# Pilot Testing of SHRP2 Reliability Data and Analytical Products: Colorado

NOVEMBER 6, 2020


NAVJOY

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| | |
|---|---|
| ADAP | Advanced Data Analytics Platform |
| API | Application Programming Interface |
| ATA | Actual Time of Arrival |
| ATMS | Advanced Traffic Management System |
| ATT | Actual Travel Time |
| AWS | Amazon Web Services |
| CDF | Cumulative Density Function |
| CDOT | Colorado Department of Transportation |
| DTD | Division of Transportation Development |
| DMO | Division of Management and Operations |
| DOR | Colorado Department of Revenue |
| DRCOG | Denver Regional Council of Governments |
| DTA | Desired Time of Arrival |
| DTT | Desired Travel Time |
| DTR | Desired Travel Rate |
| FHWA | Federal Highway Administration |
| HPMS | Highway Performance Monitoring System |
| ITS | Intelligent Transportation System |
| MDD | Massive Data Downloader |
| NoSQL | Non-Structured Query Language |
| NPMRDS | National Performance Measures Research Data Set |
| OLOS | Operations Level of Service |
| PDF | Probability Density Function |
| PTI | Planning Time Index |
| SHRP2 | Strategic Highway Research Program 2 |
| SQL | Structured Query Language |
| STIP | Statewide Transportation Improvement Programs |
| TMC | Traffic Message Channel |
| TSMO | Transportation Systems Management and Operations |
| TT-PDF | Travel Time Probability Density Functions |
| TTRMS | Travel Time Reliability Monitoring System |


SHRP2 L38 Case Study – Final Report
November 6, 2020

# Executive Summary

Colorado Department of Transportation (CDOT) partnered with Navjoy to create a Travel Time Reliability Monitoring System (TTRMS) and integrate travel time reliability into agency planning and programming. The ultimate goal was to measure, understand, and identify strategies to mitigate the effects of non-recurring congestion on travel time reliability.

To accomplish this, two products from the Strategic Highway Research Program 2 (SHRP2) Reliability Data and Analysis Tools bundle were used: *L02: Guide to Establish Monitoring Programs for Travel Time Reliability*; and, *L05: Handbook for Incorporating Reliability Performance Measures into the Transportation Planning and Programming*. Using the L02 guide, a TTRMS, with a data cleaning component, reporting module, and dashboard, was developed and implemented statewide, and with the L05 the stakeholders were able to see how reliability measures could be incorporated into project and program decision making.

Rather than examine all seven sources of non-recurring congestion, the project team focused on four: work zones, incidents, special events and inclement weather. The TTRMS consists of four distinct components: A data cleaner to join disparate data sources, a web-hosted database, a database query tool to extract cleaned data, and a summary dashboard. It was used to build a large database of non-recurring congestion impacts statewide, and project stakeholders can use the tool to process future events and continue building the database. The dashboard is interactive and provides a number of different criteria for analysis, including, corridor type, closure type, time period, and others.

The results illustrated that different congestion sources were more impactful depending on the corridor type. For example, incidents impacted travel time reliability significantly more on urban corridors than rural. Similarly, work zones affected reliability more on rural corridors than on urban corridors. Additionally, it was discovered that certain subtypes of congestion sources, such as work zone construction subtypes, had a much higher impact than others, like work zone maintenance subtypes.

Reliability measures from the TTRMS, as well as other systems, can be integrated into planning and programming based on the L05 guidance summarized in the literature review. CDOT now has the data and tools to understand the causes of travel time unreliability deficiencies and make data-driven decisions to address them based on impact and investment value. As more data are added, CDOT has the tools to maximize the utility of these data to funnel funds into the areas of greatest needs and value for the organization and the overall community.

# 1. Introduction

This project was the result of the CDOT effort to create a TTRMS for transportation agencies to monitor and evaluate travel time reliability. This pilot implementation focused on the travel time evaluation aspect of the tool, rather than monitoring. The TTRMS allows CDOT to conduct in-depth analysis of travel time reliability impacts from incidents, work zones, weather events and special events, although not in real-time. This project also identified best practices when communicating travel time performance measures, and its guidance played a significant role in CDOT efforts to streamline performance reporting.

The TTRMS consists of a data cleaning component, database, reporting module and dashboard. Insights gained from the TTRMS help identify the most impactful mitigating actions to the top factors contributing to travel time unreliability. By quantifying the travel time reliability impacts from incidents, work zones, weather events, and special events, CDOT became better positioned to make data-driven decisions that improve transportation operations, funding and performance measurement.

## 1.1. Project Background

In April 2016, CDOT successfully applied for funding from the Federal Highway Administration (FHWA) to implement two products from the SHRP2 Reliability Data and Analysis Tools bundle:

- *L02: Guide to Establish Monitoring Programs for Travel Time Reliability; and,*
- *L05: Handbook for Incorporating Reliability Performance Measures into the Transportation Planning and Programming.*

The L02 product is a guidebook to develop a TTRMS – a system that joins travel time data to non-recurring congestion data. The L05 guidebook was used to consolidate, streamline and refine existing traffic performance measures, as well as to provide direction on incorporating new TTRMS data into planning and programming efforts.

In February 2018, CDOT suffered a ransomware attack that resulted in a lockdown of numerous Intelligent Transportation Systems (ITS) sensors and devices, many of which were required to provide necessary data to the TTRMS. Therefore, work during this time shifted to planning efforts including a literature review, ITS inventory and developing a revised TTRMS approach. For this revised approach, Navjoy consulted with MnDOT regarding their own implementation of the L02/L05 products, and we revised our objectives based on their feedback. The objectives of the revised project were to

- prioritize TTRMS development in Python over corridor-by-corridor analysis with Excel;
- revise the task structure to focus on iteratively modifying the tool for each congestion factor;
- limit the scope to four congestion factors: work zones, incidents, weather and special events;
- continually modify the TTRMS with each task.

## 1.2. Need for the SHRP2 Project

CDOT has prioritized data-driven decisions for improving traffic operations. This was accomplished through ITS infrastructure, Traffic Management Centers, Transportation Systems Management and Operations. (TSMO) strategies, and various performance reports. CDOT's data focus made them well-positioned to use the L02/L05 guidance to enhance their performance measures program and utility of their existing data.

There were three problems driving CDOT's need for a TTRMS:

1. Due to Colorado's geography (mountainous terrain) many corridors do not have alternate routes (e.g., I-70 Mountain Corridor). In addition, some are high-priority freight corridors, so delays are especially costly. Incidents, severe weather, special events and road work can cause significant delays on these roadways, and it is important to understand which delay reduction strategies are most effective. Once discovered, the most successful methods can be prioritized.
2. CDOT has a comprehensive network of roadside devices and ITS to record traffic and congestion data. However, much of these data reside in disparate databases, and joining them to create meaningful analysis can be labor intensive. The TTRMS presented an opportunity to increase the utility of existing data, and make the analyzation process more efficient.
3. Several performance measure efforts were already in place, and the L05 guidance was an opportunity to consolidate, generate, communicate and refine these efforts according to best practices.

Overall, the TTRMS was needed to enhance CDOT's understanding of congestion impacts and improve the reliability of Colorado's transportation network. The TTRMS provided efficiency improvements and insights to better position CDOT to reduce the impacts of the non-recurring events.

## 1.3. Working Group

The SHRP2 working group was comprised of members from the following organizations:

- CDOT, Division of Management and Operations (DMO)
- CDOT, Intelligent Transportation Systems (ITS)
- CDOT, Division of Transportation Development (DTD)
- Denver Regional Council of Governments (DRCOG)
- Federal Highway Administration (FHWA)

**Table 1** summarizes their roles and responsibilities within the project.

### Table 1: SHRP2 working group roles and responsibilities.

| Role | Stakeholder(s) | Responsibilities |
|---|---|---|
| Project Manager (DMO) | San Lee and Brooke Podhajsky | • Project direction<br>• Working group discussions<br>• Implement scope of work (SOW) |
| Planning Section (ITS, DTD and DMO) | Ben Acimovic, Anthony Vu, Darius Pakbaz and Annie Kitch | • Determine L02/L05 scope<br>• Identify use cases<br>• Testing of L02/L05 products<br>• Provide feedback on implementation<br>• Review project materials |
| IT Section (ITS) | Weiyan Chen and Bob Fifer | |
| Research Section (DTD) | David Reeves | |
| Region 1 | Alazar Tesfaye | |
| DRCOG | Greg MacKinnon | |
| FHWA | Eva LaDow, Bill Haas and Patricia Sergeson | |

CDOT partnered with Navjoy to develop the TTRMS. Throughout the project, Navjoy worked closely with CDOT project managers and the SHRP2 working group via working group meetings, update memos and demos at major milestones.

## 1.4. Project Objectives

The objectives of the SHRP2 project were to

- review the guidance of the L02 and L05 products;
- develop and test a TTRMS on pilot corridors;
- expand the TTRMS statewide;
- understand the impacts of work zones, incidents, special events and weather events on travel times;
- share the findings with a larger group of CDOT regions, divisions and local agencies; and,
- summarize the L05 guidance to incorporate travel time reliability into CDOT planning and programming.



# 2. Literature Review

The SHRP2 L02 and L05 products each contain a guidebook, supporting case studies and a final report; all of which provide the basis of this literature review. The L02 products explain how to establish a system used to evaluate and monitor travel time reliability, and the L05 products explain how to incorporate those reliability performance metrics into planning and programming. The objective of this section is to provide a common understanding of the L02 and L05 products.

## 2.1. Guide to Establish Monitoring Programs for Travel Time Reliability (L02)

The *Guide to Establish Monitoring Programs for Travel Time Reliability* describes the steps to create a TTRMS. Case studies from

- San Diego,
- Sacramento/ Lake Tahoe,
- New York/New Jersey
- Northern Virginia,
- Atlanta, and

were used to develop the guidebook. It is highly technical and describes key elements of a TTRMS, including data collection and management, computational methods, and use cases. The guidebook is available free to project stakeholders online.

### Introduction

Travel time reliability is best defined as the absence of variability in travel times when under similar operating conditions. Travel times on a roadway will vary throughout the day, but they can be reliable if travel times are consistent for the same day of the week and peak time period.

FHWA has identified seven internal and external factors that cause travel time variability. Internal factors include traffic control devices and inadequate base capacity, while external factors include incidents, weather, work zones, special events and fluctuation in demand. See **Figure 1**.

The goals of a TTRMS are to help agencies monitor travel time performance, understand impacts of influencing factors, provide credible information about reliability expectations and make data-driven decisions to improve reliability.

| The Seven Factors |
|---|
| Incidents |
| Weather |
| Work Zones |
| Fluctuation in Demand |
| Special Events |
| Traffic Control Devices |
| Inadequate Base Capacity |

**Figure 1:** *FHWA's seven sources of non-recurring congestion.*

At a high-level, a TTRMS involves creating a system to monitor and evaluate travel time reliability. The TTRMS uses travel time data, along with supplemental information about influencing factors (e.g., work zones, incidents), to create a credible picture of system performance. The data are archived in a database to be queried for historical performance analysis.

## Defining Travel Time Reliability

A roadway is reliable when travelers experience an Actual Time of Arrival (ATA) that falls within a Desired Time of Arrival (DTA) window, with the same conditions. Reliable trips occur within the DTA window. If the ATA lies outside of the DTA window, a reliable trip was not completed. See **Figure 2** for reference.

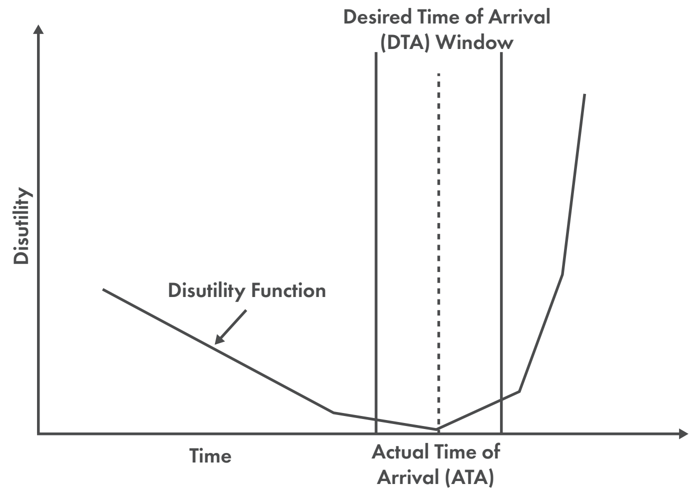



**Figure 2:** *A disutility function which characterizes desired and actual times of arrival.*

This is measured using utility theory: *Utility (of the trip) is maximized if ATA is inside the DTA window; conversely disutility is greater if the ATA is outside the DTA window.* The function to evaluate disutility is not symmetric, meaning the costs of disutility are much higher if arriving after the desired time.

Traffic Management Centers cannot monitor every single trip on a roadway, but they can collect and aggregate information from probe vehicles, spot-speed devices and travel time devices to establish Desired Travel Times (DTTs) and/or Desired Travel Rates (DTRs). The DTTs/DTRs can then be assigned a regime in which the system is operating, such as AM Peak or during an incident. A segment or route would be reliable if the Actual Travel Times (ATTs)/Actual Travel Rates (ATRs) fall within the DTT/DTR window.

