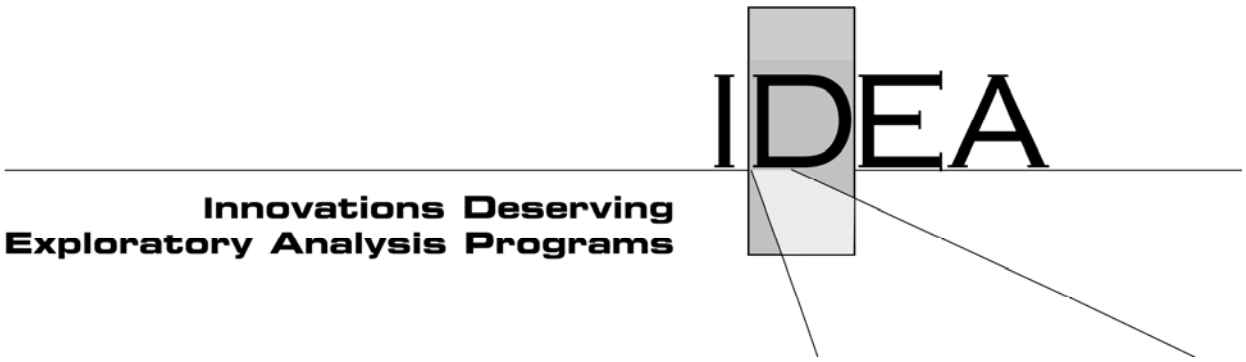

SHRP 2 RELIABILITY IDEA PROGRAM

Forecasting and Delivery of Highway Travel Time Reliability Information

Final Report for
SHRP 2 Reliability IDEA Project L-15A

Prepared by:
Zongwei Tao, Jeffrey Spotts, Bin Lu, Xuesong Zhou and Tao Xing
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Reston, Virgina

November 2012

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

Innovations Deserving Exploratory Analysis (IDEA) Programs Managed by the Transportation Research Board

This IDEA project was funded by the Second Strategic Highway Research Program (SHRP 2).

The TRB currently manages the following four IDEA programs:

- The NCHRP IDEA Program, which focuses on advances in the design, construction, and maintenance of highway systems, is funded by American Association of State Highway and Transportation Officials (AASHTO) as part of the National Cooperative Highway Research Program (NCHRP).
- The Safety IDEA Program currently focuses on innovative approaches for improving railroad safety or performance. The program is currently funded by the Federal Railroad Administration (FRA). The program was previously jointly funded by the Federal Motor Carrier Safety Administration (FMCSA) and the FRA.
- The Transit IDEA Program, which supports development and testing of innovative concepts and methods for advancing transit practice, is funded by the Federal Transit Administration (FTA) as part of the Transit Cooperative Research Program (TCRP).
- SHRP 2 Reliability IDEA Program, which promotes practical innovative ideas for improving travel time reliability, is funded by the Federal Highway Administration (FHWA) as part of the Second Strategic Highway Research Program (SHRP 2).

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Forecasting and Delivery of Highway Travel Time Reliability Information

IDEA Program Final Report

Contract Number: SHRP L-15A

Prepared for the IDEA Program
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IDEA Project L-15A
SHRP2 Program Reliability Focus Area

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- Dr. Bryan J. Katz (Chairman), Senior Transportation Engineer at Science Applications International Corporation (SAIC)
- Mr. Thomas Phillips, Division Administrator, Operations and Security Division, Virginia Department of Transportation (VDOT)
- Mr. Glenn McLaughlin, CHART Deputy Director and 511 Project Manager, Maryland State Highway Administration
- Mr. Louis McDonald, Chief Technology Officer, Virginia Center for Innovative Technology (CIT)
- Mr. Gary Voight, President and CEO, CorasWorks.

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This project was funded and supported by the Reliability IDEA Program of the Transportation Research Board.

myRoadTripAdvisor.com

During this project, a web site http://www.myroadtripadvisor.com was established to demonstrate the feasibility of a number of project concepts and to support the project's field trial. The web site was hosted in a virtual, cloud-based environment. Upon completion of this project, this web site was deactivated.

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1. EXECUTIVE SUMMARY

In September 2010, the TRB's Innovations Deserving Exploratory Analysis (IDEA) program and the Strategic Highway Research Program 2 (SHRP 2) jointly awarded Weris with the SHRP 2 L15(A) project "Provide Origin-to-Destination Travel Time Reliability Information on Google Map". The purpose of this project was to assess the feasibility of an innovative way of delivering personalized travel time reliability information directly to drivers, as stated in the original project proposal:

> *"A web-based application employing predictive algorithms driven by historical and real-time traffic data will provide pre-trip, time-dependent travel time information based on origin, destination, and departure time"*

A period of research and planning established the foundation for the development, demonstration and field trial of the IDEA Product produced by our team, which is a working prototype of a forecasting service that predicts travel time for a given route based on both historical patterns and current conditions, including incidents, weather, and work zones.

Our team's IDEA Product manifested itself as a web site (MyRoadTripAdvisor.com) where visitors could use a planning tool to obtain travel time reliability forecasts for the current date and up to five days into the future. Registered users could save frequent trips by name, and optionally request the service to "push" travel time forecasts to them by email, text message or phone call in advance of their planned departure time, giving them the option to take an alternate route, work at home, etc., should their trip be forecasted to take longer than expected.

Our IDEA Product is unique in that it was designed to give drivers actionable intelligence in the form of travel time reliability predictions, offering them the possibility of avoiding congestion and its inevitable travel delays. While restricted to portions of I-66 in Northern Virginia by the limited scope of this project, the concept is applicable to any congestion-prone corridor. Innovation was demonstrated in this project in the areas of business processes and practices, travel time reliability forecasting methodology, and technology integration.

Demonstrations and a field trial of the service established the technical and business feasibility of our team's concept. This IDEA project created an extensible service framework that can be expanded in follow-on projects to provide metro-wide network coverage, and be integrated into travel information systems operated by state DOTs or commercial enterprises.

2. IDEA PRODUCT

MyRoadTripAdvisor.com is working prototype of a forecasting service that predicts travel time for a given route based on both historical patterns and current conditions; the latter includes any information available to us about incidents (e.g., accidents), weather, and work zones.

The service was accessible to users throughout the project's field trial at http://www.myroadtripadvisor.com. In later sections we describe how the system was hosted in a virtual, cloud-based environment. While shut down as of this writing, the service can quickly be restarted, thus we use present tense to describe our IDEA Product's capabilities throughout this section.

Any visitor to the site can use a "QuickPlanner" function to obtain a forecasted travel time for a trip. Registered users can go a step further and save frequent trips by name, and optionally request the service to "push" these forecasts to them in advance of their planned departure time, giving them the option to take an alternate route, work at home, etc., should their trip be forecasted to take longer than expected.

2.1. Trip Planning

Figure 1 shows what a visitor to the site would see.

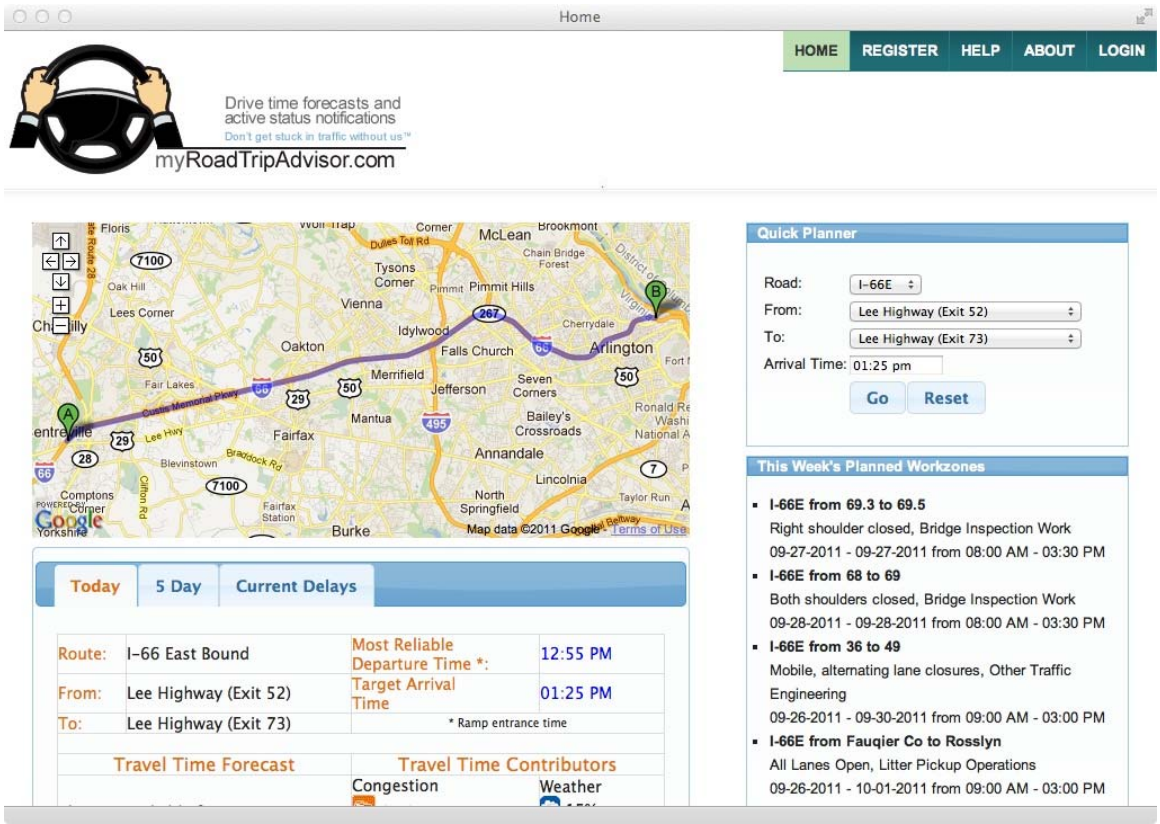


Figure 1: Visitor View of Home Page

The QuickPlanner appears in the top right portion of the page. The beginning and end points for a trip are specified in terms of interstate exit numbers. Because of the limited scope of the project, the service does not account for travel time on surface streets to and from exits.

The map to the left of the QuickPlanner window depicts the current route graphically. This map is generated using the Google Maps API. Beneath the map is found travel time forecast information. Changing any of the values in the QuickPlanner window and hitting the 'Go' button updates the map and forecast.

Three tabs in the area beneath the map present information about the current route and travel time forecast. The first tab is labeled either 'Today' or 'Tomorrow' depending on context. The service determines whether a trip one is planning or viewing can occur today or can only take place in the future, and adjust the tab labels accordingly. For example, if you visit the site at 2:00 pm and plan a trip for a 10:00 am arrival time, that trip can't occur "Today", it can only happen "Tomorrow".

The '5 Day' tab shows the forecasted travel times for the route over an extended timeframe. The Current Delays tab provides information about any current incidents or work zone activity on test corridor.

In addition to providing forecasts in terms of travel and departure times, the service also provides information about the factors that contribute to day-to-day variability. These "Travel Time Contributors" factors consisting of Congestion, Weather, Incidents and Work Zones are expressed as a percentage totaling 100%.

The bottom right portion of the home page also displays a "This Week's Planned Workzones" window. This information is updated weekly based on information published by the agencies that supported this project.

2.2. User Registration

As noted earlier, registered users are provided with additional capabilities. Visitors initiate the registration process by clicking the 'Register' button. After providing contact information, agreeing to terms of service, and submitting the registration form, the user receives an approval email containing a link they must follow to complete the registration process. Once complete, they can login and personalize the service.

2.3. Creating and Saving Trips and Subscribing to Forecast Notifications

Registered users have the ability to create and save frequent trips by name. Figure 2 shows what a logged in user might see. The home page changes slightly, with a My Trips window appearing in the top right column. This window is used add, update and delete frequent trips, and to optionally set up forecast notifications.

A user can add as many trips as they'd like. Only one trip can be designated as the user's Default Trip, meaning that it's the trip whose route and current forecast is displayed when they login.

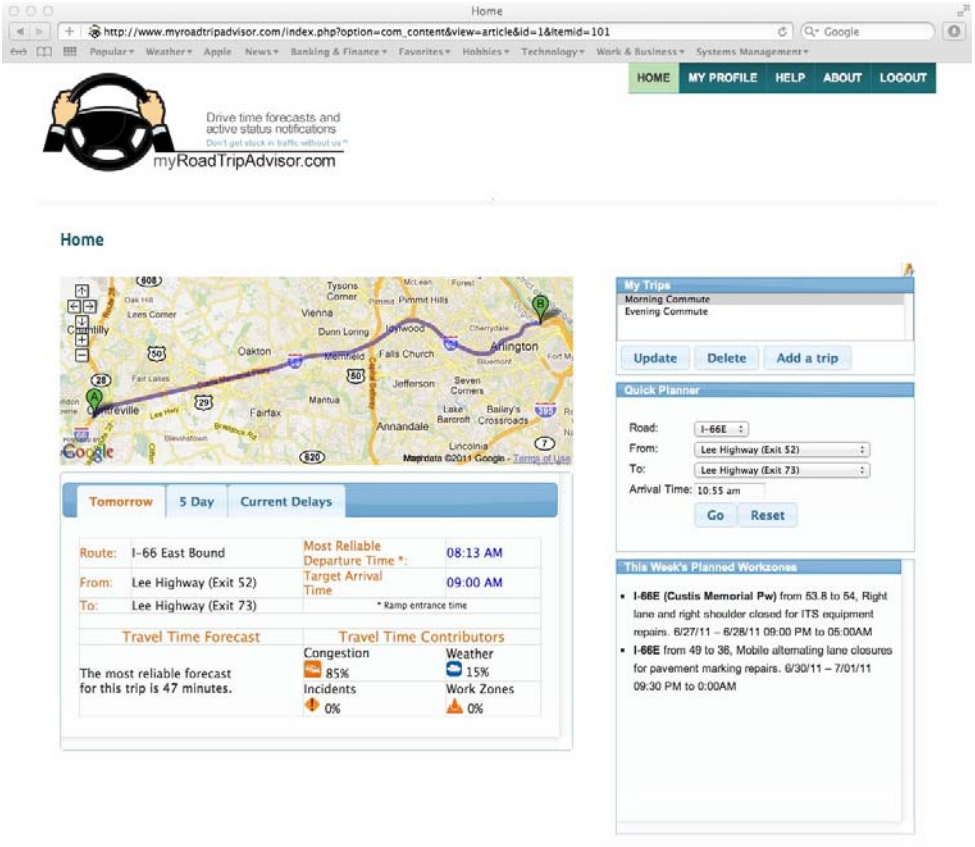


Figure 2: Logged In User View of Home Page

Clicking the 'Add a Trip' button or selecting an existing trip and clicking the 'Update' button pops up a dialog box such as that shown in Figure 3.

