Relteq Harmony is a natural extension of advanced traffic management software;
- Relteq Harmony would work great to evaluate ramp metering and managed lanes strategies;
- Relteq Harmony can be applied to incident as well as disaster management planning;
- The ability to model multiple days will allow analyzing the outcomes of traffic management strategies as distributions rather than single data points;
- Relteq Harmony could effectively support revenue forecasts for toll roads.

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