## Trip-Making Concepts

The most important unit in the TTRMS is effectively measuring travel times; to do this we must understand the definitions of trips and travel times, while noting technological measurement limitations. The following five fundamental concepts establish a foundation for measuring trips and travel times.

**Concept 1:** Trips made by persons and packages (i.e. freight and CMV) are the fundamental focus for travel time reliability.

**Concept 2:** Travel time and trip time are different. A trip is traveling from origin to destination and allows for stops and side trips; the associated trip times, therefore, include the time from stops and side trips. Travel times remove extra time and refer only to the time spent traveling between the sensors on the route; trip times need to be filtered in order to obtain travel times.

**Concept 3:** Travel rate is not the same as travel time. Travel rate is travel time per unit of distance (e.g., minutes per mile). Travel time is the measurement of time to traverse a route (e.g., minutes).

**Concept 4:** Individual trips and travel times are difficult to observe, and no data collection method is perfect. It is important to understand how data collection technologies may skew results. For example, travel times collected by Bluetooth sensors may not completely filter out trip times that include detours/side trips.

**Concept 5:** It is acceptable to use aggregate measures as surrogates for the more detailed picture of individual trips. Aggregate measures such as average travel time in 15 minute bins are derived from the more detailed information, or raw data, and used to present a more comprehensive picture of every user's experience.

## TTRMS Design and Components

There are four key steps that a TTRMS must execute in order to be an effective decision support tool (See **Figure 3**):

1. Effectively **measure travel times** along a given route; measuring an individual travel time is the foundational unit of analysis.
2. Clearly **characterize the reliability** of the route. To do this, the system must take a set of measured travel times and assemble them into a statistical model. This is done by creating Probability Density Functions (PDFs) and Cumulative Density Functions (CDFs) to characterize the route's performance specific to an operating regime[1].
3. **Identify** sources of unreliability. After reliability of a route is characterized with PDFs for each operating regime, the TTRMS needs to fuse travel time data with data from the influencing factors to help operators understand what caused the unreliability.
4. Help **operators understand the impacts of the influencing factors** on the system. The TTRMS needs to provide clear visualizations of the data.

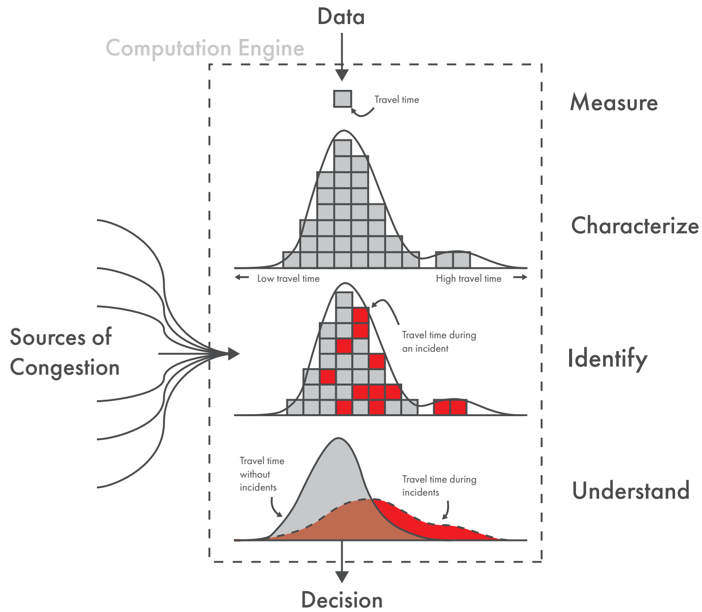



**Figure 3:** *Information flow in a TTRMS.*

[1] *Regime is used to describe the conditions under which the segment/route travel times were collected at a given point in time. Regimes are described using common traffic engineering terms (e.g., congested, uncongested, incident, weather, AM Peak).*

**Figure 4** below shows the components to a TTRMS; boxes are modules, circles are inputs or outputs, and the whole process (from left to right) is explained in the following bullet points.

- Traffic sensors feed travel times into the **Data Manager**. Other systems are also connected to the data manager to provide information about incidents, events, or other sources of unreliability. These data are then cleaned using a quality control process and placed in a database.
- The **Computation Engine** for each operating regime allows real-time data to be viewed against historical data under the same operating regime.
- **Report Generation** is a user interface that allows operators and engineers to query the TTRMS and generate reports that help understand real-time performance and the impacts of sources of non-recurring congestion.

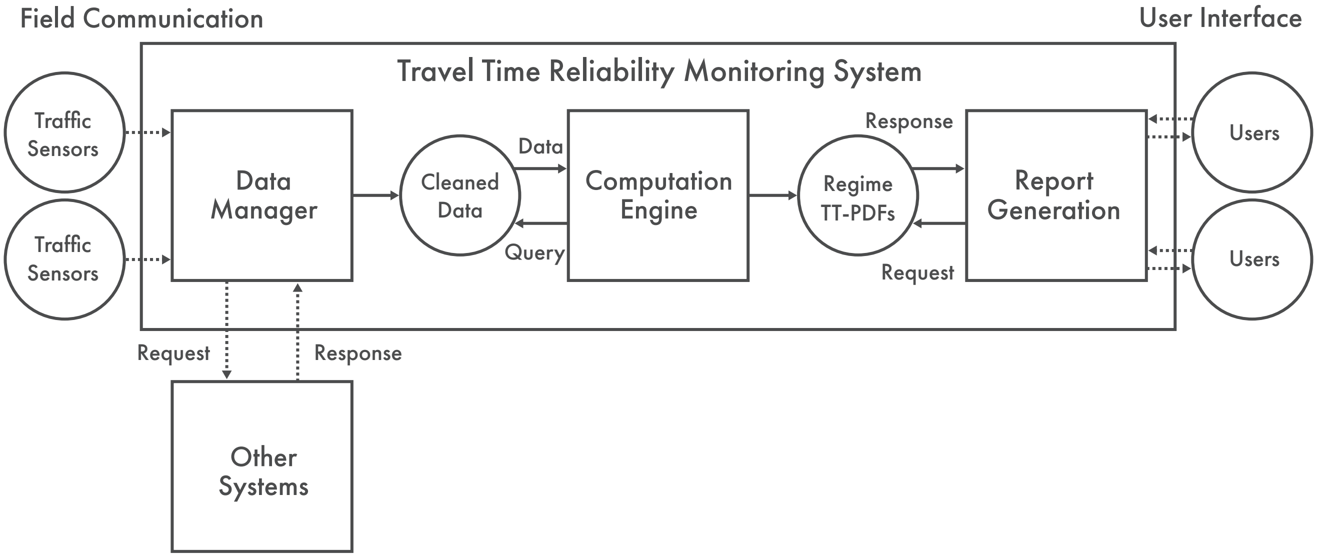



**Figure 4:** *Components and architecture of a TTRMS.*

Once in place, the TTRMS allows operators to understand how much delay is due to unreliability and how to best mitigate that delay. This helps make decisions such as whether an operator should deploy more service patrol units or focus efforts on improving special event plans. Ultimately, it helps agencies understand the relationship between travel time reliability and major sources of non-recurring congestion.

## Statistical Methods for Measuring Reliability

Three different statistical analysis techniques are commonly used to understand travel time reliability: Histograms, PDFs and CDFs. This guide focuses on using PDFs and CDFs to describe and compare the distribution of travel times for different routes and operating conditions. The statistical analysis techniques are described in further detail below.

1. **Histograms** use bar heights to represent the relative frequency that a certain binned range of travel times occurs. The travel times are categorized by the regime that was present at the time. Bar heights represent how frequently that range of travel time occurs and allows operators to see how travel times are distributed into each bin during various regimes. See **Figure 5**.

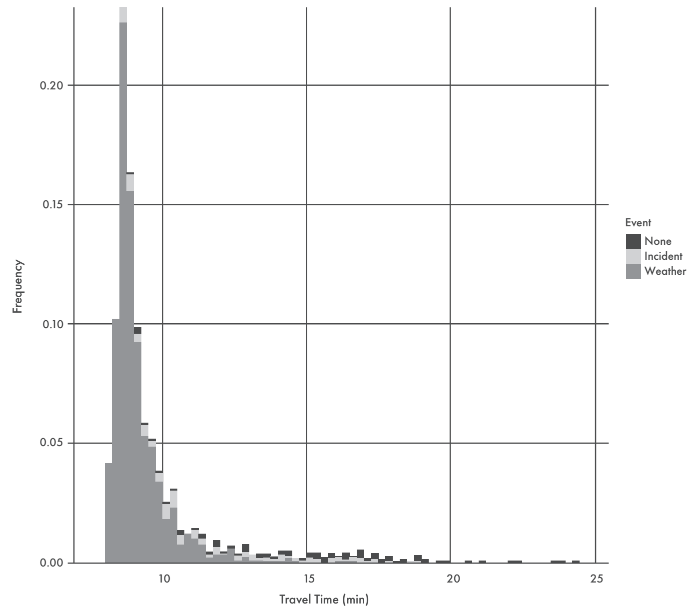



**Figure 5:** *AM Peak travel time histogram on I-8.*

2. **PDFs** utilize the values from the histograms to establish the probability of your travel time falling in a specified range. For each regime displayed in **Figure 5**, **Figure 6** displays the underlying PDF. PDFs are used to derive a number of metrics such as median travel time, 95th percentile travel time, average travel time and more.

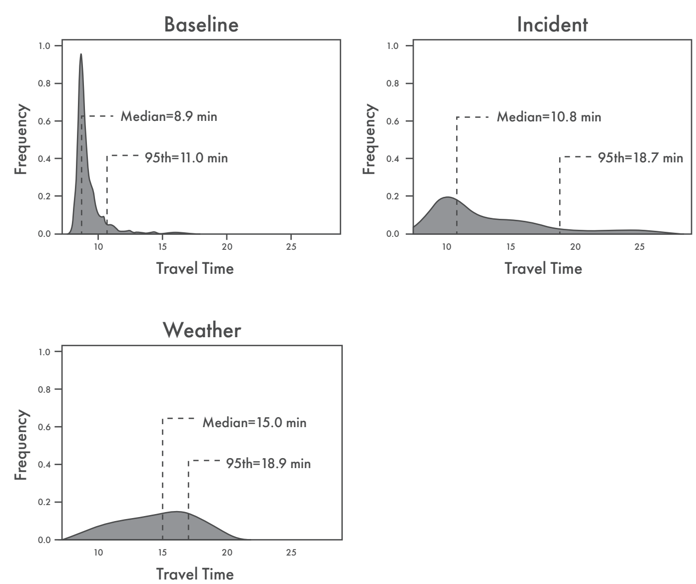



**Figure 6:** *PDFs of travel times for various operating conditions.*

3. The third technique is **CDFs**. A CDF is based on the PDF; the value shown in a CDF at any point in the graph is the integral of the PDF up to that point (i.e., the area enclosed within the PDF above the horizontal axis). CDFs condense multiple PDFs into one chart, allowing a user to easily locate key metrics such as 95th percentile or median for different operating regimes. See **Figure 7**.

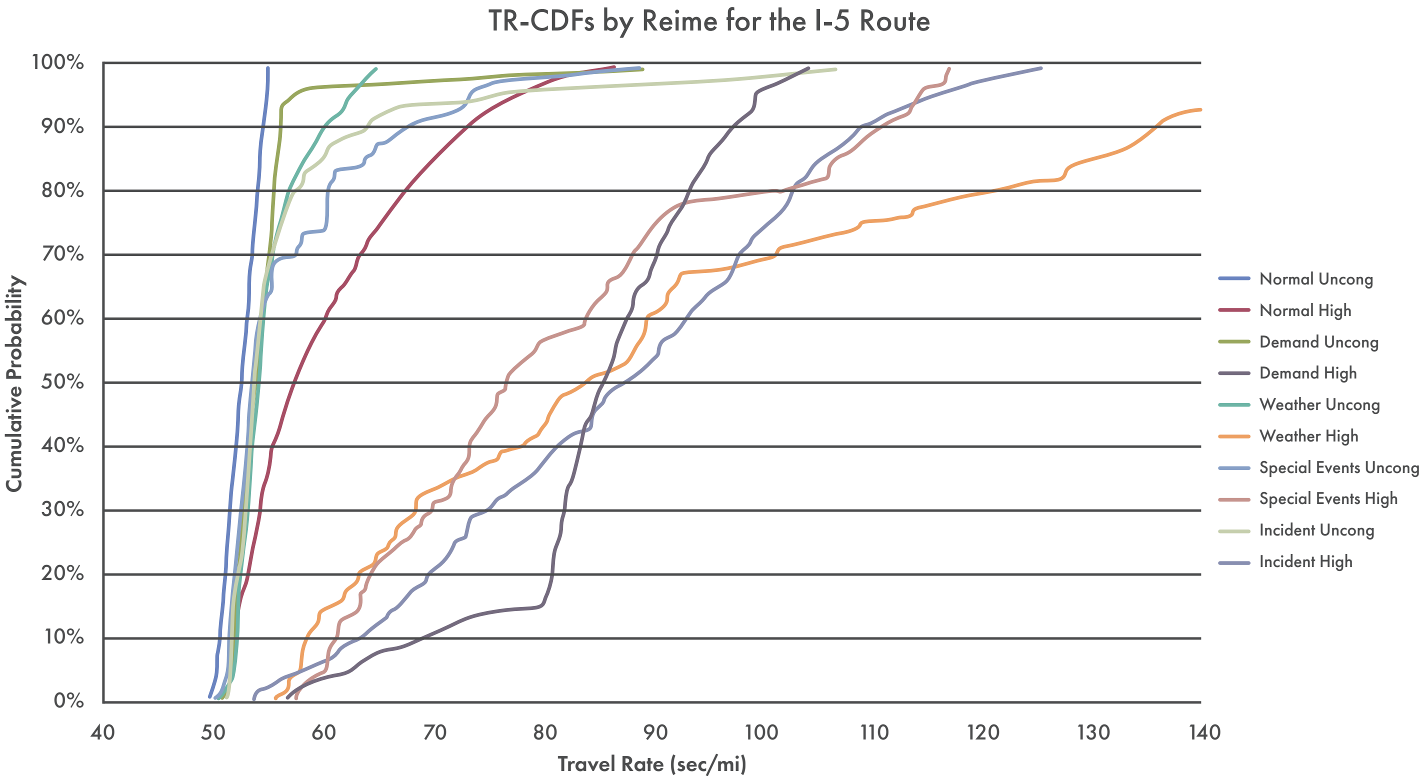



**Figure 7:** *CDFs of travel rates for various operating conditions.*

The most important concept is that all reliability metrics can be derived from the regime PDFs. PDFs completely describe the travel times (or travel rates). This means typical metrics for characterizing reliability (e.g., planning index, buffer index, average, median) can be computed based on PDFs. These PDFs can then be supplemented by ancillary data about the environment (e.g., weather, incidents) that exists in the time frame of the analysis. Travel time data providers sometimes provide key values from the PDFs such as the mean and 95th percentile.