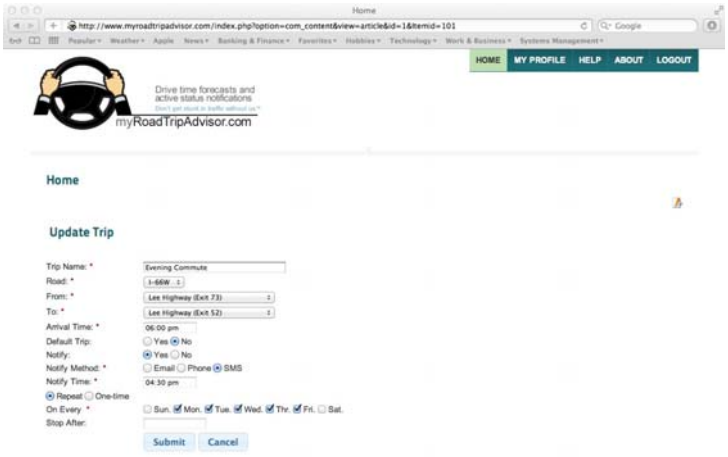


Figure 3: Adding/Updating a Trip

If the user wants the service to send forecast notifications automatically, they select the notification method, time, frequency, and an end date for the subscription, if applicable. They can be notified by email, SMS (text message), or by voice, where the system

initiates an incoming phone call and the forecast information is delivered via synthesized speech. Only one notification mechanism is available per trip, but different mechanisms can be used on different trips.

Actual text (SMS) messages from the service can be seen in Figure 4, which shows the variability of travel time forecasts for a route depending on direction and time of day.

Figure 4: Text Message Forecast Notification Example

Actual email messages from the service can be seen in Figure 5. This example shows how forecasted travel times can vary widely from day to day. Heavy rain was expected in the area on September 8th.

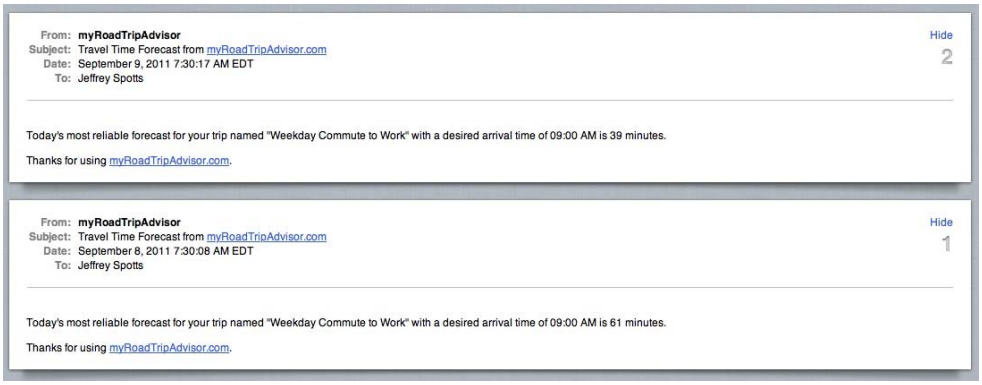


Figure 5: Email Notification

3. CONCEPT AND INNOVATION

Up until now, travel information applications have mostly focused on providing static information, average travel times, and real-time incident duration and severity predictions. One of our team's key concepts was to give drivers actionable intelligence in the form of travel time reliability predictions, so they can avoid congestion in the first place.

Innovations in this project spanned three key areas, as summarized in Table 1.

Business Processes and Practices	
Transform Travel Time Reliability into Actionable Planning Information	Forecasting travel time reliability and enabling it to day-to-day travel planning
Incorporating Recurring and Non-Recurring Factors into Travel Time Forecasts	Accounting for impact of incidents, weather and work zones, in addition to congestion.
Automatic Forecast Notifications	Personalized delivery of actionable travel time forecasts to drivers ahead of departure time.
Travel Time Reliability Forecasting Methodology	
Forecasting Travel Time Reliability	Predicting expected travel time based on historical patterns combined with real-time data.
Forecasting Non-Recurring Events	Forecasting Incident Probability Integrating Weather Forecast Quantifying Delay due to Non-recurring Traffic Conditions
Travel Time Forecasting Updating	Predicting Imminent, Short-term, and Medium-term Travel Time Reliability
Technology Integration	
Cloud Computing-Based Deployment	100% virtual compute, storage and network environment.
Use of Commercial Web Services	Email, SMS and voice forecast notifications delivered using pay-per-transaction services.
Seamless Integration of Multiple Services	Driver-centric GUI and subscription services delivered by consuming, aggregating and analyzing multiple data feeds, and invoking various web services.

Table 1: Summary of Innovations

Another way of looking at this project's innovations is to compare our prototype system to deployed travel time information systems. This is shown in Table 2.

Project		SHRP 2 L15(A)	I-95 Travel Info	PATH2GO (Networked Traveler)	Caltrans District 7
General Information	Coverage	I-66	Entire east coast	Bay Area, CA	District 7, CA
	Planning Mode	Driving	Driving	Driving, Transit	Driving
	Trip Type	Exit-to-exit	City-to-city	Street-to-street	Exit-to-exit
Trip Information	Historical Travel Time	Yes	Yes	Yes	No
	Real Travel Time	Yes	Yes	Only for transit	Yes
	Travel Time Reliability	Yes	No	No	No
	Incident Delay Prediction	Yes	No	No	No
	Weather Delay Prediction	Yes	No	No	No
	Workzone Delay Prediction	Yes	No	No	No
	Emission Information	No	No	Yes	No
	Weekly Prediction	Yes	No	No	No
Information Delivery	Website	Yes	Yes	Yes	Yes
	Email	Yes	No	No	Yes
	SMS	Yes	No	No	Yes
	Voice	Yes	No	No	No
	Mobile App	No	No	Yes	No

Table 2: Comparison of Travel Time Information Systems

This comparison suggests that our prototype is capable of delivering more useful information to travelers than other more mature applications.

4. INVESTIGATION

There were two main stages to the project, each lasting about six months. The first stage mainly involved research and planning; most of the development work and a demonstration, along with a field test of the prototype, occurred during the second stage of the project.

4.1. Stage 1: Requirements, System Design, Data, and Algorithms

The project commenced with a definition of requirements. Following that, our team finalized data access and connection approaches so that our team could proceed to set up a data repository. Statistical analysis was then performed to correlate the historical traffic data with non-recurring event records such as traffic incidents, severe weather conditions and work zone activities.

The major tasks completed during Stage 1 of the project are described below.

4.1.1. Set Project Vision and Strategy

When formulating the original proposal for this research, our team's goal was to create an application that made travel time reliability information accessible to the public in a very meaningful way. To-date, travel information applications have been focused on providing static information, average travel times, and real-time incident duration/severity predictions.

Our application vision remained focused on reliability; that is, predicting travel time and its reliability and thus helping travelers avoid congestion in the first place. We envisioned the application providing travelers with a fundamentally different way of planning their daily commutes and one-time trips. Giving the traveler an expected delay prediction based on a probabilistic incident occurring rate can allow them to change routes or departure times before they are stuck in traffic.

4.1.2. Define Requirements

While our team's aspiration was to create an application with long-term commercial potential, we recognized that the point of a Type 1 IDEA project is to explore an unproven concept to demonstrate its validity. Thus, we decided to restrict the scope of the prototype to a narrowly focused but high impact set of functionality:

- Coverage was restricted to commute-intensive, congestion-prone corridors. (We see this specialization applying long-term, too. We envision the application covering major urban centers only.)
- Travel time reliability was predicted ramp-to-ramp for the interstate portion of the trip only. Arterial street travel was excluded. The user interface for trip planning was simplified accordingly. Route information is entered in exit-to-exit terms, not origin to destination street addresses.
- The prototype focused on pre-trip planning under two scenarios:
    1. "Day Before" planning. Predicting travel time reliability up to one week in advance of departure.

2. “Imminent” planning. Predicting travel time reliability one hour or less before departure.

- Traveler updates via a “push” notification such as SMS or email were restricted to imminent departure time windows. For the prototype, we decided not to develop a mobile application that provides en-route updates to drivers while in the middle of their trip.

We concluded that this focused implementation would provide sufficient proof of the validity of the concept as well as furnish a basis for determining whether or not the more complete application vision had commercial potential.

4.1.3. Define Major Components and Functions

This task involved sketching out the major components of the system to create a conceptual framework for subsequent detailed design and implementation decisions. The major components of the prototype system our team settled upon are shown in Figure 6.

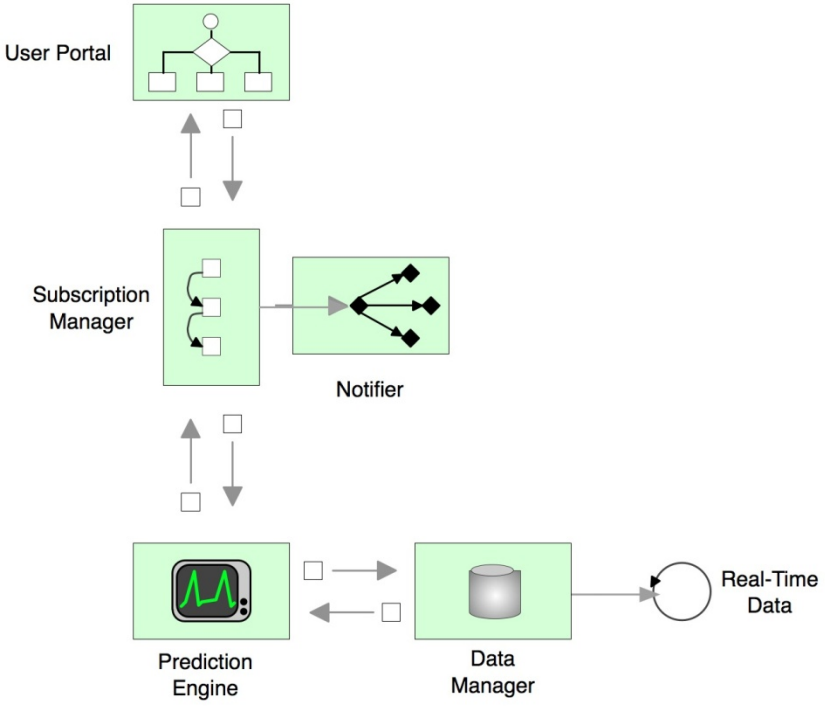


Figure 6: Architecture of the Prototype System

4.1.3.1. User Portal

A user portal was needed to provide a web-based interface to end users of the prototype system. Figure 7 shows the initial mockup of the top-level user interface we created when envisioning the system.