## How to Use Travel Time Reliability

There is a difference in the level of detail that operators or engineers would find valuable, as opposed to the traveling public and decision makers. Some key recommendations on how to communicate reliability measures are listed below.

- For the public and decision makers, a single-value measure is the easiest to communicate, but it must also accurately capture network performance. This guide recommends median travel rate or travel time.
- Engineers and operators require more complex and powerful tools to paint a detailed picture of performance on a segment under a number of operating regimes. Travel Time Probability Density Functions (TT-PDFs) and CDFs are recommended.

### How Did CDOT Use the L02 Product?

The L02 product is a guidebook, rather than a software program, so agencies can make a custom solution that aligns with their existing data sources and can be flexible in scope depending on the agency's priorities. CDOT used the L02 guidebook to enhance understanding of travel time reliability, develop a TTRMS and improve existing travel time data systems. The TTRMS was designed to meet the needs of engineers, planners, operators, decision makers and the traveling public.

## 2.2. Incorporating Reliability into Planning & Programming Processes (L05)

The L05 product, *Guide to Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes* is intended for transportation planners, operators and system managers. It provides guidance on incorporating various travel time reliability metrics into funding/investing decisions for programs and projects. More specifically, the purpose of the L05 guide is to assist agencies with the following:

1. Understand and communicate reliability.
2. Identify tools and methods to track system reliability.
3. Begin to incorporate reliability into existing analysis tools.
4. Identify emerging analysis tools that better help agencies evaluate reliability and make program and project investment choices that address the system reliability.

### Introduction

As previously described, variability in travel times comes from several sources of congestion. There is real value for decision makers to understand these sources of variability and how different responses impact travel conditions. It is important that the planning process considers and addresses sources of congestion beyond just capacity projects.

Traditional planning and programming are structured to plan for large capacity improvement projects. Investments in operations and management (e.g. coordinated signal timing, ITS installations, incident response) aren't typically considered in the same level of decision making, but they should be. Both are imperative to addressing congestion problems.

To ensure reliability is addressed with a collaborative planning approach, there are a number of institutional arrangements that can be made:

- Institutionalize establishing reliability goals, identifying changes to business practices, implementing new processes, and measuring outcomes against reliability goals.
- Develop a collaborative and coordinated effort among many transportation organizations and within key units of the organization.
- Collaborate with other agencies to achieve respective goals and objectives.
- Address differences in perspective, institutions, and funding between different stakeholders such as engineers, operators and planners.

This will help planning, programming, and operating managers identify the data, tools, and methodologies for examining reliability. It establishes a framework to integrate reliability into planning and programming.

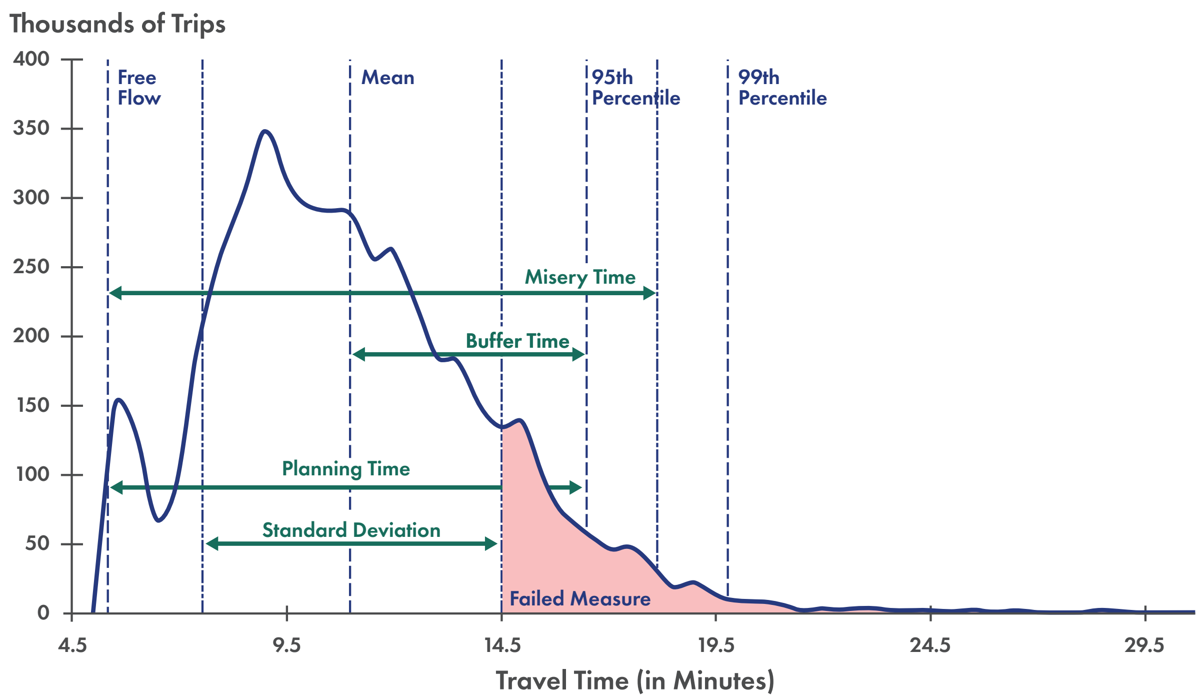



**Figure 8:** *Travel Time distribution and performance measures.*

## Measuring and Tracking Reliability

Well-defined reliability measures based on quality, supporting data are critical to understand and communicate how a transportation system is performing. Performance measures are vital to monitor function, set program funding levels and prioritize projects. They also provide an opportunity to compare unlike programs or benefits; such as comparing capacity project benefits to operations project benefits. Performance measures help identify the right combination of strategies to address transportation needs. As previously discussed, travel time distributions in the form of PDFs allow for a variety of travel time metrics to be calculated. **Figures 8 and 9** show different travel time metrics that can be calculated using PDFs.

It is the role of planners to experiment with different travel time metrics and determine which ones are best suited to their use cases. For example, the Knoxville Regional Transportation Planning Organization measured Planning Time Index (PTI) along with incident clearance time. The goal was to correlate improvements in time clearing traffic incidents to improved PTI.

The best way to measure reliability is to monitor travel times and archive them in a database that can then be analyzed across a wide range of conditions. The TTRMS can augment this travel time data with information about non-recurring congestion.

| Measure | Calculation | Description |
|---|---|---|
| Planning-Time Index[a] (PTI) | $\dfrac{\text{95th Percentile of TT}}{\text{Free Flow TT}}$ | The extra time required to arrive at a destination on time 95% of the time. Can be calculated for trips, corridors, or segments. The PTI is the recommended measure because it gives intuitive and consistent results. |
| Buffer-Time Index[b] (BI) | $\dfrac{\text{95th Percentile of TT} - \text{Average TT}}{\text{Free Flow TT}}$ ***(Could replace Average with Median TT)*** | The extra time required to arrive at a destination on time 95% of the time, compared with average or median travel time. A BI of 1.5 indicates that 95% of the time, it will take you 50% more time to arrive at your destination than it would under average conditions. |
| Standard Deviation | $\sqrt{\dfrac{1}{N}\sum_{i=1}^{N}(TT_i - \text{Average TT})^2}$ | The variation in travel time compared with the average. A standard deviation of 5 minutes indicates that it is not unlikely for it to take 5 minutes more to travel than it would during average congestion. |
| Semi-Standard Deviation | $\sqrt{\dfrac{1}{N}\sum_{i=1}^{N}(TT_i - \text{Free Flow TT})^2}$ | The variation in travel time compared with free flow. A semi-standard deviation of 5 minutes indicates that it is not unlikely for it to take 5 minutes more to travel than it would during uncongested conditions. |
| Failure Measure | $\dfrac{\text{Trips with TT} < 1.1 \times \text{Median}}{\text{Total Trips}}$ | The percentage of trips arriving on time. A failure measure of 85% indicates that 85% of trips are arriving on time. |
| Misery Index | $\dfrac{\text{Average of the Highest 5\% of TT}}{\text{Free Flow TT}}$ | How much longer it takes to travel on the worst 5% of all trips. A misery index of 4 indicates that the worst trips take 4 times as long as they would if it were uncongested. |

**Figure 9:** *Travel time measures that can be derived from PDFs.*

## Incorporating Reliability in Policy Statements

Agencies should establish that travel time reliability is a core strategic goal or objective. Agencies can take steps to address reliability in policy statements[2] by working with the public and stakeholders to determine user needs and setting goals to reflect those needs. **Figure 10** diagrams different levels of policy statements; agencies must determine which is the appropriate level to incorporate reliability goals. At what level the agency chooses to incorporate reliability depends on agency priorities and preexisting conditions.

| Description | Element | Approach to Incorporating Reliability |
|---|---|---|
| Broadest statement. Identifies the purpose of the organization. | *Vision* | Reliability included only if it is a top agency priority. |
| Broad statement that identifies how an agency delivers the vision. | *Mission* | Reliability may be included if it is a major issue impending the agency. |
| Short statements describing a small set of the most critical issues that an agency is addressing. | *Goals* | Reliability included if a significant issue. |
| Additional specificity for the goals. | *Objectives* | Reliability commonly addressed. |
| Steps to implement the goals and objectives. | *Policies, Strategies, Actions* | Actions to address reliability included. |

**Figure 10:** *Hierarchy of policy statements where agencies could incorporate reliability.*

## Evaluating Reliability Needs and Deficiencies

The first step is to understand the extent of reliability deficiencies and needs, such as when travel times are least predictable or what would it cost to address existing deficiencies. The outputs of this process (e.g., maps, charts, and figures) provide background when developing policies, setting the size of the reliability program, and prioritizing projects. A key goal is to help policymakers and stakeholders understand reliability needs and deficiencies so that policy statements can be substantive, funding levels are appropriately set for operations, and maintenance programs and projects are prioritized in a data-driven way.

[2]*Used broadly to describe all strategic statements that direct transportation system investments*

While performance measures describe how well a system is performing, thresholds are required to identify reliability issues. Reliability can vary greatly across locations, time of day and time of year, so there is no standard threshold that will indicate when reliability is unacceptable. Different users may have different thresholds; for example, it may be acceptable for the average commuter to be late a couple times a month, but for freight it may be unacceptable to be late at all. For these reasons, an iterative approach to setting thresholds at the corridor level is recommended. Once thresholds are set, they can be used to quickly compare and identify reliability deficiencies. SHRP2 guidance recommends using maps with color-coded thresholds to quickly identify deficiencies and understand the geographic scope. The key point is that thresholds need to tell a story that stakeholders and agency staff can easily understand.

### Incorporating Reliability Measures into Program and Project Decisions

A goal of the planning process is to inform agency investment decisions. There are three levels at which this takes place: The Program Trade-offs level, Project Prioritization level and Project Alternative level. Travel time reliability can be incorporated to each level the following ways:

1. **Program Trade-offs:** This determines how much funding to provide to each program. Reliability measures can help evaluate how to fund competing programs that affect reliability such as operations and maintenance, safety, capacity, etc. Typically, agencies distribute funding to programs based on federal and state requirements as well as historical practice. Reliability measures can help decide funding as part of a long-range plan with clear influence on Statewide Transportation Improvement Programs (STIP).

2. **Project Prioritization:** How to select priority projects within or across programs. Use reliability performance measures alongside other measures to identify a constrained list of projects to be implemented, typically in the form of a STIP.

3. **Project Alternative Selection:** How to select the preferred alternative among location specific projects. Reliability performance should be considered alongside other measures to ensure the preferred alternative addresses the full set of concerns.

### How Did CDOT Use the L05 Product?

The L05 guidebook was used to enhance CDOT's use of reliability performance measures (both existing measures and measures provided by the TTRMS) in decision making. The guidebook established a common understanding among the SHRP2 working group stakeholders and provided them with best practices when considering corridor-level projects and project alternatives. The guidance also helped streamline and revise existing performance measure reports.

## 2.3. Summary

The SHRP2 L02 product is an in-depth guide to create a TTRMS – a tool to measure travel time reliability and understand the impacts from the seven sources of non-recurring congestion. Its primary function is to augment travel time data with information about non-recurring congestion, such as incidents, weather events and roadwork. The four major components are the data manager, computation engine, report generator, and the dashboard.

The data manager merges travel time data with non-recurring congestion data, the computation engine develops regime-based TT-CDFs, and the report generator allows users to query the TTRMS and generate reports or dashboards. TT-PDFs are the fundamental unit of travel time performance measurement and can be used to derive various travel time reliability metrics such as PTI. However, the CDFs can provide more intuitive insight into travel time distributions. Because the product is a guidebook rather than a software, the scope of the TTRMS can fit any agency's user requirements and existing data sources. The framework provided by the guidebook was used to design a TTRMS according to user needs.

The SHRP2 L05 product is a guide to integrate travel time reliability (from the TTRMS or other systems) into planning and programming decisions. It explains how travel time reliability measures can be used in capital projects such as STIPs to fund operations-focused projects. The measure used in reporting depends on the audience, and it is valuable to summarize performance measures so they can be clearly communicated to decision makers. Decision makers can understand sources of variability and how responses impact travel conditions. The planning process can then take advantage of a more holistic picture of congestion problems and prioritize projects that are more valuable investments.

Together, the L02 and L05 tools help users build a quality TTRMS and integrate the data into agency culture and decision making to maximize agency utility and budget.

# 3. TTRMS Methodology

The goal of the L02 project is to develop a TTRMS that evaluates the travel time reliability impacts from incidents, special events, work zones and weather events statewide. After initial planning stages, the development process was iterative, with the stakeholder working group providing use cases, feedback and direction. This section describes in detail the approach taken to develop the tool, data sources used, test corridors and pilot implementation.

## 3.1. Project Approach

### Planning

The initial planning stages consisted of a literature review, inventory of available data sources and developing an initial scope of work. The inventory was used to identify which congestion factors would have the most reliable data, and which travel time sources should be used. Based on the availability of non-recurring congestion data, the scope was limited to incidents, weather, work zones and special events. The scope was meant to be iterative and refined throughout the project.

Next, we created a methodology to select test corridors representative of the varying conditions across the state, using three functional classes and urban/rural area designation. Roughly the same number of events would be processed across pilot corridors of each roadway classification. The six classifications are:

1. Urban Interstate
2. Rural Interstate
3. Urban State Highway
4. Rural State Highway
5. Urban Freeway US Route
6. Rural Freeway US Route

## Proof of Concept

Using one event on one corridor – a two-month work zone on I-225 in the Denver Metro area – Excel was used to map out the basic calculations that the TTRMS would have to perform as a proof of concept. Next, Python was used to create a basic tool to automate this data merging process and provide a basic user interface. The pilot was reviewed with the stakeholder working group for feedback and direction and the TTRMS was refined accordingly.

## Building the Database

Following the successful pilot, the TTRMS was used to process all work zone events and archive the cleaned data in a TTRMS database. After reviewing the work zone database, the TTRMS was modified to process the remaining event types – Incidents, Special Events and Weather Events.

## Summary Tools

While the database was in development, work began on building the Database Query and Summary Charts modules of the TTRMS. These modules would be used to query and retrieve cleaned data and generate interactive HTML summary charts.

## Dashboards

Following the successful development of the Database Query and Summary Charts modules, the stakeholder working group decided an interactive dashboard would provide the best way to access and interact with the database. A Python library was used to develop a dashboard with different parameters and filters that could be applied. This dashboard replicated and enhanced the functionality of the TTRMS Summary Charts module and improved user experience.

## Summary

The TTRMS development process can be summarized in the following steps. The initial scope developed for work zones and used as a template for all four event types, is shown in **Figure 11**.

1. Complete a literature review, inventory of data sources, pilot corridors and TTRMS scope.
2. Create a proof of concept for one work zone event.
3. After success criteria is met, process all work zone events.
4. Modify the TTRMS to process incidents, special events and weather events.
5. Build a full database.
6. Create database queries and summary charts tools.
7. Create an interactive dashboard connected to the database.
8. Continually improve and refine the TTRMS before final release.

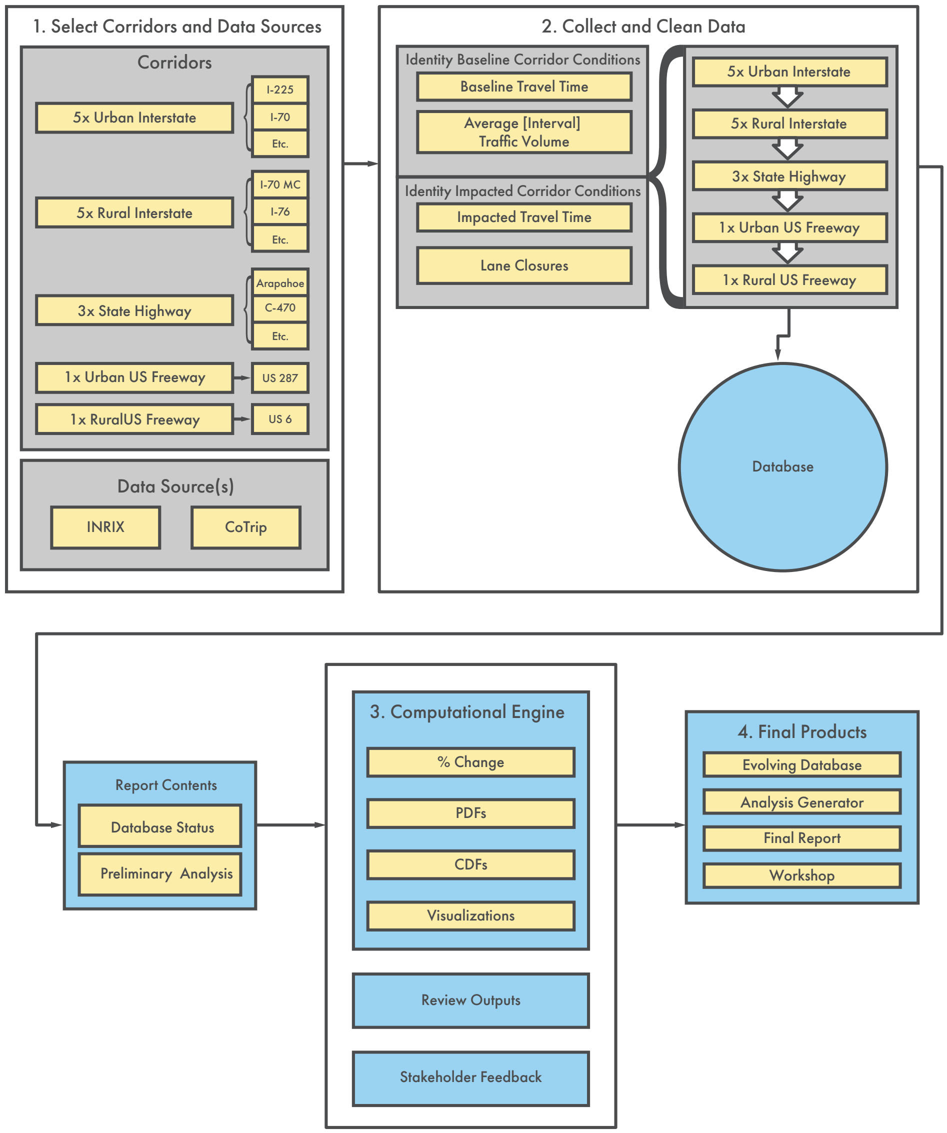



**Figure 11:** *TTRMS scope and process for Work Zones*

## 3.2. Data Sources

There are two key sources of data required for the TTRMS: A travel time data source, and a data source for the type of non-recurring congestion being studied. This section summarizes the data sources incorporated into the TTRMS project for travel time and the four sources of congestion.

### Travel Time Data

Two travel time data sources were used for the TTRMS: INRIX Massive Data Downloader (MDD) and the National Performance Measures Research Data Set (NPMRDS). INRIX, as well as HERE, are both probe vehicle data contributors to the NPMRDS. A key difference between the data is that the NPMRDS travel time segments include additional fields from the Highway Performance Monitoring System (HPMS) such as road class, urban class, rural class, and AADT. We modified our TTRMS to use travel time data from INRIX or the NPMRDS. The 'cleaned' data produced using NPMRDS data includes the additional HPMS fields, which may be helpful to the end user. The travel time data from both probe vehicle sources are reported using Traffic Message Channel (TMC) segments defined below.

### Congestion Data – Work Zones

For work zone congestion, CDOT CoTrip Construction Reports were used as the data source (see **Figure 12**). The road work closure logs can be downloaded from the site as Construction Reports. Relevant information in the reports include planned work start and end times, description, and daily lane closures. This was the most accurate and comprehensive data source for identifying road work times. However, the reports are only available in PDF format and fields such as closure or work description are inconsistent and require manual input into the TTRMS.

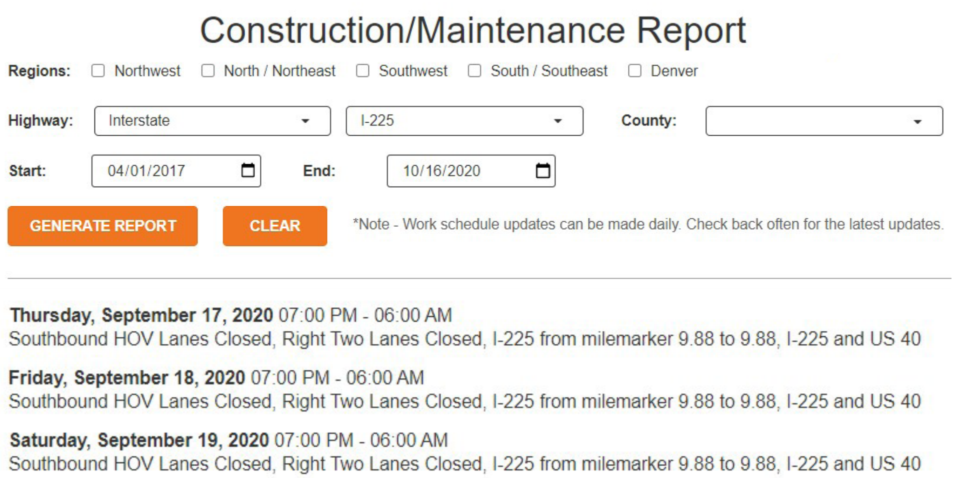



**Figure 12:** *CDOT Construction/Maintenance Report and output*

### Congestion Data – Incidents

There are currently three datasets available that contain crash/incident data: the CDOT COGNOS Event Audit Report, the CDOT COGNOS Courtesy Patrol Report, and Vision Zero Suite. Initially, the Vision Zero Suite was selected because the crash data are reviewed and revised by the Colorado Department of Revenue (DOR) for accuracy. However, the DOR review process creates a significant reporting lag, and the most recent data are generally at least six months old. Ultimately, the COGNOS Event Audit report was selected due to its regular updates and level of detail. The COGNOS Event Audit report captures the incidents recorded by operators in Colorado's Advanced Traffic Management System (ATMS), and includes event start/end time, mile marker, closure, incident type and incident subtype information.

### Congestion Data – Weather Events and Special Events

Both weather events and special events are gathered using the COGNOS Event Audit Report. These reports provide the location, mile marker, event subtype and time frame of the impacts. As weather events are only ever reported as warnings, Weather Underground's location-specific historical data were used to verify that the weather event cited did occur. Special events were verified using local news sources when necessary.

## 3.3. Test Corridors and Events

For each congestion source, at least 30 test corridors were selected that cover the full range of roadway classes: urban interstates, rural interstates, urban state highways, rural state highways, urban freeways and rural freeways. 30-40 test corridors for each congestion source were processed and uploaded to the database.

## 3.4. Pilot Implementation Details

### Work Zone Proof-of-Concept

We began TTRMS development by selecting one congestion source (work zones) and a pilot corridor to develop the processes for computation and processing. Using Python, we built, tested and refined a program to merge and clean travel time and work zone data, perform calculations to generate baseline and impacted travel times, create graphical outputs, and place the cleaned data and outputs in a database to be queried for summary metrics.