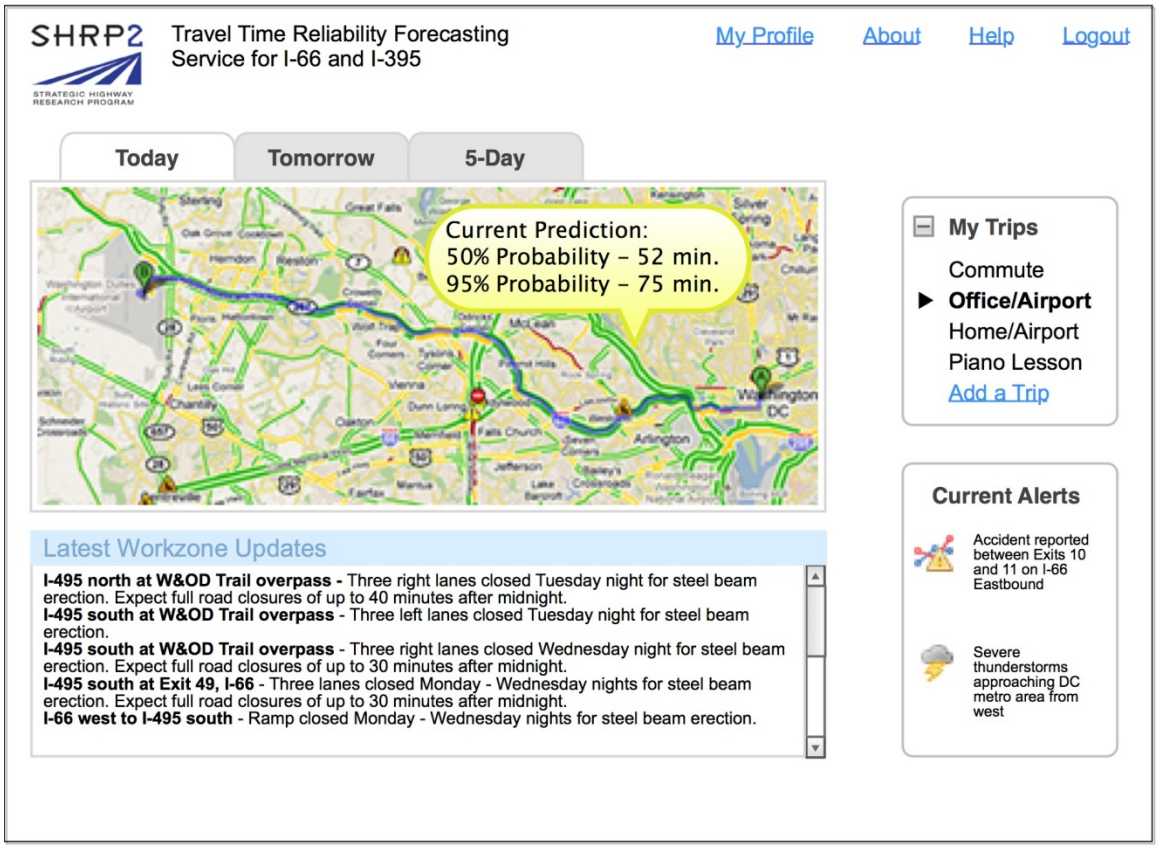


Figure 7: User Interface Mockup
(Map Data ©2012 Google)

The User Portal was conceived to provide the following functions:

- User Management – New users will be able to self-register, and registered users will be able to login to see a personalized view of current and future travel time reliability predictions for named trips (see below) that they have created. Registered users will also be able to edit their user profile, which includes information such as email address and mobile phone number.
- Trip Management – Users will be able to create and save an arbitrary number of named trips, e.g., Commute to Work, Commute Home, etc. Each trip will have a required set of attributes such as origin, destination, and desired arrival time. A *Notification* is an optional set of attributes related to a trip, including notification mode, day(s) of the week to be notified, and desired notification time.
- Forecast Display – Similar to the way that weather forecast information is often presented, a logged in user will be able to look at the TTR (travel time reliability)

forecast for the currently active trip, with Today, Tomorrow and 5-Day forecasts available on separate tabs.

- Publishing – Various traffic information for the system's service region will be published in the User Portal. This information could include planned work zones, or alerts related to weather, incidents or other non-recurring events or conditions.

We also decided that the User Portal would allow a visitor (i.e., a user without login credentials) to get a one-off prediction for a trip, but would not be able to save trips and receive notifications.

User Interaction Model

Figure 8 shows the various interaction paths we envisioned users would take through the user portal. This was useful for guiding subsequent, detailed design and implementation decisions.

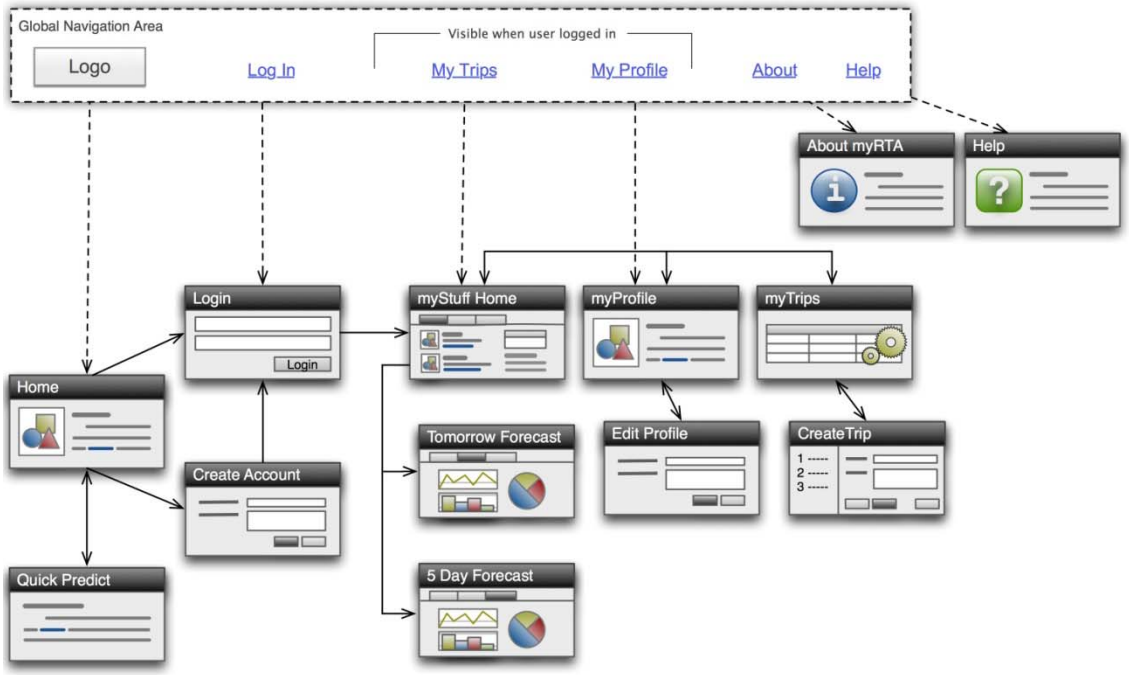


Figure 8: User Interaction Model

4.1.3.2. Subscription Manager

The Subscription Manager component was conceived to maintain an active list of TTR forecast subscriptions for:

1. Users logged into the system whose forecast displays are updated periodically as new TTR forecasts become available, and
2. Users who have set up notifications for a trip.

The Subscription Manager requests the latest forecast from Prediction Engine. This occurs on a polling basis at five-minute intervals based on the level of granularity at which new data becomes available to the Prediction Engine from our data sources.

Forecast results obtained from the Prediction Engine are the predicted travel times for each link of the highway system. The Subscription Manager component also maintains a link-to-trip mapping table that allows the system to quickly generate trip travel time for any highway exit pairs.

4.1.3.3. Notifier

The Notifier component was conceived to send a notification message to a user at the desired time via the specified delivery mechanism. Recognizing that we ultimately could not control user behavior, we decided that the best we could do is to emphasize that notification times should be prior to the traveler's usual departure time, and not while en route. Regardless of delivery mechanism, we decided to keep messages brief in order to minimize driver distraction in the event a message was delivered to them on a mobile device while they were en route.

Notification Mechanisms

We decided upon the following message delivery mechanisms:

- Email – an email message advising the user of the TTR forecast for their imminent departure sent to the email address contained in their user profile.
- Text – an SMS message sent to the mobile number contained in their user profile.
- Voice – a voice call placed to the mobile number contained in the user profile, with the TTR forecast spoken to the user using text-to-speech (TTS) technology.

4.1.3.4. Prediction Engine

The Prediction Engine was conceived to provide up-to-date TTR forecasts for the entire service area, in response to requests from the Subscription Manager. It needed to be capable of supplying near-term as well as mid-term forecasts.

4.1.3.5. Data Manager

The Data Manager component of the prototype system was conceived to provide data management functions to:

- Service requests for data from the Prediction Engine.
- Provide an Add/Change/Delete capability for the maintenance of static data sets.
- Support the bulk download and updating of historical data.
- Provide necessary data transformation services, e.g., lat/long to network link conversion.
- Continuously poll for and download the latest real-time data.
- Append the latest real-time data to historical data.
- Periodically purge historical data older than is useful for making predictions.

4.1.4. Define Major Data Sets

We recognized that the system was dependant upon a range of data in order to produce reliable TTR forecasts. This data fell into two general categories:

1. Static Data – Data sets that are relatively fixed and change very infrequently. We assumed them to be static for the duration of this project. Such data sets are:
    - Network
    - Sensor Locations
2. Historical Data with Real-Time Updates – These data sets contain up to 18 months of historical data that must be updated on regular intervals as real-time (or near real-time) updates become available. These are:
    - Sensor Data
    - Incident Data
    - Weather Data
    - Work Zone Data (expected to be updated on a daily to weekly basis)

4.1.5. Establish Key Design Principles

Even though the prototype system's intended use was limited to establishing the technical and business feasibility of a traveler-focused service, we decided to follow best practices in its design wherever practical. These practices include:

- Distributed Architecture – The system design was based on the functional separation of major components. Benefits of such an approach include modular development and testing, flexibility, extensibility, scalability and reliability.
- Platform Independence – Minimizing dependency on proprietary technology to insure portability and cost effectiveness.

4.1.6. Review Analytical Framework and Algorithm

The provision of pre-trip and real-time origin-to-destination travel time reliability information to be applied in our application relies on the travel time prediction under variant current and future stochastic non-recurring traffic conditions. Specifically, two underlying tasks are required:

1. Statistical prediction of non-recurring conditions (e.g. severe weather and probability of having incidents), which can be produced based on live data feeds and historical databases;
2. Travel time prediction under non-recurring traffic conditions, which is the core of the travel time reliability information provision.

While developing a new statistical algorithm was outside the scope of our project, we needed to select a credible model that addresses the above theoretically challenging questions.

At the beginning of the project, we reviewed both commercial and academic practices for travel time prediction, with a special focus on traffic forecasting methods under non-recurring conditions, which is fundamental to the ultimate success of this project. The

Appendix at the end of this report summarizes our review of current travel time prediction practice.

Table 3 shows a comprehensive comparison of several traffic prediction systems in current practice. From the implementation perspective, the IBM model is easy to apply but not sensitive to the non-recurring traffic condition. On the other hand, the Inrix model and the Dynamic Traffic Assignment (DTA) model require a larger number of network-wide parameters and calibrations, leading to longer development cycles. Additionally, for traffic flow model-based models, Newell's model has fewer parameters and better computational efficiency compared to the cell transmission model.

	Statistical Models		**Traffic Flow Models**		**Dynamic Traffic Assignment Model**
	IBM Model	**Inrix Model**	**Cell Transmission Model**	**Newell's Model (Cumulative flow count-based)**	
Study Area	Network-wide	Network-wide	Corridor-level	Corridor-level	Network-wide
Input Data	Speed or volume	Speed, flow and non-recurring condition	Incoming and outgoing flow, link capacity	Incoming and outgoing flow, link capacity	Dynamic OD demand and capacity change
Algorithm	Pattern recognition	Bayesian algorithm	Cell-based traffic flow model	Newell's model, use cumulative count curves	Simulation-based DTA model
Parameters	Historical profile, spatial-temporal correlation	Causal relationships between non-recurring events and traffic states	Density, flow of each cell and boundary conditions	Arrival and departure curve, capacity, delay and queue length	Real-time OD demand, DTA simulator
Implementation difficulty	Easy implement	Large causal matrix, complex	Lager number of cells, complex	Easy implement	Large number of network parameters, complex
Sensitive to Non-recurring Condition	No	Yes	Yes	Yes	Yes

Table 3: Model Comparison for Travel Time Prediction

Currently, commercial traffic information service providers typically process reports from regional traffic management centers (TMC) or other traffic management and planning agencies to generate incident, road construction, and road closure reports. The traffic data contents distributed from traffic information providers, such as NAVTEQ Traffic and Inrix, typically include two types of information:

1. Speed and flow measurements from a sensor network.
2. Textual data on traffic incidents (e.g., 1 or 2 lanes are closed for X minutes) and special events. Typically, traffic incident data could cover planned events such as road construction and closures and unplanned events such as traffic accidents and stalled vehicles.

This supplementary textual information on traffic incidents is especially useful for generating traffic variability/reliability-oriented information on arterial streets and rural

areas that lack both a detection infrastructure and enough vehicle-based probes to directly measure traffic states and travel time reliability.

Based on our review of current practice, for this project we chose to use a hybrid traffic prediction model for congestion-prone corridors. As shown in Figure 9, the this hybrid model consists of two major prediction components:

- Historical pattern recognition model for predicting recurring congestion
- Newell's traffic flow model for predicting non-recurring congestion

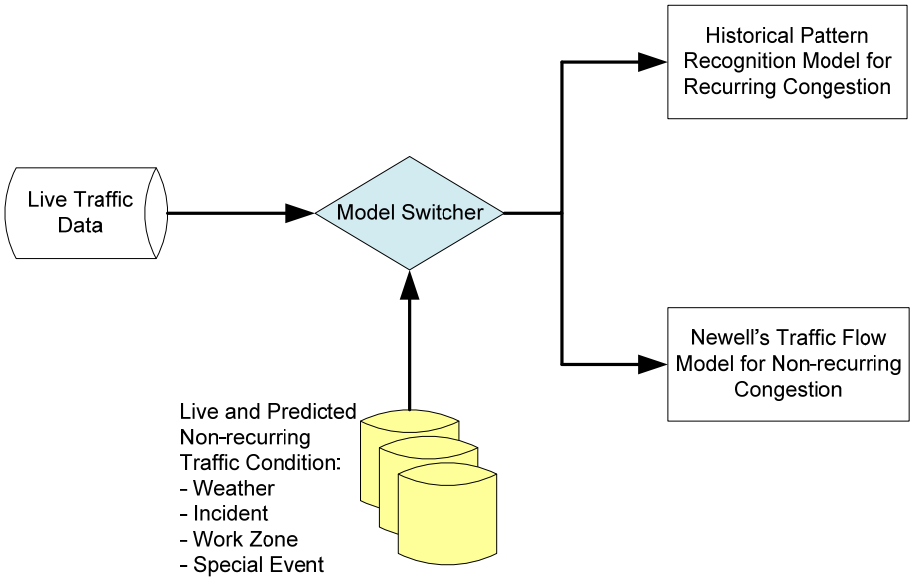


Figure 9: Structure of Travel Time Prediction Engine

For a congestion-prone corridor, when real-time traffic data are available, a model switcher is first used to decide which prediction module (as discussed below) should be applied, based on current and predicted non-recurring traffic condition data.