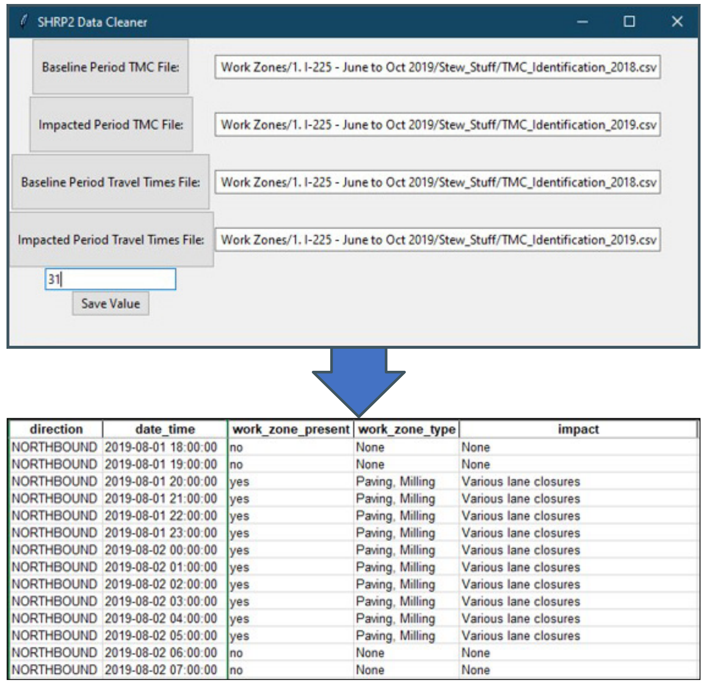
1. **Identify Data Sources:** For travel time data, we selected INRIX's MDD. The MDD provides the 'raw' mean travel times from probe vehicles and has an option to use real-time data only; i.e., without any historical/cleaned data. The CoTrip report was selected because it provides detailed information regarding active work hours, work description, and lane closures.

2. **Identify Test Work Zone:** Using the Construction Report, we selected a resurfacing project on I-225 between I-25 and Parker Road (mile markers 0 to 4) to use for the pilot. Work hours were from roughly 8 PM to 5:30 AM, Sunday – Thursday, June 2019 to October 2019. INRIX's heat maps and performance summaries were used to determine corridor limits impacted by congestion. We selected I-225 from I-25 to Colfax Avenue (mile markers 0 to 9), about 5 miles longer than the work zone.

3. **Clean Travel Time Data:** Python was used to create a tool that merges the TMC segment information with travel times to create a usable table of travel times by direction for every time interval. It prompts the user to input details from the construction report. Four fields are added to the travel time data: "impact present", "impact type", "impact subtype," and "corridor response." See **Figure 13**.

4. **Clean Baseline Travel Time Data:** A number of different methodologies were tested to calculate a baseline travel time that the work zone travel times would be compared against. The selected methodology was the *monthly average travel time for that day of week and time interval, of the previous month*[3]. The TTRMS Data Cleaner described above was used to generate a baseline travel time file. The output of steps 3 and 4 are a clean data set that is ready for analysis.

5. **Create Graphical Outputs:** The first output from this cleaned data set is an interactive HTML chart for the user to inspect an individual work zone, as shown in **Figure 14**. For clarity, it shows only the active work zone times, baseline travel times and percent change between the two. The date range is interactive. CDFs for the work zone travel times are also generated (not shown in Figure 14).




| direction | date_time | work_zone_present | work_zone_type | impact |
|---|---|---|---|---|
| NORTHBOUND | 2019-08-01 18:00:00 | no | None | None |
| NORTHBOUND | 2019-08-01 19:00:00 | no | None | None |
| NORTHBOUND | 2019-08-01 20:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-01 21:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-01 22:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-01 23:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-02 00:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-02 01:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-02 02:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-02 03:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-02 04:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-02 05:00:00 | yes | Paving, Milling | Various lane closures |
| NORTHBOUND | 2019-08-02 06:00:00 | no | None | None |
| NORTHBOUND | 2019-08-02 07:00:00 | no | None | None |

**Figure 13:** *TTRMS Data Cleaner*

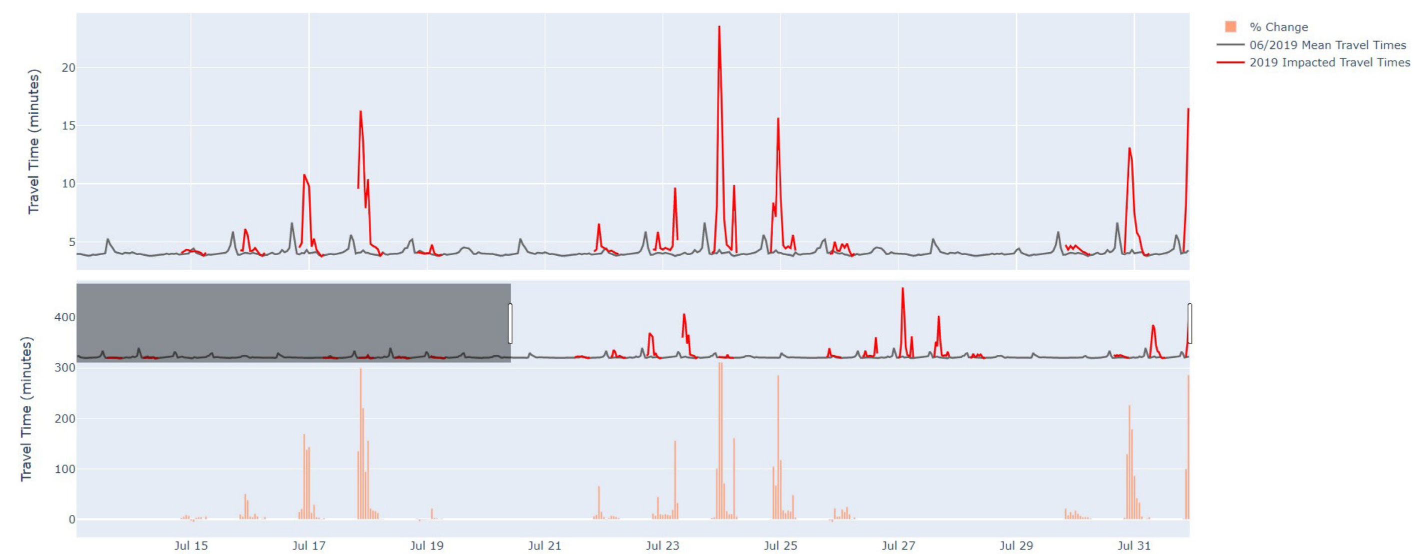



**Figure 14:** *I-225 Work Zone HTML Output.*

[3] *For example: the 'baseline' August travel time for Monday from 8AM – 9AM is the average of August 6th, 13th, 20th, and 27th, 2018 from 8AM – 9AM.*

### Populating the Work Zone Database

The I-225 work zone pilot was reviewed with the stakeholder group to receive feedback on the process and methodology. With the working group's approval, we began populating a work zone database. The TTRMS data cleaner was used to merge and clean approximately 40 work zone events and store the cleaned data sets in the Non-Structured Query Language (NoSQL) database MongoDB.

### Modifying the TTRMS for Incidents, Weather, and Special Events

In tandem with populating the work zones database, we began modifying the TTRMS to look at incidents, weather, and special events. As part of this we developed a data dictionary listing all possible event types, subtypes and closure types. The TTRMS data cleaner was modified to accept travel times in epochs of 5-minutes for incidents, 15-minutes for special events and weather, and 1-hour for work zones. We used COGNOS Event Audit Data to identify each impact type on a pilot corridor, replicating the process used for work zones.

### Modifications and Improvements

A number of modifications to the TTRMS were implemented following the pilot implementation to improve the user experience, address unanticipated problems or add new functionality. The most significant modifications – ones that were not anticipated in the scope – include the following:

1. **Segment Length Errors:** If the TMC segment lengths are not the same between the baseline period and impact period, an error box will appear and identify the difference in length. This was developed after encountering scenarios where the TMC segments did not match between the baseline and event time periods, due INRIX map updates.

2. **Error Handling Loops:** The TTRMS generates error warning pop-ups when common errors are detected in the INRIX files, such as missing time intervals or erroneous travel directions.

3. **Modified Travel Time Charts:** The per-event travel time charts went through a number of iterations. In the final version, percent change is shown on a separate subplot, includes negative values and chart titles are auto generated.

4. **Violin Plots:** The initial summary charts tool provided box plots to show the distribution. These have been replaced with violin plots, which show the same information, but also provide a visual of how the data is distributed.

5. **Dashboard:** An interactive dashboard, described in detail in section 4.4, was developed to make the TTRMS summary data significantly easier for the stakeholder group to access and distribute.

As a research project, the TTRMS established a methodology that can be easily replicated and implemented on a much larger scale for analyzing the travel time reliability impacts of non-recurring congestion. Navjoy is currently working with CDOT to integrate the TTRMS data model into the Real-Time Data Hub. The final TTRMS is shown in Section 4. The TTRMS and all documentation will be available via the project GitHub repository.

## 3.5. Next Steps

CDOT has two significant projects related to travel time/operations data currently underway:

1. The Real-Time Data Hub
2. Advanced Data Analytics Platform (ADAP)

The Real-Time Data Hub will aggregate and standardize the real-time data from all CDOT systems. Systems contributing to this hub will include INRIX, NPMRDS, CTMS, Waze and others. The ADAP will be used to develop data models, analytics, dashboards and other insights using this data. The standardization of all data sources greatly expands the types of data models that can be developed. The initial proof of concept for ADAP is in development using methodologies from CDOT's Operations Level of Service (OLOS) use cases project. The objective is to create data models in ADAP for the use cases defined in the OLOS project.

The goal of the OLOS use cases is to establish a comprehensive performance measurement method to evaluate facility performance relative to the overall performance of that facility type statewide. Six specific OLOS use cases have been identified:

1. Identification of bottlenecks
2. Identification of improvement potential vs. other similar facilities
3. Operations evaluation and assessments
4. Incident/event management and corridor/construction project evaluation and management
5. Efficient analysis for funding pool approvals
6. Project prioritization for long-term planning

Developing the data models requires clearly documenting the data dependencies, cleaning, calculations and aggregations required for each use case. The data models for Use Cases 1 through 3 were developed earlier in the OLOS project and created a template to develop additional data models. It was determined that Use Case 4 significantly overlapped with the TTRMS methodology developed as part of this SHRP2 project. Navjoy provided a detailed summary of the TTRMS data model and recommendations as to how it can be adapted to the ADAP for Use Case 4.

The standardization of data types has the potential to greatly expand the capability of the TTRMS to process large amounts of historical data, use additional data sources and update in real-time. The data model was developed with these additional capabilities in mind, as opposed to exactly recreating the current process. The data models for Use Cases 5 and 6 were also developed but use only INRIX data and a methodology similar to those previously developed for Use Cases 1-3.

One key difference between the current TTRMS methodology and proposed ADAP methodology is the use of INRIX's historic average speed[4] and reference speed[5] values to establish baseline travel times. Using either of these values to calculate baseline travel times removes the need to download a separate "baseline" time period. This new baseline methodology was selected for two reasons: 1.) It removes issues encountered with TMC updates; and, 2.) because this data is already provided by INRIX with the impact period data, it is much less complicated to automate. The Historic Average Travel Time (in minutes) calculation is shown in **Figure 15** below. The Percent Change in Travel Time (against the historical travel time) is shown in **Figure 16**.

$$TT_{AVG} = \left( \frac{TMC\ Segment\ Length}{Historical\ Average\ Speed} \right) x\ 60$$

**Figure 15:** *Historic average travel time calculated from historic average speed data.*

$$TT\Delta\%_{AVG} = \left( \frac{Impacted\ Travel\ Time - Travel\ Time_{Historic\ Average}}{Travel\ Time_{Historic\ Average}} \right) x\ 100$$

**Figure 16:** *Percent change in travel time using the historic average travel time.*

In the future, when ADAP and the Real-Time Data Hub are fully functional, the dashboard for Use Case 4 will replace the TTRMS.

*Note that the methodology was proposed as of October 2020 and is currently being reviewed; the final OLOS Use Case 4 methodology and dashboard may be different.*

[4] *The historic average speed is calculated for each segment for that hour of day and day of week using all available historical data.*

[5] *The reference speed is the calculated free flow mean speed for that segment; it is calculated based upon the 85th-percentile of all observed speeds for that segment for all time periods.*

# 4. TTRMS Tool

The TTRMS consists of four distinct components:

1. **Data Cleaner:** This module cleans travel time raw data, merges impact data fields, creates a baseline period and checks for TMC segment errors. The resulting "cleaned event" can be viewed in a travel time chart to determine if it appears reasonable. If it is reasonable, it can be uploaded to the Database.

2. **Database:** The "cleaned event" spreadsheet is uploaded to the web-hosted database. It is accessible from the web anywhere with a secure connection key, which can be entered into the TTRMS.

3. **Reporting Database Query/Graph Generator:** The same secure connection key can be used to access the database to retrieve a .csv file of clean travel time data meeting selected criteria. The user can then interact with this file using the Graph Generator to create violin plots and CDFs. Combined, these modules allow the user to make comparisons according to corridor type, urban/rural classification, impact type and subtype, time of day, time period, lane closure, and more.

4. **Reporting (new) – Dashboard:** An interactive dashboard was developed that replicates and enhances the Database Query/Graph Generator. This functionally replaces the summary charts module as it is significantly easier for users to access, updates in real time and supports more advanced filtering criteria (e.g., time periods, day of week, corridor ID). The user can select from two parameters and a number of filters to update the violin plots and CDFs in real-time.

Each component is described in further detail below.