Historical Pattern Recognition Model

This model takes real-time travel time measurements as input. As recurring congestion occurs periodically, by comparing the current traffic pattern with historical average traffic profiles, this model outputs a near-term travel time prediction under recurring traffic condition.

Newell's Traffic Flow Model (Cumulative Flow Count-based Model)

For non-recurring traffic condition, a cumulative flow-count model will take multiple traffic measurements as inputs, including flow, density and temporal-averaged travel time. As shown in Figure 10, the arrival curve and departure curve in the cumulative flow count diagram (N-curve) link flow, travel time and queue length together. With such a simplified queuing model, additional delay caused by non-recurring traffic conditions can be captured and predicted. Consequentially, the output of the proposed model will be the predicted travel time for the targeted highway corridor. For simplification purposes, this problem is considered without user rerouting behaviors.

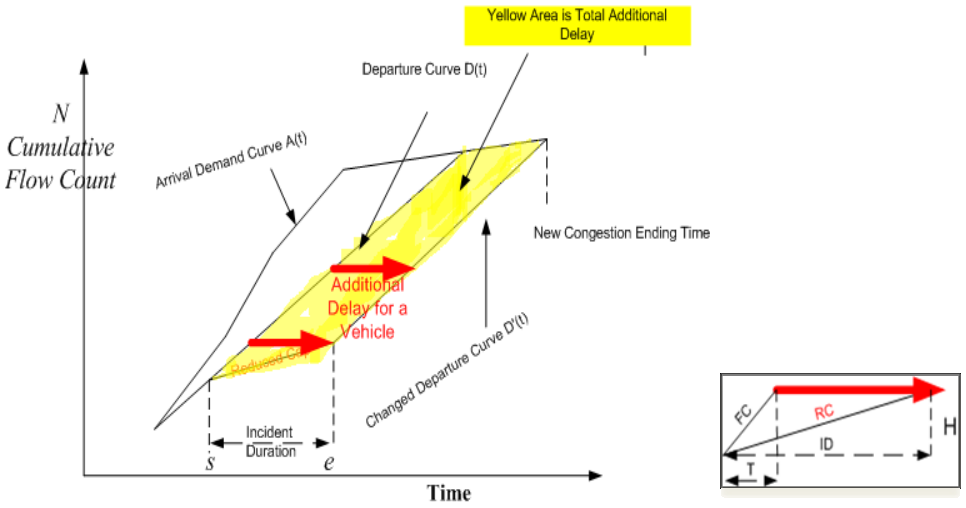


Figure 10: Cumulative Flow Count Diagram (N-curve)

As an example, Figure 10 shows the additional travel time delay caused by an incident. In the N-curve diagram, the slope of departure curve represents the discharge rate of the targeted corridor. As the incident happens, the capacity of the corridor is first reduced, accordingly imposing additional delays for each vehicle in the queue. Essentially, as the relative capacity reduction ration can be estimated from incident textual reports, and a prediction of the incident duration is quickly available for a real-time on-line traffic prediction application, we will be able to calculate the additional delay geometrically, thereby predicting the travel time under such non-recurring traffic condition.

4.1.7. Set Implementation Approach

This task involved making final decisions about how the various system components would be implemented and how they would interoperate.

We decided to develop the User Portal, Subscription Manager and Notifier components for deployment on a so-called LAMP (Linux, Apache, MySQL and PHP) platform. This software "stack" is widely used for web-facing applications. This allowed us to leverage low- or no-cost open source packages. It also offered a range of cost-effective deployment options.

4.1.7.1. User Portal

We decided to use the popular, open source Joomla content management system (CMS) as the basis for the User Portal. This gave us built-in user management and content publishing functionality that could be extended and customized for our application. We chose PHP as the primary development language, along with client-side JavaScript. AJAX methods (asynchronous JavaScript and XML) were chosen to dynamically update changing information on the main portal page (e.g., updated forecast and condition information) without interfering with the rest of the display.

Joomla also provided an easily extensible "User Profiles" mechanism that we used to manage user-related attributes necessary for personalization and notification.

4.1.7.2. Subscription Manager

This component starts up at system initialization and functions as a background service (daemon). It accesses the Joomla Users, User Profiles and User Trips tables to build and maintain a list of active TTR forecast subscriptions.

We chose to have the Subscription Manager obtain TTR forecast information from the Prediction Engine through a REST API, an easy-to-implement and test web service based on an HTTP GET operation to a fixed URL.

We decided to have TTR data returned to the Subscription Manager (the client) from the Prediction Engine (server) using a lightweight data-interchange format known as JSON (JavaScript Object Notation).

4.1.7.3. Notifier

This component was designed to handle the mechanics of sending email, text or voice messages to users. Like the Subscription Manager, it is a daemon that initializes at system startup and services notification requests. Sending emails programmatically is very straightforward and will not be discussed here. Sending text messages and making voice calls involve other considerations.

Text messaging and voice calling require that the prototype system have some kind of connection to the public switched telephone network (PSTN). Text messaging in particular requires the use of an SMS Gateway service to provide an access point to major mobile networks. While it's technically feasible to integrate a collection of open source software and use VOIP service providers for the needed connectivity, that approach involves considerable complexity and risk.

We identified an attractive alternative for text messaging and voice calling in the form of pay-as-you-go hosted services that are invoked using standard SOAP Web Service mechanisms. These services are designed for high-volume, commercial applications and thus are well suited for use in the prototype system and even an eventual production incarnation.

4.1.7.4. Prediction Engine

The Prediction Engine leveraged previous research done by our project team members at the University of Utah. This component was designed to generate new TTR forecasts on a continuous basis for the entire highway network covered by the system, as new real-time data became available.

The Prediction Engine implemented the prediction algorithms described previously. Since this repurposes C# code from earlier work, it is implicitly tied to Microsoft development tools and operating systems. This code was extended to implement the server side of the REST-based web service described in the Subscription Manager discussion.

4.1.7.5. Data Manager

The Data Manager stores and preprocesses both historical and real-time data for the entire system. We chose to use SQL Server as the main database, with C# code to process

the historical data and get real-time updates every five minutes from various data sources and store them in the database.

4.1.8. Select Deployment Platforms

The design principles described earlier gave us flexibility in terms of how the components are deployed. We decided to deploy the system in a virtual run-time environment using commercial cloud computing services. The User Portal, Subscription Manager and Notifier components utilize the following Amazon Web Services offerings (more info at aws.amazon.com):

- Elastic Compute Cloud (EC2) for a Linux virtual machine instance on which the components will run.
- Elastic Block Storage (EBS) for persistent data.
- Simple Email Service (SES) for sending email notifications.
- "Route 53" Domain Name System (DNS) service for routing end users from the published URL for the service to the numeric IP address at which it actually is available.

As described previously, the Notifier sends text and voice messages using commercial, cloud-based services specifically designed to provide these functions:

- CDYNE SMS Notify! API to send SMS messages (more info at www.cydne.com)
- CDYNE Phone Notify! API to send voice calls

The Prediction Engine and Data Manager components are closely associated, and, as described earlier, leveraged code that is tied to Microsoft runtime environments. Since the only connection required is an accessible URL over which the Subscription Manager and Prediction Engine can communicate via HTTP, we had flexibility on where the Prediction Engine and Data Manager could be deployed. In the end we chose to deploy these components on Windows Azure, which is Microsoft's cloud computing service. The Utah team has experience with this environment.

4.1.9. Select Field Test Corridors

As discussed earlier, we decided to restrict the application to commute-intensive, congestion-prone corridors. Based on this consideration, we selected I-66 and I-495 in Northern Virginia for the prototype. The rationale for this choice was straightforward. These routes fit the definition of commute-intensive, congestion-prone corridors to a tee:

- I-66 and I-495 are the two busiest commute corridors in the region, connecting downtown Washington DC and surrounding residential areas in Northern Virginia.
- There are major ongoing construction projects on or along those corridors. Lane closures and work zones occur frequently.

Figure 11 shows the metro region with the planned test corridors highlighted in red.

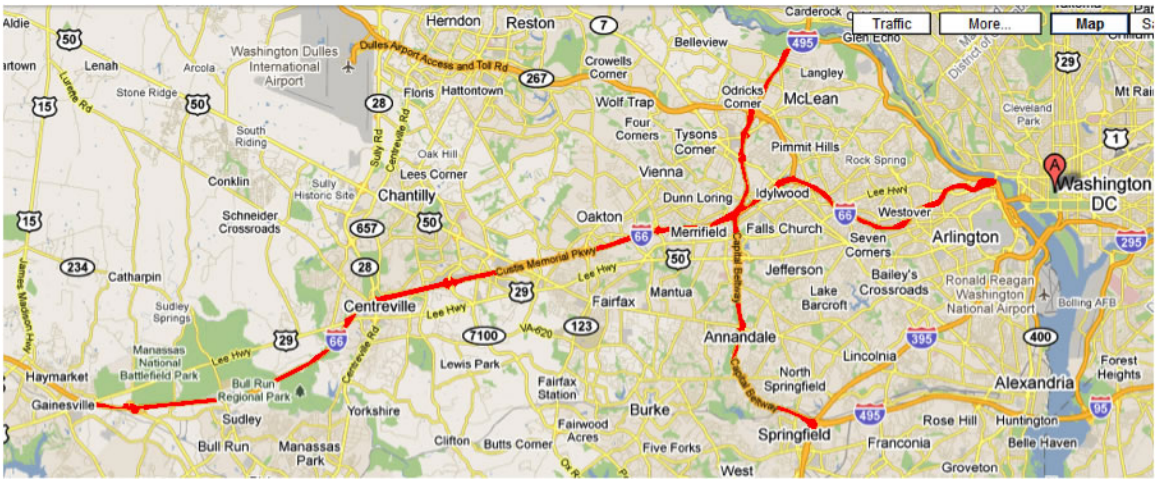


Figure 11: Planned Field Test Corridor (I-66 and I-495)
(Map Data ©2012 Google)

4.1.10. Finalize Prediction Engine/Data Manager Design

A large part of our work early in the project focused on reviewing current practices in TTR forecasting and deciding upon an approach that was most appropriate for the problem set we faced.

These decisions then drove the detailed design of the Prediction Engine and Data Manager components introduced earlier.

4.1.10.1. Guiding Principles and Analytical Models

This project aimed to provide pre-trip and possibly real-time end-to-end travel time reliability information based on the up-to-date travel time prediction results under a wide range of observed and forecasted traffic-impacting factors such as incidents, weather conditions and work zones. We first list several key guiding principles for our travel time reliability Prediction Engine before detailing the underlying data structures and processing flow.

4.1.10.2. Prediction Data Input: Flow and Speed

In practice, many traffic forecasting applications only use travel time or speed as the single variable in a prediction function mainly relies on univariate statistical relations such as moving average or auto regression. To fully utilize all available traffic information sources, we utilize both traffic flow and speed measurements from road sensors, as well as event-related information, for capturing the non-recurring traffic congestion sources, such as incidents, severe weather, and work zones.

4.1.10.3. Historical Database Generation: Recurring vs. Non-Recurring

To better identify travel time reliability patterns, separate historical databases are constructed for recurring and non-recurring traffic conditions: (1) baseline recurring historical traffic patterns without impacts of incidents, weather conditions and special

events; (2) non-recurring traffic historical database that records the impact of various factors on day-to-day travel time reliability.

4.1.10.4. Methodology for Measuring Travel Time Variability

Based on a simplified queuing framework, we model travel time variability as a function of three parameters: capacity reduction ratio (α), event duration (β), and probability of event (γ). Specifically, the additional travel time caused by non-recurring traffic events is calculated through analytical equations as $f(\alpha, \beta, \gamma)$, while all three parameters have been calibrated using log-normal distributions. Thus, we compute travel time variability using the following formula.

$$\text{Delay variability of certain event} = \alpha \times \beta \times \gamma$$

$$= \left(1 - \frac{\text{Reduced capacity}}{\text{Full capacity}}\right) \times \text{Event duration} \times \text{Probability of event}$$

Equation 1: Travel Time Variability Computation

This formula can be derived from several deterministic queuing analysis equations based on Dr. Adolf May's *Traffic Flow Fundamentals* (Prentice Hall, 1990). Figure 12 demonstrates the derivation of this equation during an incident.

To calibrate three parameters, capacity reduction ratio (α) can be determined from the reduced capacity and the full capacity of a link from both historical recurring and non-recurring flow data. Additionally, the event duration and probability of events can be estimated from both incident/weather/work zone reports and the non-recurring historical traffic database.