## 4.1. Data Cleaner

The Data Cleaner module is responsible for all data cleaning, merging, calculations and quality assurance/quality control. Sequentially, it does the following:

1. Merges and cleans the travel time data sets from INRIX or NPMRDS,
2. Calculates the baseline travel times,
3. Alerts the user to any data errors encountered such as mis-matched TMC segments or missing travel times,
4. Prompts the user to input the impact type, subtypes and closure information for merging with the travel time data,
5. Generates an interactive HTML travel time chart and CDF for review,
6. If any anomalies are detected, additional investigations may be necessary; in some cases, a new baseline period may be selected for reprocessing, and
7. Upload to database.

The user interface for the Data Cleaner is shown in **Figure 17**.

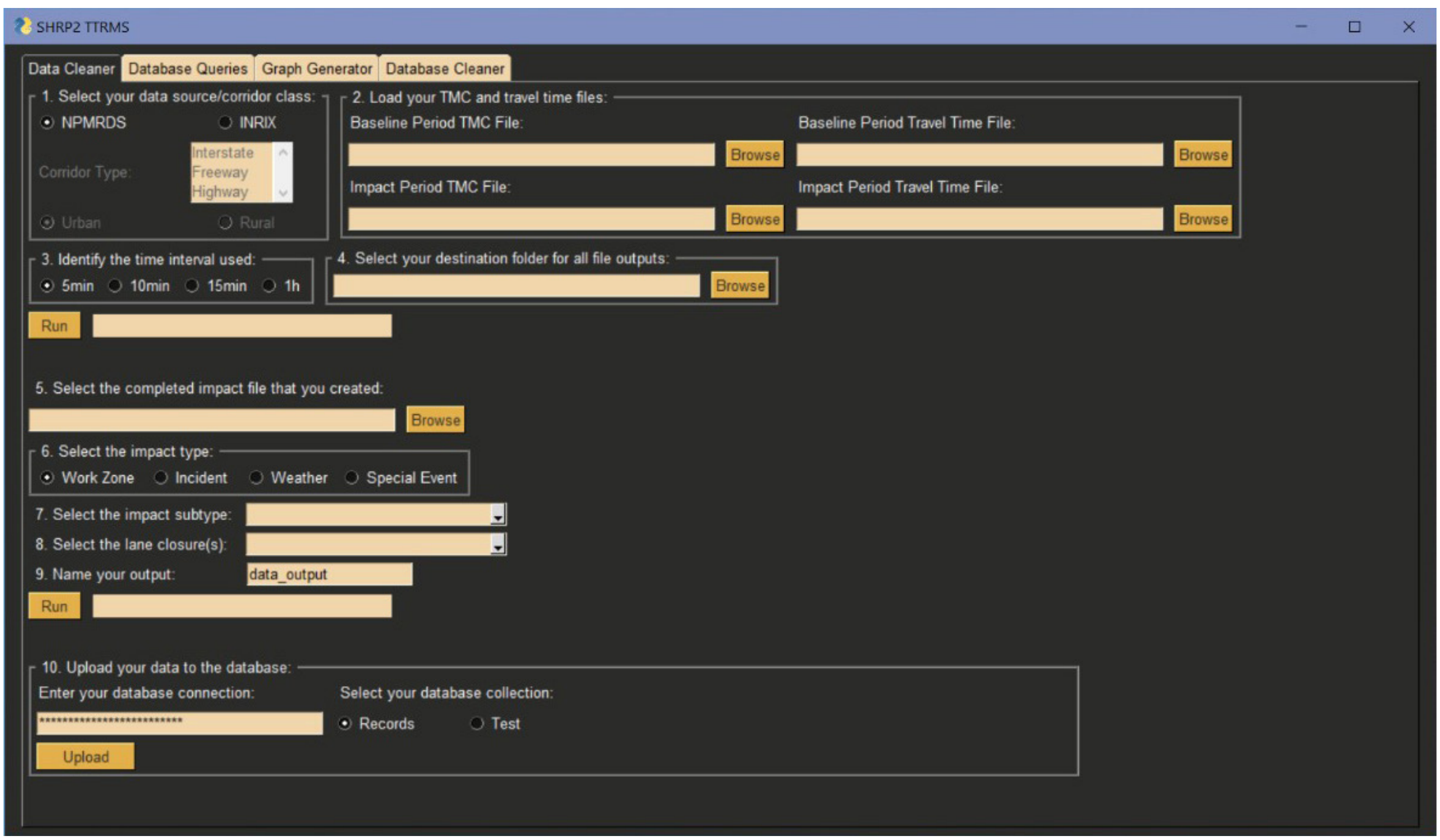



**Figure 17:** *TTRMS Data Cleaner module.*

## 4.2. Database

There is a connection between the TTRMS and a web-hosted database. When the user uploads an event after cleaning the data, the data are stored and managed on an Amazon Web Services (AWS) server hosting a NoSQL database called MongoDB. Unlike Structured Query Language (SQL), MongoDB is a non-relational database which makes it flexible, scalable, and, typically, faster than a relational database.

This database can be (and is by default) connected to the Database Queries module, which allows the user to retrieve a cleaned dataset from the database in a .csv file. Filters can be applied to limit the data retrieved. The dashboard is also connected to this database; when the database is updated the new data will be reflected in the TTRMS dashboard.

## 4.3. Database Query and Summary Charts

The Database Queries module of the TTRMS allows the user to retrieve cleaned travel time data from the database in a .csv file. This .csv can then be graphed using the summary charts tool or used for a custom analysis. The database query filters include: Corridor type, urban/rural, travel direction, corridor ID, impact type and subtype, corridor response (roadway closure), date range, and day of week. The user interface for Database Queries is shown in **Figure 18**.

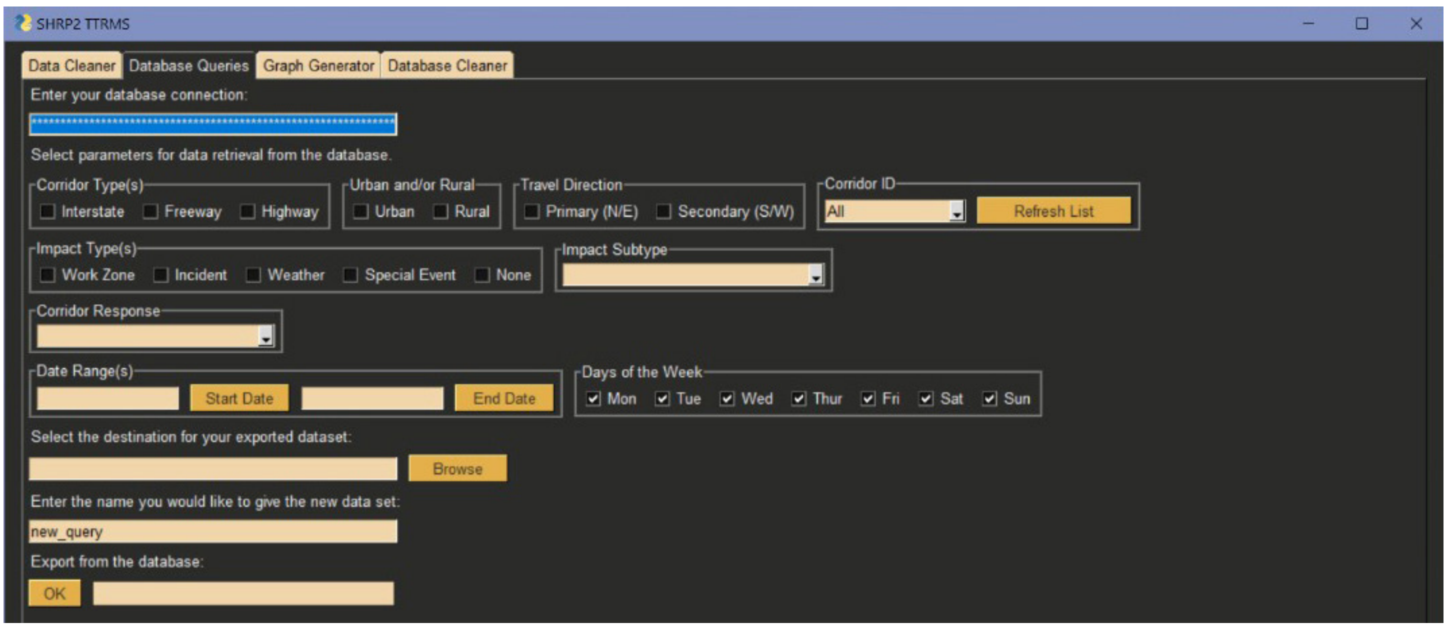



**Figure 18:** *TTRMS Database Queries module.*

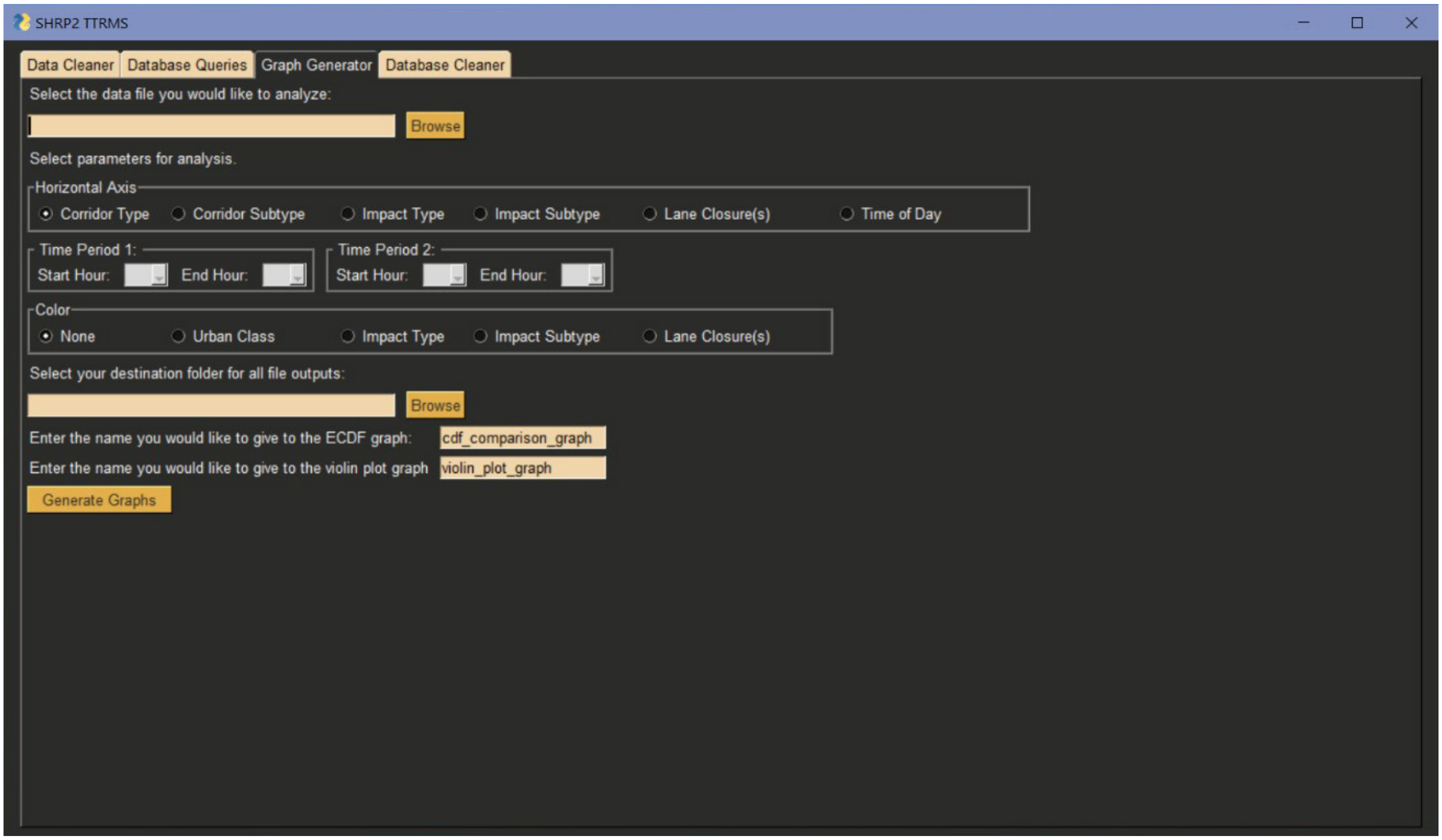



**Figure 19:** *TTRMS Graph Generator Module.*

The Graph Generator module (**Figure 19**) creates interactive HTML charts from the .csv files retrieved from Database Queries. From the TTRMS the user selects different axis fields, time periods and color to visualize the data in a way that meets their specific use case. The travel time comparisons according to corridor type, urban/rural classification, impact type & subtype and lane closures. The Graph Generator creates two plots – a violin plot and a CDF – of the data. A violin plot is a combination of a box plot and density plot, as shown in **Figure 20**.

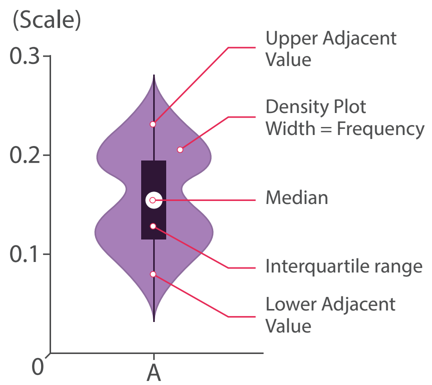



**Figure 20:** *Violin plot.*

## 4.4. Dashboard

The TTRMS database query and chart summary tools have been recreated as a dashboard that can be accessed over the web. The dashboard is shown in **Figure 21**. The dashboard was developed using the free tool Dash and has been distributed to the working group. It allows the user to interact with the full database to generate violin plots and CDFs. To help the user orient themselves and understand what travel time data are being analyzed, the count of travel time measurements by roadway is shown in a third plot at the bottom (**Figure 22**).

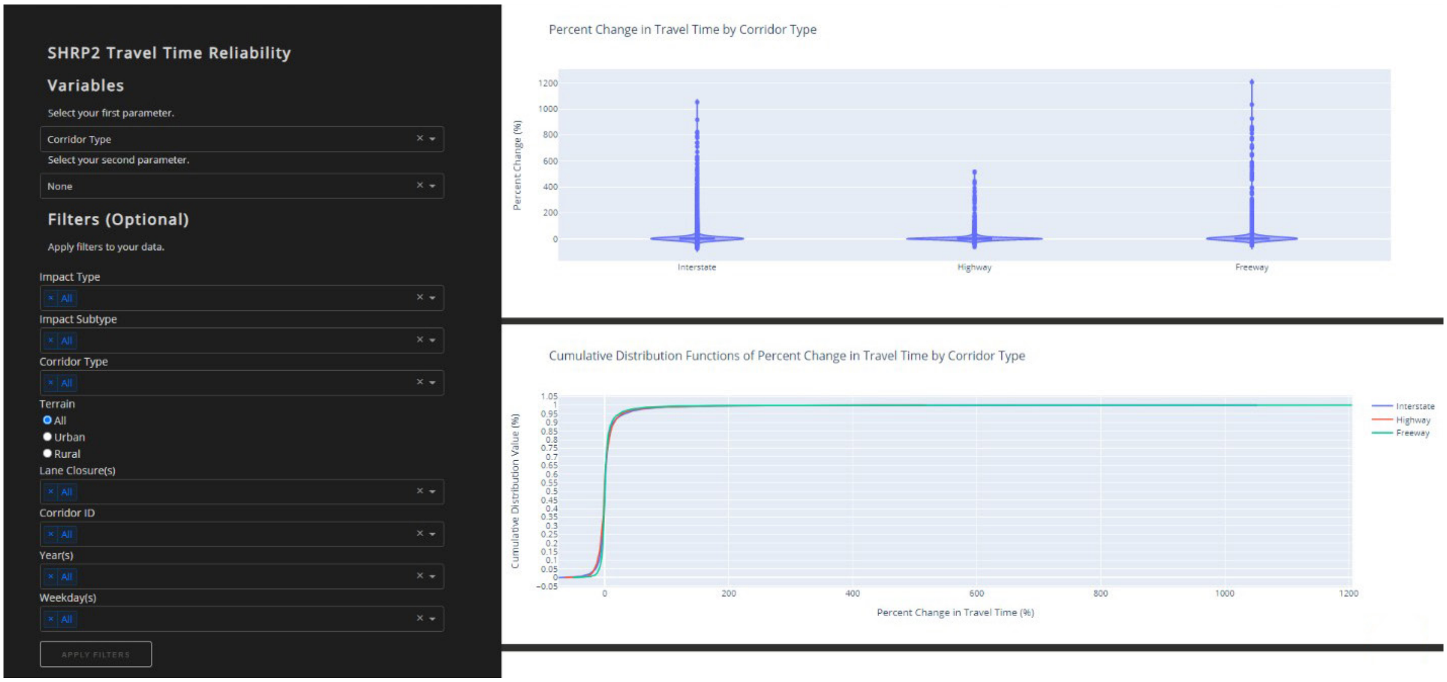



**Figure 21:** *TTRMS dashboard.*

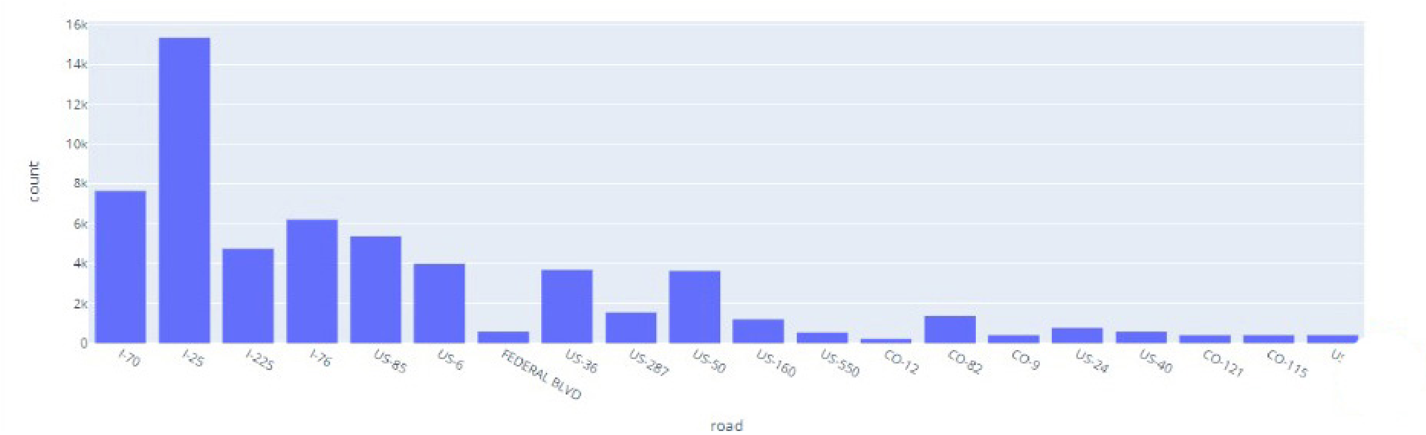



**Figure 22:** *TTRMS dashboard measurement count chart.*

In the dashboard, the user can select from two variables at a time, including corridor type, incident type/subtype, urban classification, and time of day. This can then be filtered further by impact type, subtype, corridor type, urban/rural, lane closure, corridor ID and time period.

Dash is a platform developed by Plotly that allows users to build data visualization applications entirely in Python for display in a web browser. With this platform, Navjoy has integrated much of the code already written for the TTRMS into a responsive, publicly available dashboard. The dashboard will be linked to the full SHRP2 database, so users can add and remove filters dynamically without having to download a database export.

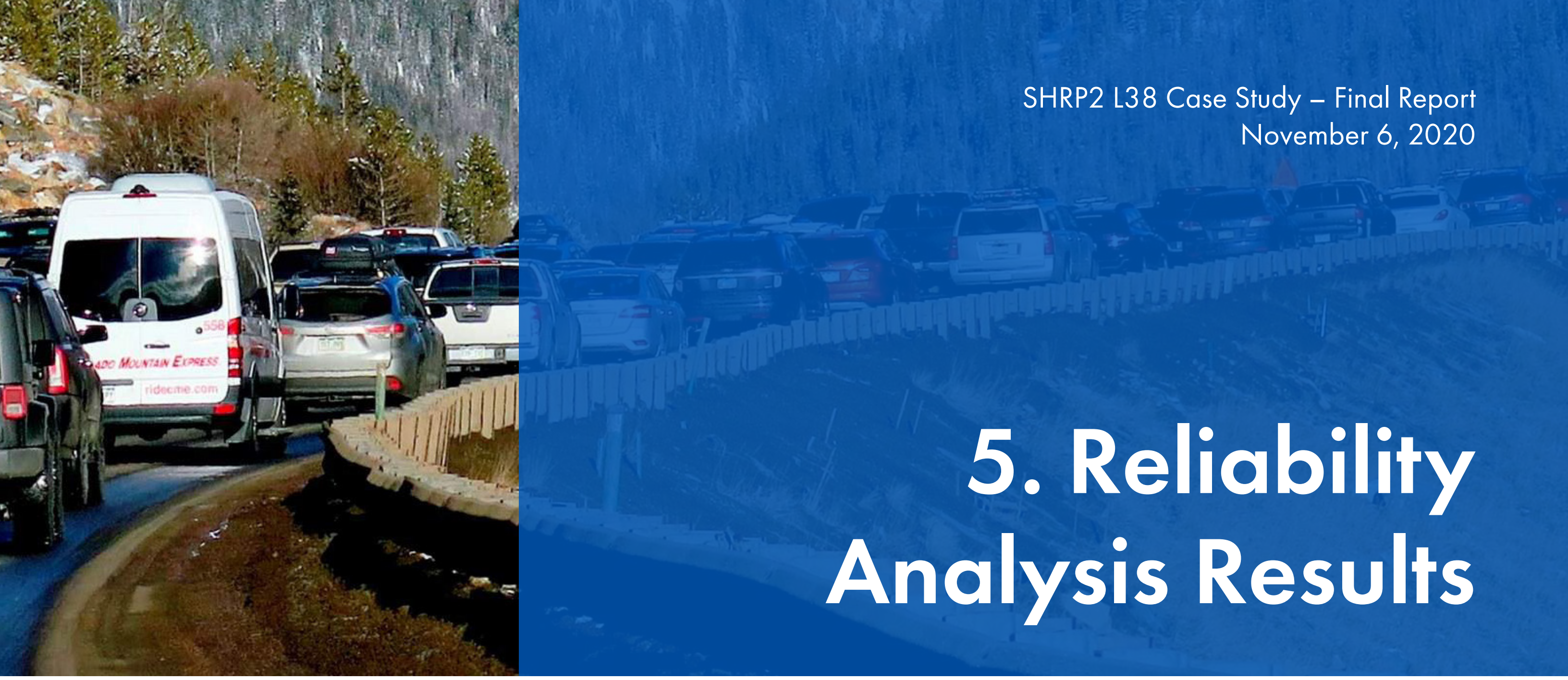
The Dash dashboard will not allow users to clean and upload additional travel time impact events to the database; it will only have access to the data collected prior to the completion of this project. We are still working to find the best way to distribute the TTRMS tool itself to the stakeholder group so additional events can be processed with the tool and uploaded after this project (see GitHub repository).

A statistical output table has been added to the dashboard for users to easily quantify results with key values from the distribution of percent change in travel times. The selected values will be the Mean, Median, Lower and Upper Quartile values, described below. See Table 2 for values from the database as it currently is, with no filters applied.

- Lower Quartile (Q1): The median of the lower half of a set of data.
- Median (Q2): Cuts the data set in half.
- Mean: Average value of the data set.
- Upper Quartile (Q3): The median of the upper half of a set of data.

### Table 2. Example of the percent change distribution table with preliminary results.

| Type | Q1 | Median (Q2) | Mean | Q3 |
|---|---|---|---|---|
| Work Zone | -2.5% | 0.4% | 6.8% | 4.9% |
| Incident | 0.4% | 8.5% | 73.3% | 67.7% |
| Weather | -2.5% | 0% | 2.0% | 3.7% |
| Special Event | -3.3% | 0% | 4.3% | 3.9% |



# 5. Reliability Analysis Results

In sub-sections 5.2 – 5.5, the travel time reliability impacts of work zones, incidents, weather and special events are analyzed using the figures generated by the TTRMS. For each impact type, the travel time reliability impacts are broken down by:

1. Urban/rural classification;
2. Impact subtype; and,
3. Lane Closures.

The analysis and figures were produced using the charts (violin plot, CDF, table of values) generated by the TTRMS dashboard. The first sub-section, 5.1, is the most high-level comparison of travel time reliability impacts by each impact type. The goal of this section is to identify the primary causes of travel time unreliability.

It should be noted that for our purposes, a "negative impact" on travel time insinuates a lower travel time, whereas a "positive impact" would represent an increase in travel time. Additionally, "most impactful" usually refers to the 75th percentile.

## 5.1. Comparison by Impact Types

We started our study broadly by examining the difference in travel time reliability between the four impact types: *work zones, incidents, weather, and special events* as well as a *none* baseline. The greatest increase in travel time was for *incidents*, which stood out amongst the rest. *Incidents* had a 67% change in travel time or less for 75% of travel time measurements. In comparison, the second highest, *work zones*, had only 4.9% change in travel time for 75% of the vehicles. There is a more than a 20-fold increase in the change in 75th percentile for *incidents* over the baseline.

On the opposite end of the spectrum, *weather* events showed the smallest travel impacts. When we compare *weather* with our *none* baseline, we noticed only a small increase. For instance, the mean of 1.87% for *none* and 1.99% for *weather* or the 75th percentile of 3.23% for *none* and 3.68% for *weather*. Similar to *weather, special events* proved to be not very impactful. When comparing with the *none* baseline, we see only a few percent higher change to travel time in the mean and 75th percentile.