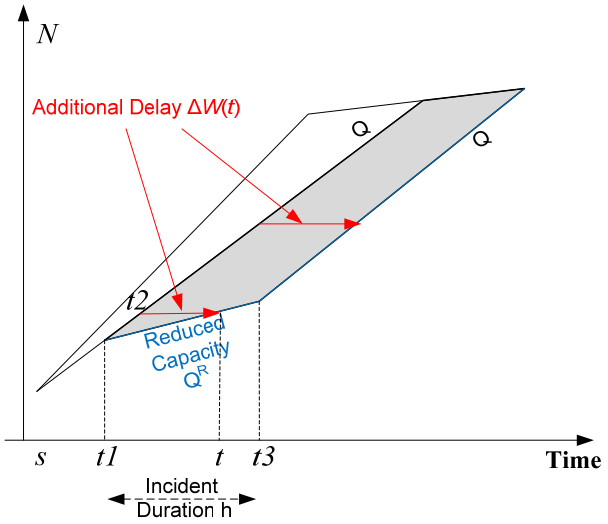


Figure 12: Deterministic Queuing for Travel Time Delay Caused by a Capacity Reduction Event

4.1.10.5. Prediction Engine Internal Structure

The Prediction Engine module provides link-based travel time forecasting according to the processed historical data and real-time traffic observations. Figure 13 shows the

system structure of the prediction module. Based on current and predicted traffic event information, recurring or non-recurring traffic conditions are first determined. Under recurring traffic conditions, historical patterns are used to predict link travel time. Under non-recurring conditions, analytical equation (1) is applied to predict travel time delay.

The overall structure of the Prediction Engine is described as follows:

- **Input**: Real-time data of traffic measurements and traffic-related events (weather/incident/work zone).
- **Processing**: Historical regular pattern matching for recurring traffic congestion and analytical approach for non-recurring congestions.
- **Output**: Link-based travel time prediction results.

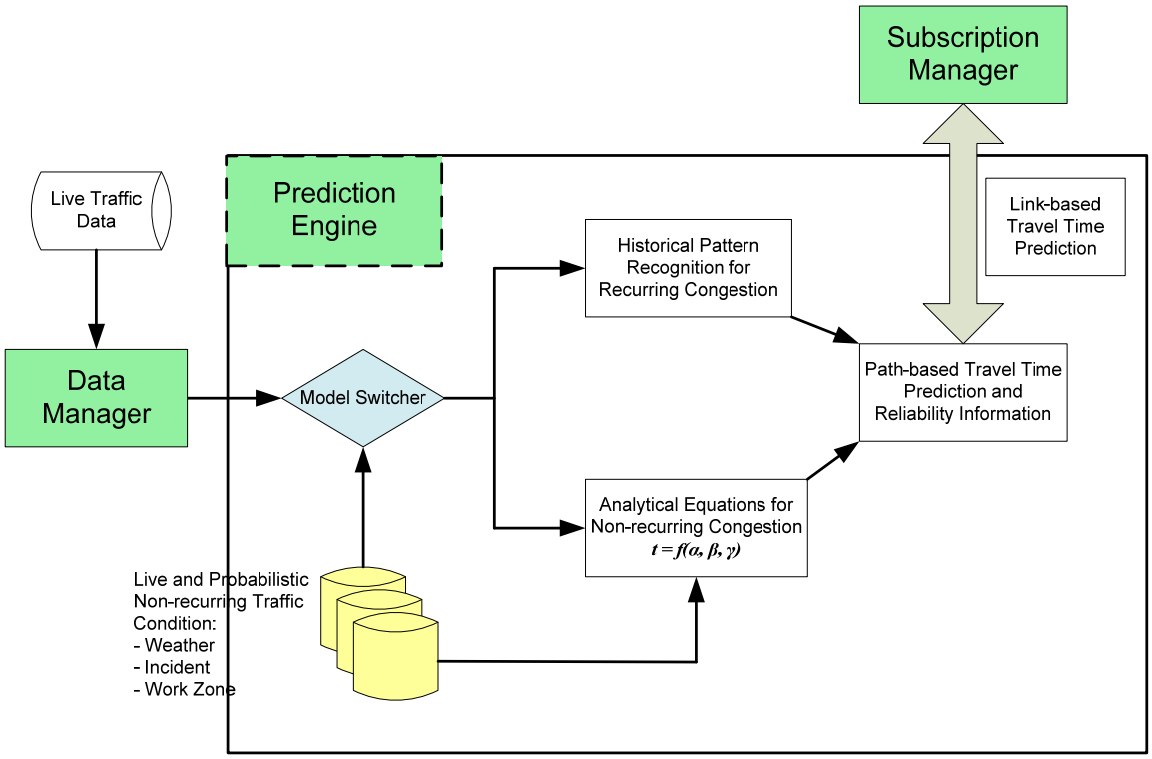


Figure 13: Online Traffic Prediction Flow

For different user requests, traffic forecasts are conducted for near-term (next half hour), mid-term (next day) and long-term (next 5 days). Table 4 shows the data requirement for each type of prediction.

Data and Information to Be Used in Prediction	**"Imminent" Predication**	**"Tomorrow" Prediction**	**"5-Day" Prediction**
Historical Recurring Congestion Pattern	X	X	X
Historical Non-recurring Traffic Impacts	X	X	X

Probability of Incident Occurrence		X	X
Planned Work Zone Data	X	X	X
Weather Forecast	X	X	X
Real-Time Traffic Data (VOS)	X		
Real-Time Incident Data	X		

Table 4: Data Needed for Different Prediction Periods

4.1.11. Acquire and Prepare Data

In this project, a variety of data is required for both historical traffic analysis and real-time traffic prediction, including network data, sensor information and readings, and traffic events from both historical and real-time sources.

4.1.11.1. Revise Test Corridor Plan

Our team's initial plan was to use I-66 and I-495 in Northern Virginia for the prototype since they are quintessential commute-intensive, congestion-prone corridors. Data availability issues related to I-495 compelled us to narrow our focus to I-66. (Due to extensive construction, sensors could be inoperable for indeterminate periods, and data might be available only intermittently.) In our judgment, narrowing the scope to I-66 did not in any way compromise the primary goal of this project, which is to establish the technical and business feasibility of using our novel method of TTR forecasting to deliver a new, end-user oriented travel information service. We have designed a fair amount of functionality into the prototype and the implementation approach is easily extensible to a larger network.

4.1.11.2. Data Preparation

Network Data

We created a traffic network with a node-link structure for the I-66 study area in Northern Virginia. Figure 14 shows the data model for this network.

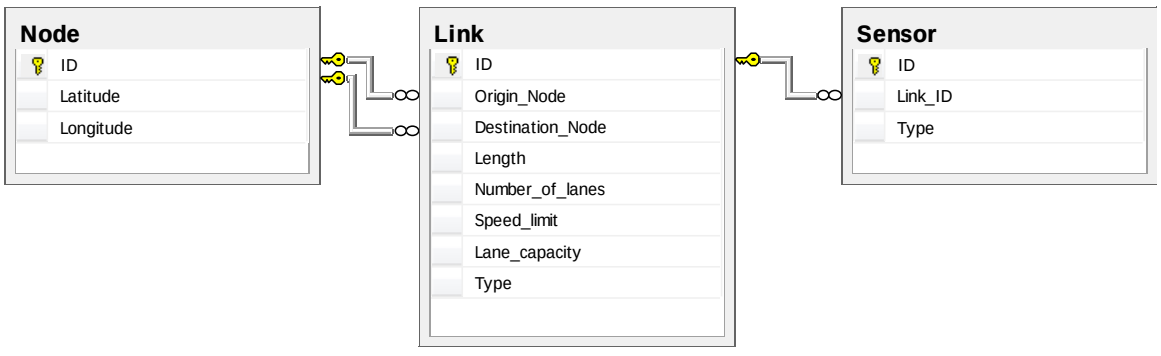


Figure 14: Network Data Model

The entities and attributes in this model are:

- **Node** – An X/Y coordinate expressed in Latitude/Longitude.
- **Link** – A highway segment and its characteristics, including origin, destination, length, lanes, speed limit, lane capacity and type.
- **Sensor** – Information about sensors on each link. (To be collected: Sensor location information for HOV lanes.)

Sensor Locations

The latitude/longitude of sensors are converted into link-based locations in order to calculate end-to-end travel time for a path along multiple links (Figure 15). Data includes Original Sensor/Station ID, Link ID, and Sensor Type.

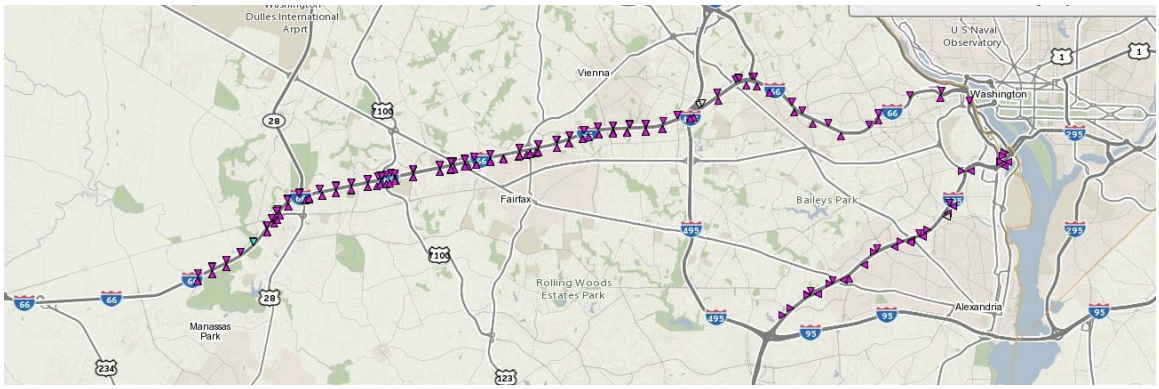


Figure 15: Sensor Locations on I-66

Sensor Data

We acquired historical sensor data of speed and flow for 5-minute intervals from 07/01/2009 to 01/01/2011. The real-time sensor data stream will also be collected for travel time prediction. The sensor data includes Timestamp (local time), Station ID, Total Flow Count per Observation Interval, Average Density, and Average Speed.

Work Zone Data

Both historical and scheduled work zone location and duration are required for this project. Work zone-related information includes Date, Start Time, End Time, Event Type, Latitude, and Longitude.

Weather Data

Historical, real-time and forecast weather data are obtained from the National Weather Service:

- Historical data - 15-minute to hourly data is available from the National Climatic Data Center.
- Real-time data - Current weather condition data is available from the National Oceanic and Atmospheric Administration.
- Forecast data: - Hourly data is available from the National Digital Forecast Database.

Weather data includes Date, Start Time, End Time, Event Type, Latitude, and Longitude.

Incident Data

Both historical and real-time traffic incident data are required for this project. The probability of incidents is calculated from historical records. Historical data includes Incident Location, Duration and Link-based Probability. Real-time data includes the Real-Time Incident Source and Predicted Duration. Date, Start Time, End Time, Event Type, Latitude and Longitude are stored for both forms of incident data.

4.1.11.3. Data Manager

The data manager component generates recurring and non-recurring traffic condition data through traffic pattern analysis. In this component, several steps are performed to prepare historical database for recurring and non-recurring traffic conditions. The process is illustrated in Figure 16.

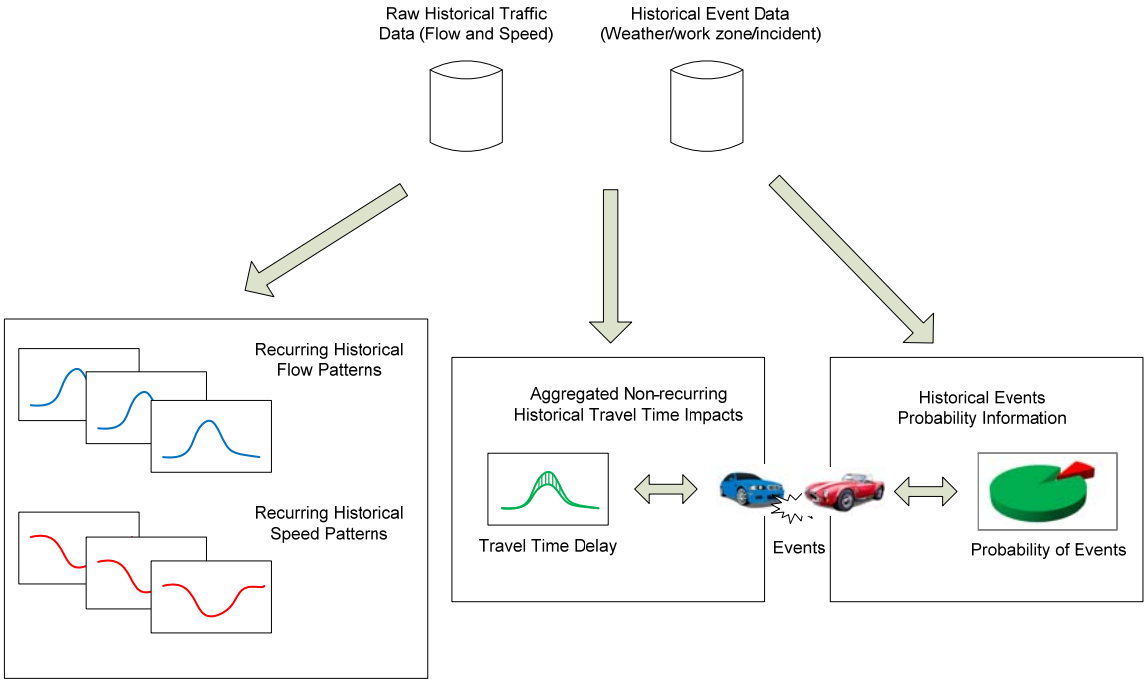


Figure 16: Offline Processing Flow

Step 1: Generate recurring historical traffic pattern as clean base line

We first create average flow and speed patterns for each link as the clean baseline traffic pattern, which does not include time period with incident or other events. The historical traffic pattern is generated by aggregating the above time series according to link and time of day (Table 5). The identified historical traffic pattern is further applied as the baseline for analyzing non-recurring traffic conditions.

Day of Week	Time of Day	Link ID	Average Travel Time

Table 5: Historical Traffic Pattern

Step 2: Aggregate non-recurring traffic data

Next, we process historical traffic data with incident or special event impacts. Specifically, for each non-recurring traffic time period in the historical database, the capacity reduction and travel time addition are estimated by comparing its prevailing traffic flow and speed conditions with the corresponding historical pattern. Furthermore, according to the type and duration, the resulting non-recurring traffic impacts are then aggregated using keys such as link and time of day. The result of non-recurring traffic pattern aggregation is shown in sample Table 6. The data would be indexed by Link and Time of Day.

Event Type		Capacity Reduction	Duration	Additional Travel Time	Speed Limit for Reference
Severe Weather	Snow				
	Rain				
Incidents	Crash				
	Injury				
Work zones	1-lane close				
	2-lane close				

Table 6: Non-Recurring Traffic Impact Lookup Table

Step 3: Estimate Probability of Events

Finally, in order to predict traffic delay patterns for the mid-term (next day) and long-term (next week), the probability information of the non-recurring traffic conditions are also aggregated through the procedure (stored in database as illustrated in Table 7). With the probabilistic traffic information for each link, the off-line module is able to provide path-based travel time reliability for the entire highway network.

Day of Week	Time of Day	Event Type	Probability	Overall Delay

Table 7: Probability of Non-Recurring Conditions

4.2. Stage 2: Prototype Development and Field Demonstration

In Stage 2, system components were developed and integrated into a working prototype. Three major functional components were implemented: a statistical analysis component for historical data, pre-trip travel time planning, and en-route travel time dissemination and updating together with internal databases including a historical recurring congestion database and a historical non-recurring congestion database.

The final activity of the research project was to demonstrate the prototype, conduct a field trial, and validate our travel time predictions.

The major tasks completed during Stage 2 of the project are described below.

4.2.1. System Development

Following our Phase 1 review meeting with the regional expert panel, PM and program staff, our team received formal approval to proceed with development of the prototype system. The architecture of the system and rationale for our development and deployment choices has been discussed previously. During this time we completed development and testing of the system according to that approach and plan. In this report we'll note a few highlights from these efforts.

4.2.1.1. Development Efforts

Our software development efforts validated our choice of tools and platforms. The use of a loosely-coupled architecture, existing frameworks, and cloud services made it possible for us to focus on user functionality instead of infrastructure.

Data flow from the CATT Lab to our Data Manager/Prediction Engine, and in turn to the User Portal/Subscription Manager, was very reliable.

4.2.1.2. Unit and System Integration Testing

As soon as the major components of the system were completed we began to test them in isolation. When mutually dependent components were ready we began to test their interoperation. For example, we began testing the basic mechanics of trip planning with local, sample data. Once we were regularly acquiring real-time data we were able to test more extensively using forecast data generated within the last five minutes. We incrementally added functionality until we were sending notifications via email, text message and voice calls to team members who had set up user accounts, trips, and subscriptions on the system.

4.2.1.3. User Interaction

As we progressed from UI mockups to working interfaces we carefully considered usability, terminology, information organization, and the usefulness of the information we were presenting. Along the way, we made some strategic simplifications and changes that, in our opinion, improve the user's experience and puts a focus on the value that we believe this system can deliver:

- **Made travel time forecast information more prominent.** We originally planned to overlay forecast information on a map (generated by calling the Google Map API). We changed our implementation approach to feature travel time forecast and related information in a dedicated area beneath the map displaying the trip's origin, path and destination.
- **Reduced the number of forecast tabs from three to two.** Instead of Today, Tomorrow and 5 Day Forecast tabs we can determine whether a trip a user is planning or viewing can still occur on the current date or can only take place in the future. For example, if a user visits the site at 2:00 pm and plans a trip for a 10:00 am arrival time, that trip can only occur the next day. We changed our approach to display the appropriate tabs based on context: Today/5 Day for a trip later on the current day, or Tomorrow/5 Day for with an arrival time that has already passed.
- **Presented a single travel time forecast for a trip.** We originally planned to provide two travel time forecasts, one with a 75% probability (travel time reliability) and one with a 95% probability. Initial feedback from prospective users that were not transportation professionals suggested this could be very confusing. We judged that the average user only really cares about what time they need to leave in order to make it on time to where they are going. We now present only a single 95% probability forecast, which is always referred to as the "most reliable forecast". The term "probability" was not used.
- **Presented more information about the factors that contribute to travel time.** Related to the point that the average user wants straightforward information, they will have an intuitive sense of how long frequent trips should take. Since our forecasting algorithms take into account multiple factors and the travel time forecast typically varies from day-to-day, we judged it prudent to give the user some insight into the factors that contribute to this variability. While professionals might call these delay factors, we present Congestion, Weather, Incidents and Work Zones as "Travel Time Contributors" expressed as a percentage totaling 100%.

4.2.2. Validate Travel Time Reliability Predictions

Our team validated the accuracy of our TTR predictions using travel time and road speed data obtained through TrafficCasts's BlueTOAD (Bluetooth Travel-time Origination And Destination) system, which detects anonymous MAC addresses, wireless identifications used to connect Bluetooth™ technologies on mobile devices in vehicles such as phones, headsets and music players. The system calculates travel time through analysis of subsequent detections.

For the validation of our prediction results, we selected one origin-destination pair on each direction of I-66 (Figure 17), and evaluated the predictions for both peak and non-peak hours. The eastbound test location is a 10-mile corridor that starts at I-66 Exit 55 and ends at Exit 64. We selected 7:30 am to 8:00 am (EST) as the peak hour time window and 5:00 pm to 5:30 pm as the non-peak hour interval. The 8-mile westbound test corridor starts at Exit 73 and ends at Exit 64, with a peak hour from 5:00 pm to 5:30 pm and a non-peak hour from 7:30 am to 8:00 am. Weekdays during two weeks of December 2011 were selected as the test period (12/05/2011 – 12/16/2011).

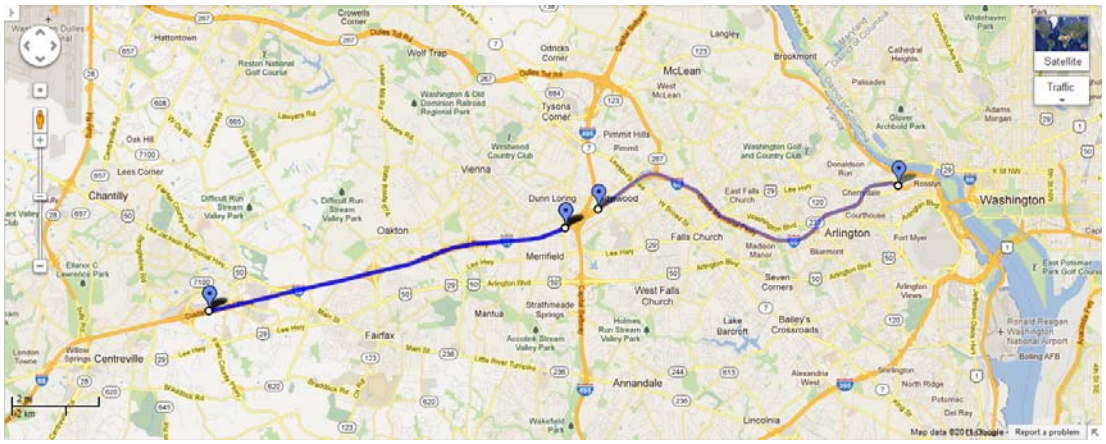
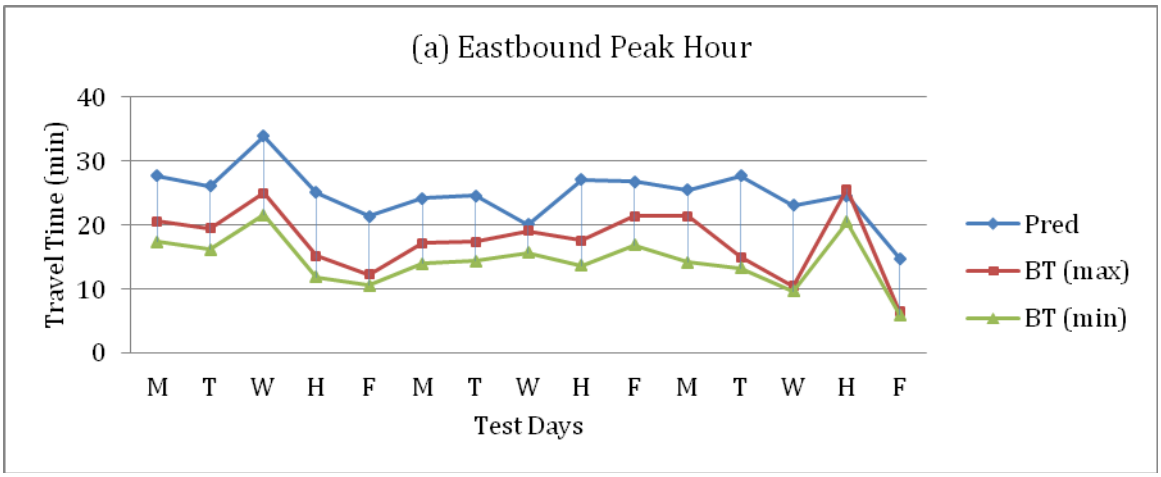


Figure 17 - Selected Highway Corridors for Validation (Left: Eastbound, Right: Westbound)

The so-called "Most Reliable Travel Time" prediction we provided to participants in our project was a 95th percentile reliability travel time, meaning that in 95% of cases a driver will arrive at the targeted destination exit within the scheduled time.

To evaluate the prediction results, we compared our reliability forecast with the longest travel time during the selected time window. For instance, when evaluating the most reliable travel time forecast of the eastbound test corridor at 7:45 am (700 sec), we found the longest Bluetooth travel time between 7:30 am and 8:00 am (680 sec), and calculated the travel time gap in between (700 – 680 = 20 sec) as the validation result. To compare the validation results between different corridors and time windows, a relative gap is defined as the ratio of travel time gap and the maximum Bluetooth travel time. Figure 18 shows the travel time gaps between the most reliable forecasts and the Bluetooth data measurements. Table 8 presents the average validation values of the selected corridors on peak and non-peak hours.



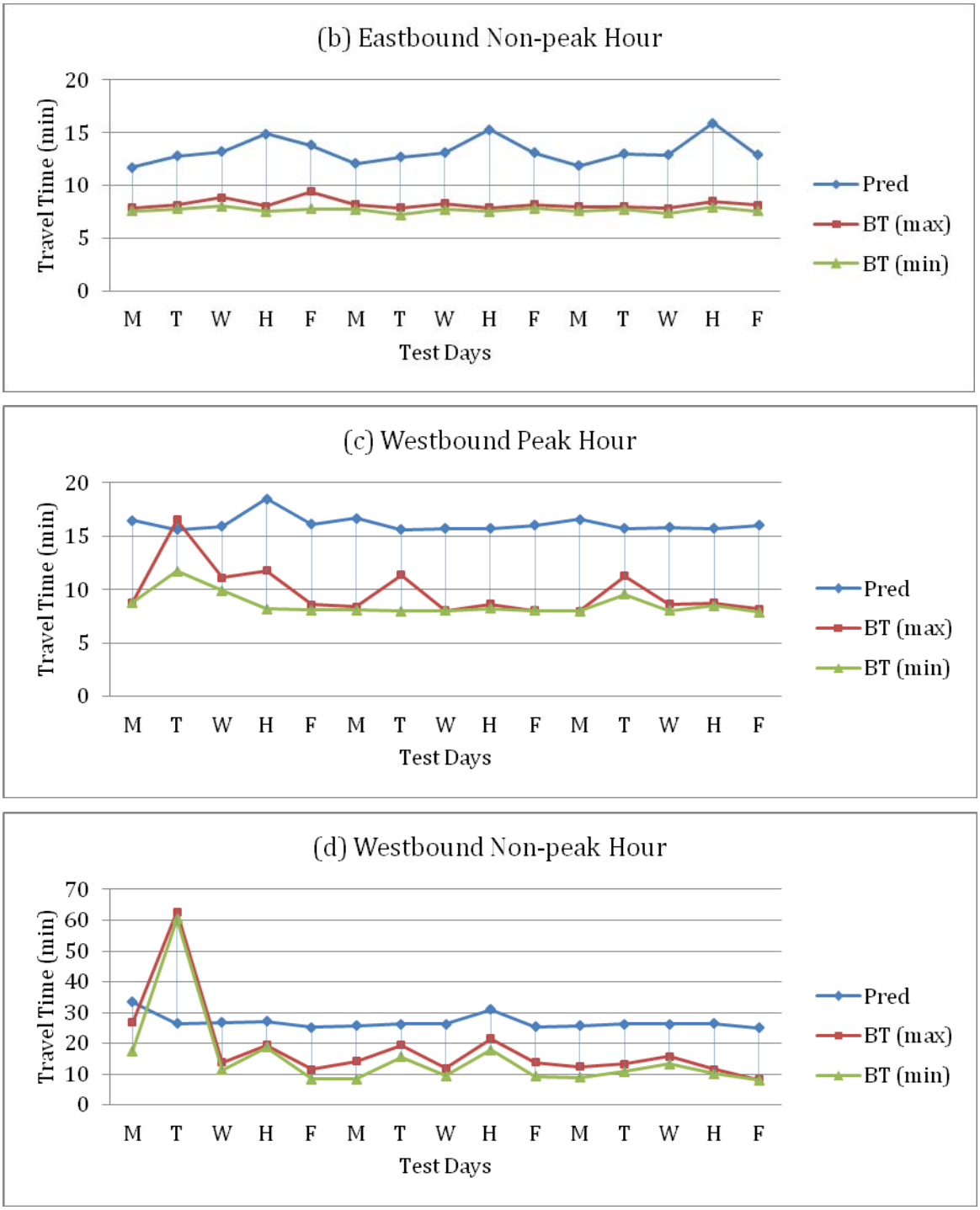


Figure 18: Travel Time Reliability Predictions Compared to Bluetooth Travel Time Measurement Range

	Average Bluetooth Travel Time (min)	Predicted Travel Time Based on 95% Probability (min)	Buffer Time (min)

EB Peak Hour	17.6	24.8	7.2
EB Non-peak Hour	8.2	13.3	5.1
WB Peak Hour	18.4	26.9	8.5
WB Non-peak Hour	9.7	16.1	6.4

Table 8: Bluetooth Travel Time Compared to Predictions

From the experiments conducted for the reliability forecast validation, we found that in most cases, the predicted results provided reliable planning travel times so that travelers could arrive at their destination with low delay risk, and also limit the buffer time to reasonable ranges: 5-6 minutes for non-peak hours and 7-8 minutes for peak hours on 8-mile corridors. This is due to the fact that our forecasting algorithm predicts the 95th percentile travel time instead of average travel time by predicting the occurrence of non-recurring events. Our current implementation also utilizes a high buffer index to build in adequate buffer time (or time cushion) into our travel time forecasts. The data validation results show that this 95% reliability-based travel time, expressed as the "most reliable travel time" in our application, appears to be most valuable to travelers for planning purposes.

4.2.3. Conduct Field Test

The field test was designed to establish, from an end-user perspective, that our travel time application concept is viable and valuable. The field trial specifically evaluated:

1. ***Application*** – Does the functionality provided and ease-of-use meet user expectations, both the web interface for planning one-time and recurring trips, plus forecast updates via email, voice, and text messages?
2. ***Information*** – Does the travel time forecast information provided on the web and via notifications provide accurate, actionable information that allows travelers to alter departure times or routes?

Our team conducted a peer review of the prototype through a web-based conference with SHRP 2 program managers, colleagues, and the project expert panel. The primary goal of this step was to assess if the application adequately fulfilled the requirements and addressed the identified technical issues.

4.2.3.1. Field Test Participants

With the approval of the IDEA Reliability program, we proceeded with a field trial, where a small group of commuters was asked to use the application on a trial basis for a period of approximately 3 weeks. This user group consisted of 9 people who have fixed commute routes on the selected corridors in Northern Virginia. These commuters were able to get predicted pre-trip travel times every day.

We solicited feedback on a user-by-user basis rather than by using a survey, since by design, our test group was small. This enabled us to obtain in-depth, quality feedback on

a regular basis. Our team kept in touch with participants on a frequent basis throughout the testing period via email and phone calls.

4.2.3.2. Field Tests Results

Upon the completion of our demonstration and field trial, the research team summarized the feedback from these stakeholders to ascertain whether the travel time application performed reasonably well and met user expectations.

Table 9 shows the performance measures that we used to track and evaluate the feedback received from field trial participants.

Area of Focus	Evaluation and Performance Measurement	User Feedback
On-line Application	Overall User interface	Users felt that it is quite easy to understand and navigate through the application.
	Quick Planner and Forecasting Interface	Most current travel time applications focus on delivering real-time travel time information, so this as brand new to most users, especially the 5-day forecast. Users felt that the forecasting interface offered a new perspective on trip planning.
	Map Interface	Users felt familiar with the map interface since it is based on Google Maps. Some users liked the separation of route display and forecast information and others wanted to see the latter overlaid on the map.
	Trip Planner and Notification Interface	Users indicated the entire trip set up process is straightforward. All the fields for setup up are easy to understand.

Area of Focus	Evaluation and Performance Measurement	User Feedback
	Accessibility	Both the web site and application functions were accessible for the entire testing period. It was not within the scope of the field trial to test system is accessibility by people with disabilities.
	Responsiveness	System uptime was 100% for the field test period. All online functions performed well. Both map updating and forecasting functions provided excellent response times.
Real-time Notification	Email Delivery and Content	Email delivery worked as expected. Messages were delivered on time. Users reported that the content was concise and understandable.
	Voice Delivery and Content	Voice delivery worked as expected. Calls arrived on time. Users reported that speech was a little too fast, or some cases, not clear. Users suggested providing a function to repeat a message.
	Text Message Delivery and Content	Text message delivery function worked as expected. Messages delivered on time. Users reported that the content was concise and understandable.
Travel Time Information	Accuracy of Forecasted Travel Time	Not addressed by user feedback from field trial, but validated via separate effort. See Section 4.2.2. Since forecasted travel time is different from real-time travel time, the field trial focused more on the usefulness of the forecasts.

Area of Focus	Evaluation and Performance Measurement	User Feedback
	Usefulness of Forecasted Travel Time	Most users indicated they looked more at the "imminent" travel time forecast than the 5-day forecast. They primarily used the 5-day forecasting function to check for any significant "out-of-range" delay due to any extra-ordinary or non-recurring events.
	Usefulness of Travel Time "Contribution Factors"	Users in general perceived this information as valuable. If factors other than congestion were contributing to the forecasted travel time, they were more conscious of the need to adjust their plans. Users suggested that these factors should also be included in email, text and voice notifications.
	Usefulness of Non-Recurring Congestion Information	From a planning aspect, users indicated that they preferred to have this forecasted travel time instead of conventional average travel time because it enabled them to see the extent of travel time variation due to both recurring and non-recurring congestion conditions.

Table 9: Field Trial Evaluation & Measurement

5. PLANS FOR IMPLEMENTATION

Our team's plans for implementation are depicted in Figure 19. Our ultimate goal is to turn this "travel time reliability prediction" concept into a "commercial travel time service" that can directly benefit state DOTs and the general public. In order to reach this goal, we envision a series of "stepping stones" that broke the big task down to three phases.

- Phase 1 (completed) – Prove the concept and develop a demonstrable tool using travel time data provided by Virginia DOT through the University of Maryland's CATT lab
- Phase 2 – Develop a production-grade prototype via collaboration with selected state DOTs. We expect that our work in this phase will be funded from research programs such as NCHRP-IDEA or SHRP2-IDEA.
- Phase 3 – Develop a commercial "travel time prediction service". We expect that our development work will be fully funded by the private sector given the attractiveness of the product that emerges from Phase 2. We also plan to form partnerships with AASHTO and FHWA in order to deploy this application nationwide.

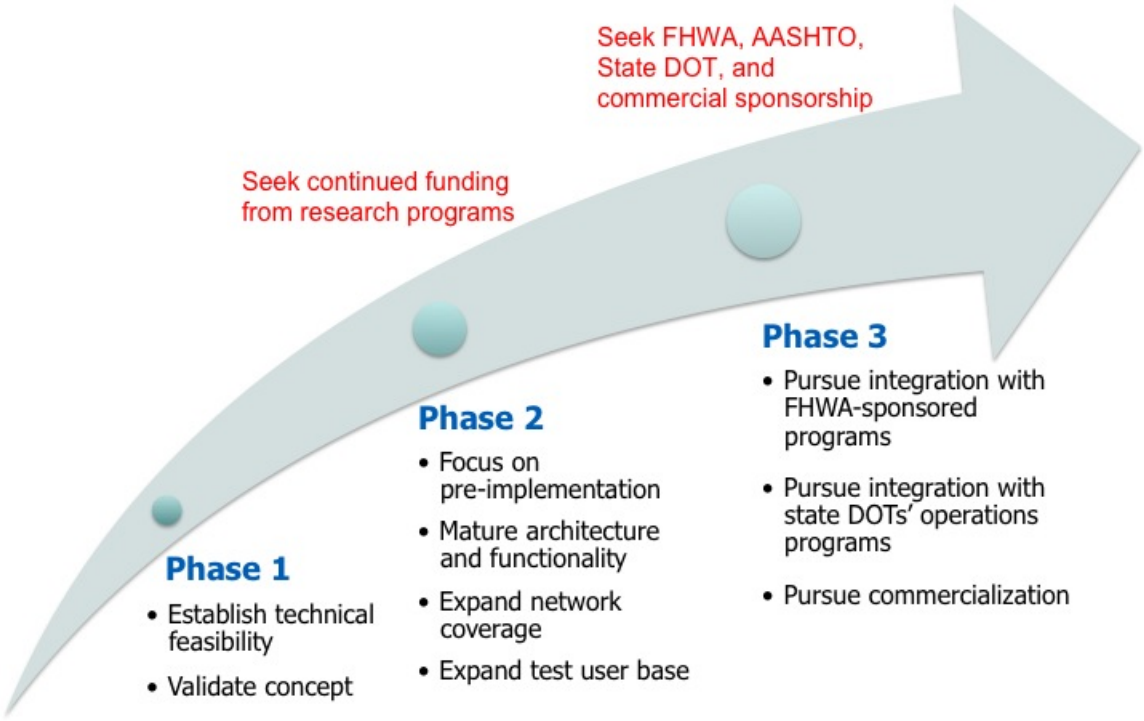


Figure 19: Implementation Strategy

Phase 1

Phase 1 has been completed and is the subject of this report. As will be discussed further in the Conclusions section, we believe that we have established the technical feasibility and validity of the concept via the prototype and successful field trial.

Phase 2

In the near-term, our strategy is to advance the "demonstration of concept" tool developed in the SHRP2 L15[A] project to a generalized "production-grade" prototype targeting state DOTs and the general public.

This would involve enhancing the system architecture to provide scalability over a larger highway network, and adding additional functionality, such as expanding the travel time reliability prediction from a single-route to include alternate routes so that both reliable route and reliable departure time can be provided to the users. What we accomplished in Project L15[A] is a critical stepping stone to building this capability, as shown in Figure 20.

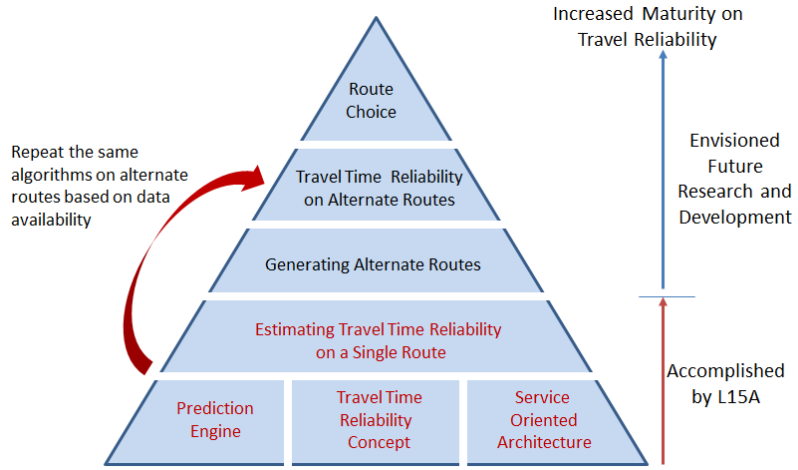


Figure 20: Capability Maturity Model

As depicted in this maturity model, the concept of travel reliability evolves from predicting travel time reliability on a single route to choosing a reliable route that provides the "optimal" travel time. The new functionality will define how the core components delivered in L15A can be repeatedly applied to alternate routes, assuming sufficient data is available. These core components include the anchor travel time reliability concept, the prediction framework or engine, and the service-oriented system architecture.

Additionally, we would like to pilot the prototype in selected metropolitan regions via partnerships with transportation agencies to assess its readiness for commercialization.

For example, we would like to work with state DOT's to pilot the integration of our prototype with their 511 applications (both web and mobile versions). The pilot will help us evaluate both the functional and technical integration. Our goal is to determine the reliability of the technical connections and to prove that the prototype can serve as additional add-on functions seamlessly.

Phase 3

Ultimately, we see the system evolving into a set of consumable services that can be easily integrated into:

- State DOT operations programs, such as Dynamic Message Signs, Active Traffic and Demand Management, and 511 web sites. Such efforts might also address institutional policies and procedures.
- Commercial web sites.
- New, cloud-based services, e.g., Google Calendar.

A vision for such a complete product/service that would be possible in Phase 3 is depicted in Figure 21. The feasibility of a Phase 3 implementation would depend on obtaining support from FHWA, AASHTO, state DOT's, and/or commercial entities.

In Phase 1, we had to provide a portal to enable users to try the service. The architecture depicted for later phases shows the evolution to a set of services that can be consumed by, and thus deployed through, other applications and information services.

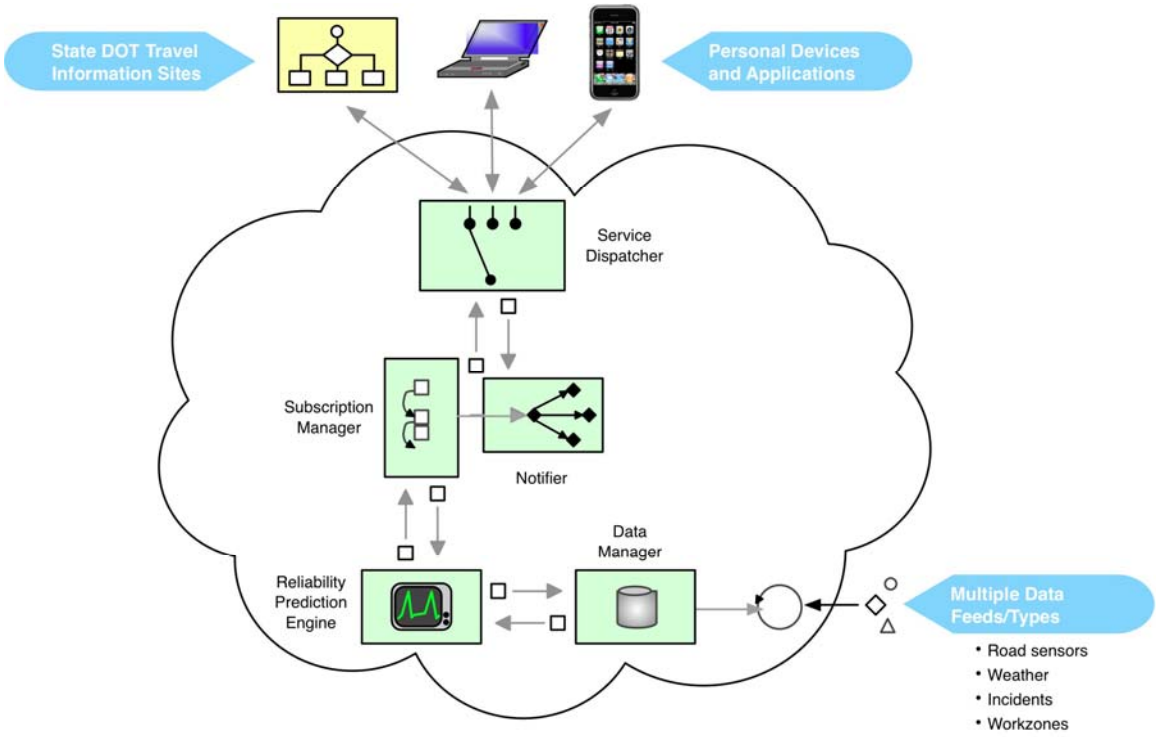


Figure 21: Vision for a Completed Product/Service

6. CONCLUSION

Based on the accomplishment of this project including both the entire process of research investigation and the delivered prototype application together with final data validation and field user trial, our team believes that the proposed travel time application concept has been successfully proven to be not only valid and but also feasible to implement:

1. From both technology and analytical perspectives, it was feasible to develop and implement the proposed reliability-based travel time application based on both historical and real-time data, and the statistical correlation and inference between them;
2. From a practical or user standpoint, both pre-trip and en-route travel time reliability information are deemed to be valuable and useful by travelers.

Web-based Application – The feedback from our field trial and demonstrations to the project expert panel and the SHRP 2 Reliability Technical Coordination Committee consistently praised the overall user experience.

- All the functions are very easy to access and the system provides excellent performance.
- Users feel it is easy and straightforward to use the Quick Planner forecasting function.
- The Google-based map provides users with a familiar environment for visualizing trips.
- The "5-Day" and "Tomorrow" planning information are perceived by most users as brand new functions. However, the information content under these two tabs enabled users to quickly grasp the essence of the information presented.

Real-time Notification – The real-time notification via email, voice mail, and text message for imminent travel time information are deemed by all users as an integral part of the concept and application's value.

- All three delivery methods successfully deliver the prescribed travel time information.
- The online set-up for these three delivery methods is straightforward.
- Users expressed strong appreciation of this real-time notification function and the delivered information augments the forecast information presented by the on-line application.

Travel Time Reliability Information – The "reliability-based" travel time information was well received by users, as compared to average travel time. As a result, users became aware of non-recurring events and the likely impact of these on their commute schedules.

- The non-recurring information presented as a percentage impact to travel time due to weather, incident, and work zones is generally perceived by users as valuable,
- The "Most Reliable Departure Time" based on 95th percentile travel time reliability is favored by users as useful planning information for "imminent" trips.

- Most users indicated that the "5-day" and "Tomorrow' forecast information are new to them since they have previously only had access to real-time travel time information; however, they also feel that these concepts are easy to comprehend and valuable once understood.
- Users used the near-term forecasting function primarily to check if there might be a significant "out-of-range" delay due to any extra-ordinary or non-recurring events.

Analytical Methodology – The validation of our forecast results, along with feedback from users, establish that it is feasible to forecast travel time with an acceptable degree of accuracy for non-recurring congestion based on historical travel condition patterns combined with real-time traffic data.

- One of our project guiding principles was to implement/integrate existing statistical forecasting models rather than creating any new ones. To this end, our team selected and successfully implemented a hybrid forecasting model.
- The predication of future incident occurrence and its potential impact to traffic congestion based on historical traffic data proved to innovative.
- The established analytical framework gives us the flexibility to switch to or add other analytical models if necessary to evolve this application.

Technology Implementation – The success of the application, including both its on-line planning functions and real-time notifications lies on the solid technology architecture and implementation that was put together by our team. It establishes that it is possible to deliver this kind of application today in a highly cost-effective manner.

- The application was deployed under a 100% cloud computing-based virtual compute, storage and network environment.
- Email, SMS and voice forecast notifications delivery uses commercial web service on a pay-per-transaction basis.
- The service-oriented architecture enables seamless integration and invoking of multiple services, including driver-centric GUI and subscription services delivered by consuming, aggregating and analyzing multiple data feeds.
- The entire system development was accomplished with a 6-month period of time without any software and hardware procurement.

Overall, our team believes that this research project produced strong evidence that our travel time reliability forecasting application represents a major advance in providing meaningful travel time information to drivers, especially for non-recurring congestion. Instead of typical static route information and average travel times, this project's IDEA product successfully enabled travelers to see the extent of travel time variation due to both recurring and non-recurring congestion. We believe that, by following the suggested implementation plan, this concept can continue evolving and will ultimately bring fundamental change to the way many travelers plan their daily commute or one-time trips.

7. INVESTIGATOR PROFILE

Dr. Zongwei Tao (Principal Investigator) – Dr. Tao is a senior transportation system and technology consultant with over 18 years of experience in designing, developing, and implementing transportation IT systems. Dr. Tao not only has intimate knowledge of state DOT and TMC operations but also has extensive hands-on experience that spans in the full system development life cycle. His technical expertise encompasses ITS technologies, real-time and archived traffic data management, large-scale database and system design, and transportation asset management.

Dr. Tao is currently providing ITS technology and project management support to Virginia DOT's Northern Region Traffic Management Center Dr. Tao has spent significant amount of time at VDOT's Traffic Management Centers managing the deployment of new IT systems and technologies including traffic data collection, incident management, and travel time applications. It was that intimate knowledge and insight that provided him the impetus and aspiration to propose this research project.

Dr. Xuesong Zhou (Co-Principal Investigator) - Dr. Zhou is an Assistant Professor at the Department of Civil and Environmental Engineering at University of Utah. Prior to that, he served as a Traffic Data Architect and Senior Software Engineer at Dash Navigation, Inc, developing the first commercialized Internet-connected GPS navigation system in the U.S. He is a co-inventor of the Key2SafeDriving technology, which disables cell phone usage via a Bluetooth-enabled key while driving and encourages safe driving behavior. Dr. Zhou has been assisting the FHWA's DYNASMART for the past eight years. Dr. Zhou is currently participating in the following SHRP 2 projects:

- L02: Establishing Monitoring Programs for Mobility and Travel Time Reliability
- L04:Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools
- C05: Understanding Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs

Jeffrey Spotts (Technology Architect) - Mr. Spotts has over 30 years of experience in the information technology industry. He began his career as a software developer and was soon steered into customer-facing roles. As a systems engineer, Mr. Spotts worked directly with clients on mission-critical applications in many industries, which exposed him to a wide range of technologies. As a product manager, he learned to work with cross-functional teams to translate customer and market requirements into viable technology products. This led to increasingly responsible roles where he was responsible for setting and driving business and product strategy for a number of IT vendors. Some of the products he helped conceive and bring to market are recognized leaders in their respective segments today.
Mr. Spotts now works with clients to understand their business requirements, envision the most appropriate technical approach, and then implement a cost-effective system solution. He was the technology architect of Reliability Project L13.

Tao Xing (ITS System Developer) - Mr. Xing is a PhD candidate at University of Utah. He is highly proficient in computer programming. In a California Partners for Advanced Transit and Highways (PATH) sponsored project, he led a team of five (5) graduate

students and developed a web-based multi-criteria dynamic routing system that can be accessed via both mobile device and webpage. Mr. Xing developed a safety driving system and won the prestigious Windows Mobile Award of US final in the Microsoft Imagine Cup Competition, 2009.

Bin Lu (Application Developer) -Mr. Lu is a senior consultant with 15 years of experience in designing, developing, and integrating information systems for clients in federal government, education, financial, telecommunication, and retail. He specializes in architectural designs and delivery of high performance, reliable enterprise solutions (Business Process Management, Content Management, Portal, etc.) using JAVA EE technologies, Web Services, and Web 2.0 standards, and has strong experience in full software development life cycle (SDLC), Object Oriented Analysis and Design, design patterns, and processes (RUP, Agile).

8. APPENDIX: Review of Current Practice for Travel Time Prediction

8.1. Non-Recurring Congestion Sources

In both academic and industrial fields, non-recurring congestion has been well recognized as one of the key factors influencing travel time reliability (Cambridge Systematics, Inc, et al., 2003). As reported by FHWA (Cambridge Systematics, 2005), about 55% of congestion is caused by non-recurring traffic conditions, including traffic incidents, severe weather, work zones, and special events. The impacts of various non-recurring congestion sources have been decomposed and been the subject of several literature studies such as Kwon et al. (2010). Focusing on highway corridors, Kwon and his colleagues calculated the 95th percentile of travel time with a quantile regression-based method, and further identified the contribution of individual non-recurring sources to the buffer time (travel delay). From a conceptual demand/capacity analysis perspective, sources of non-recurring conditions can be interpreted as follows:

- Traffic incidents: **capacity** reduction
- Severe weather: **capacity** reduction and possibly **demand** reduction
- Work zones/road work: medium-term **capacity** reduction
- Special events: **demand** increase

The above high-level demand-supply analysis on different congestion sources could help decision-makers better understand travel time prediction algorithms under non-recurring congestion, especially for traffic flow model-based prediction approaches.

8.2. Review of Travel Time Prediction Methods

The travel time prediction problem has been extensively studied in past decades. A variety of models have been proposed and developed with different theoretical foundations. Depending on underlying traffic process assumptions, the existing traffic state prediction models can be classified into three major approaches:

3. Approach purely based on statistical methods, focusing on traffic flow/travel time forecasting on a freeway segment or an arterial street.
4. Approach based on macroscopic traffic flow models, focusing on traffic flow estimation and prediction on successive segments of a freeway corridor.
5. Approach based on Dynamic Traffic Assignment (DTA) models, focusing on wide area estimation and prediction of origin-destination demand, route choice probabilities, as well as resulting traffic network flow patterns.

The first class of models predicts travel time by exploring the statistical characteristic of single or multiple traffic states, and is widely used for route guidance, adaptive ramp metering and local signal control management. Some traditional approaches using statistical models include:

- Time-series methods, e.g. Auto-Regressive Integrated Moving Average (ARIMA) models (Box and Jenkins, 1970);

- State space methods, e.g. Kalman Filtering (KF) technique, which combines both the historical data and real-time observations into the estimation and prediction process, is first applied in traffic volume prediction by Okutani and Stephanedes (1984);
- Non-parametric methods such as K Nearest Neighbor (KNN) (Davis and Nihan, 1991) and Neural Network (Clark et al., 1993) approaches.

In practice, most of the traffic prediction systems that use statistical models are developed based on these traditional approaches with additional enhancement. For example, an IBM research team developed a statistical model-based traffic prediction tool for the near-term prediction of traffic conditions (Min et al., 2007). With the consideration of spatial and temporal correlations, the method proposed by IBM adjusts the prediction based on the deviation of current traffic from the historical periodic trend. In another practical case of a statistical model, Inrix, a leading traffic information provider, uses Bayesian statistics to uncover the causal relationships between non-recurring events and traffic states.

The second category of models aims to predict traffic flow, density and travel time on each segment or sub-corridor, with the demand and capacity change as the input. In such traffic flow based prediction models, several methods have been widely studied, including cell transmission model (CTM) and Newell's model. The cell transmission model, proposed by Daganzo (1994), decomposes a road corridor into multiple cells and estimate/predict traffic using density, flow of each cell and boundary conditions. It should be noted that, the numerical implementations of CTM, in order to be fully consistent with the theoretical derivation of the shock wave propagation behavior, require high-resolution network representations that lead to computationally intensive tasks for current real-time traffic estimation/prediction applications.

In 1993, Newell (1993a, b, and c) proposed a simplified theory based on the classical traffic wave theory. In this model he used the cumulative count curves instead of flows for most of the calculations and a triangular flow-density relation to describe traffic flow (i.e., forward wave and backward wave) propagation. Newell's model has been tested and verified on freeway segments by Hurdle and Son (2000) and demonstrated the model's computational efficiency and prediction results on severely congested cases. A more complicated, but also more general, two-detector problem has been studied by Daganzo (2001). Different from statistical models, the traffic flow model-based prediction approach fully utilizes the inherent relationships among traffic states: speed, flow and density.

The last type of approach applies real-time simulation-based Dynamic Traffic Assignment (DTA) to measure the traffic performance with accurate dynamic origin-destination demand input. The real-time DTA based models consider user rerouting behaviors and can capture system-wide travel time estimation. In practice, DTA-based models contain too many network-wide parameters to be estimated (such as dynamic origin-destination demand matrix), which increases the difficulty for decision support systems to maintain consistency between simulated states and reality.

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