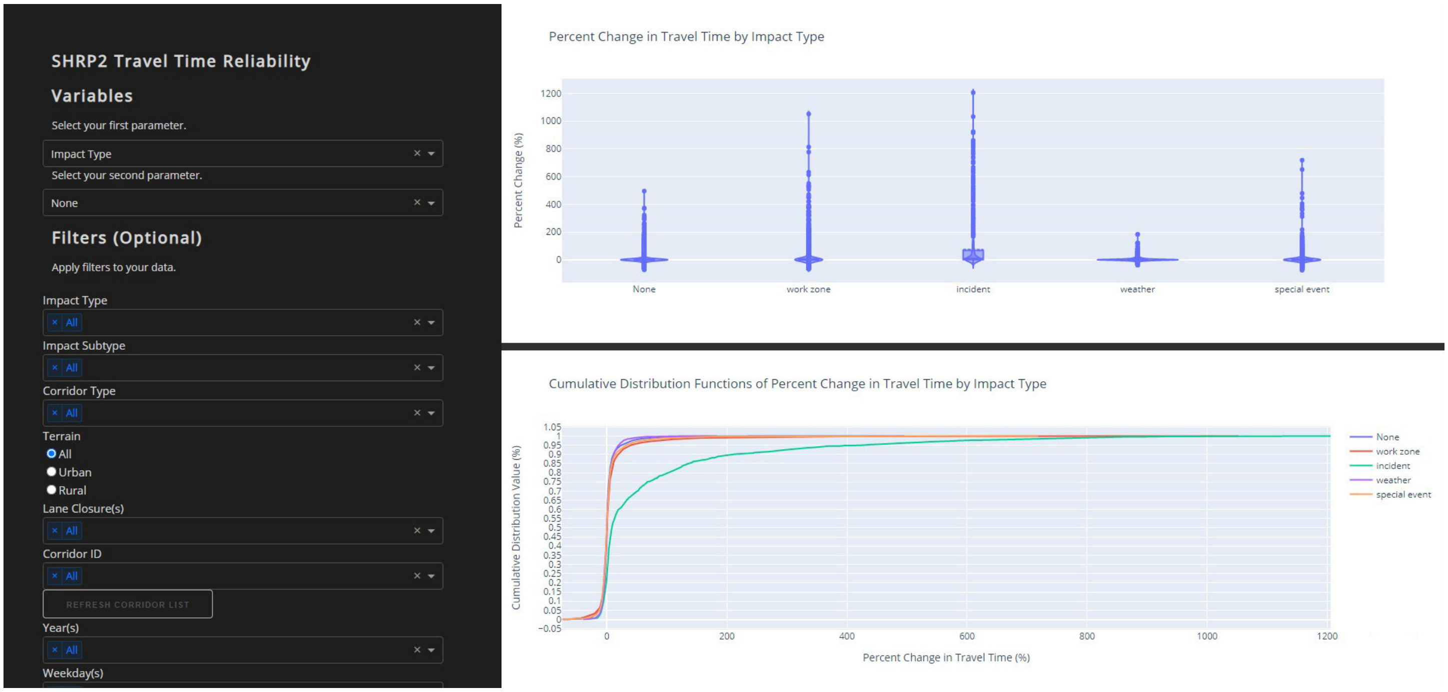



**Figure 23:** *Dashboard view of travel time reliability by impact type.*

## Table 3: Summary Statistics on Travel Time Reliability by Impact Type

| | None | Work Zone | Incident | Weather | Special Event |
|---|---|---|---|---|---|
| **Mean** | 1.87 | 6.84 | 73.33 | 1.99 | 4.26 |
| **SD** | 16.97 | 40.03 | 156.65 | 11.36 | 30.83 |
| **Min** | -72.66 | -66.68 | -31.71 | -39.20 | -74.64 |
| **25% (Q1)** | -3.37 | -2.51 | 0.38 | -2.53 | -3.32 |
| **Median** | -0.03 | 0.35 | 8.52 | 0.00 | 0.00 |
| **75% (Q3)** | 3.23 | 4.88 | 67.66 | 3.68 | 3.87 |
| **Max** | 495.65 | 1052.00 | 1205.76 | 183.19 | 718.52 |

# 5.2. Work Zones

## Work Zones by Urban/Rural Classification

In **Figure 24** the difference between urban and rural work zone classifications is illustrated. As shown in blue, rural work zones were more impactful than urban work zones. There was more than a twofold increase in the 75th percentile of for rural work zones over urban ones (6.3% to 2.7%, respectively). It should be noted that there are a small number of highly impactful, anomalous, rural work zone events causing the 'tail' of the blue violin to elongate.

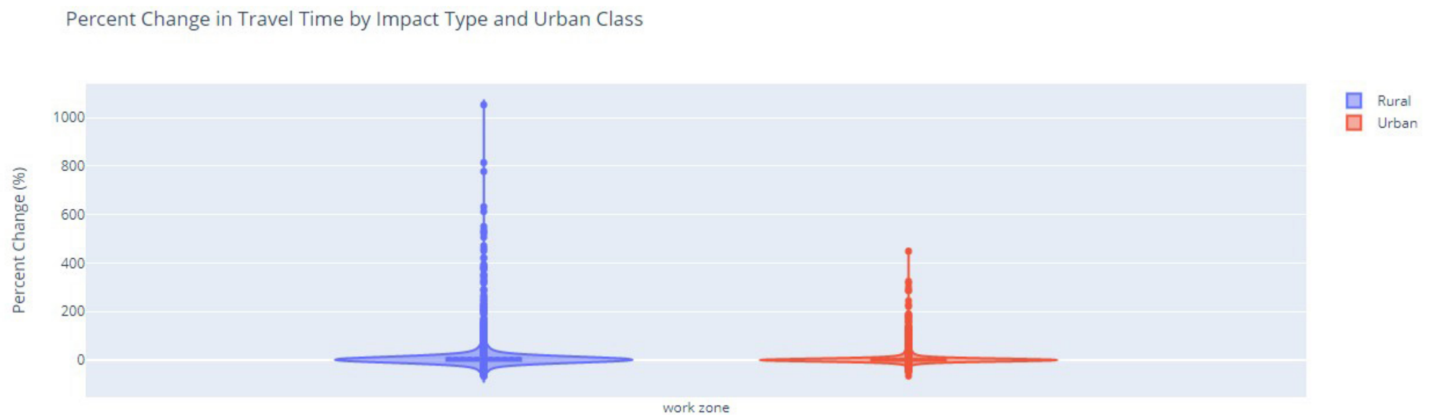




**Figure 24:** *Travel Time Reliability by Work Zone and Urban/Rural Classification.*

### Table 4: Summary Statistics on Travel Time Reliability by Work Zone and Urban/Rural Classification

| | Rural | Urban |
|---|---|---|
| **Mean** | 8.34 | 4.11 |
| **SD** | 46.05 | 25.42 |
| **Min** | -66.68 | -65.56 |
| **25% (Q1)** | -2.49 | -2.57 |
| **Median** | 0.96 | -0.25 |
| **75% (Q3)** | 6.32 | 2.71 |
| **Max** | 1052.00 | 448.14 |

## Work Zones by Sub Type

In **Figure 25** we can see how different work zone subtypes compare. *Construction* was much more impactful than *maintenance* activities. Averaging and comparing the *construction* subtypes, *road* and *bridge construction*, shows a 75th percentile of 8.3% versus 1.9% for averaged *maintenance* subtypes (*road, tunnel, bridge maintenance*); these maintenance subtypes had some of the lowest travel time impacts for all work zone subtypes. On the other hand, *road construction, bridge construction, paving,* and *IT/Fiber operations* were the most impactful event subtypes. This may have been due to the increased number of lane closures required for construction zones compared to maintenance zones.

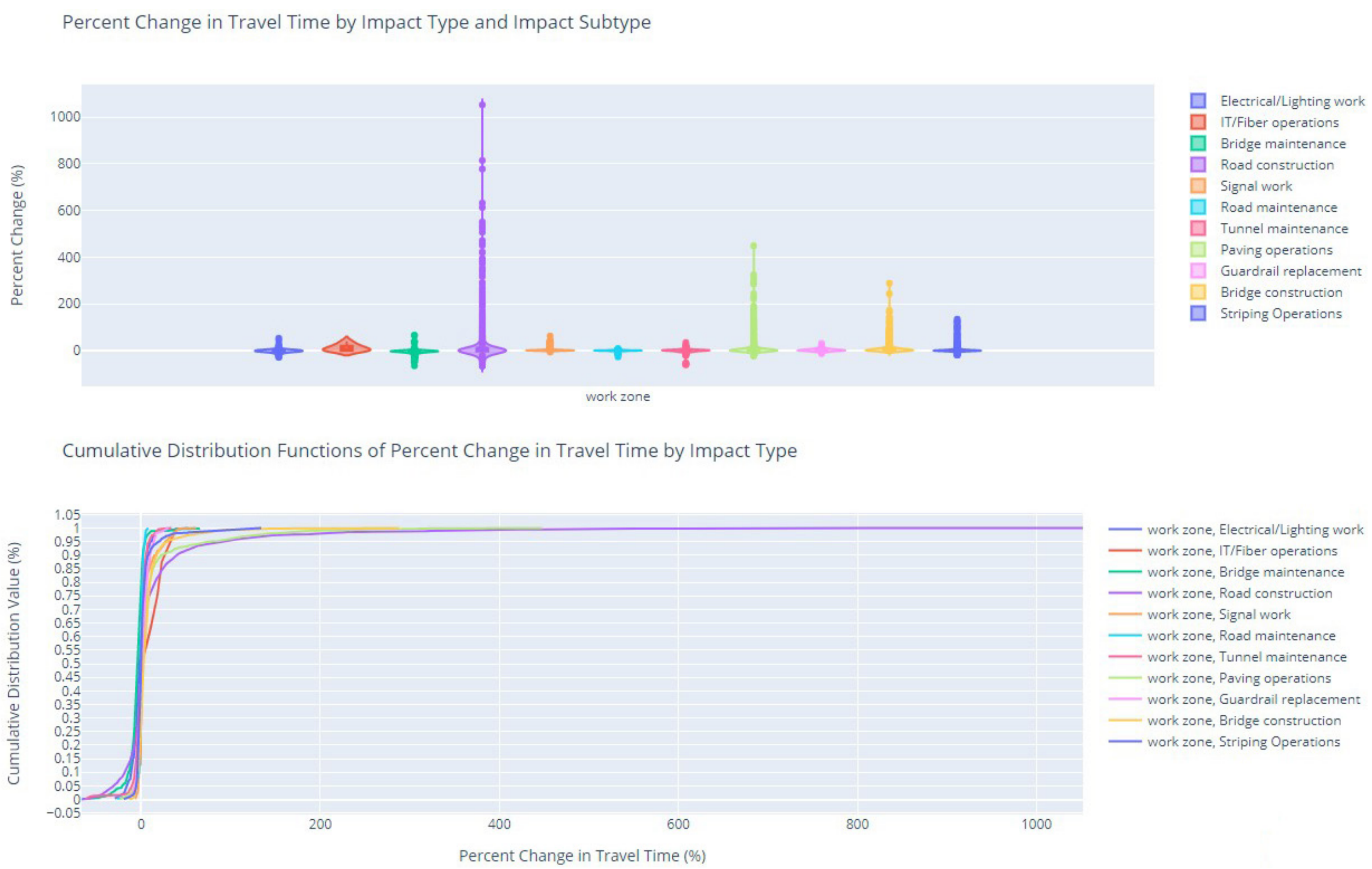



**Figure 25:** *Travel Time Reliability by Work Zone Sub Type.*

### Table 5: Summary Statistics on Travel Time Reliability by Work Zone Sub Type

| | Electrical/ Lighting Work | IT/Fiber Operations | Bridge Maintenance | Road Construction | Signal Work | Road Maintenance |
|---|---|---|---|---|---|---|
| **Mean** | -1.83 | 11.13 | -5.20 | 13.03 | 4.02 | -0.60 |
| **SD** | 8.75 | 14.57 | 10.27 | 64.89 | 9.40 | 3.41 |
| **Min** | -29.51 | -1.07 | -65.56 | -66.68 | -6.68 | -27.32 |
| **25% (Q1)** | -5.83 | -0.04 | -7.72 | -4.51 | -0.54 | -1.37 |
| **Median** | -2.14 | 5.34 | -4.01 | 0.15 | 0.95 | -0.28 |
| **75% (Q3)** | 1.92 | 19.19 | -1.12 | 8.75 | 3.34 | 0.68 |
| **Max** | 52.34 | 39.05 | 65.16 | 1052.00 | 61.86 | 7.94 |
| | **Tunnel Maintenance** | **Paving Operations** | **Guardrail Replacement** | **Bridge Construction** | **Striping Operations** | |
| **Mean** | -0.86 | 11.40 | 2.11 | 6.75 | 2.56 | |
| **SD** | 8.80 | 39.58 | 6.65 | 18.56 | 14.00 | |
| **Min** | -61.72 | -23.83 | -13.81 | -12.97 | -19.61 | |
| **25% (Q1)** | -3.11 | -1.36 | -1.68 | -0.91 | -1.96 | |
| **Median** | 0.00 | 0.87 | 1.24 | 2.67 | -0.21 | |
| **75% (Q3)** | 2.33 | 6.69 | 4.89 | 7.82 | 2.30 | |
| **Max** | 33.75 | 448.14 | 30.28 | 287.95 | 134.13 | |

## Work Zones by Closure Type

For our study on travel time by impact type, we found a few things of note. *Mobile lane* closures (orange) showed negative travel time impacts. This was due to our difficulty in obtaining more of these event subtypes. Without a large sample size, *mobile lane closures* would have caused the rest of the data to shift unpredictably. Therefore, in the CDF for *mobile lane closures*, there is an unusual result – a short, straight line hovering in the negative percent change region. No significant conclusions were able to be drawn for *mobile lane closures*, and their results have not been considered for further comparisons. Also unique to work zones, is closures are logged in greater detail on COTrip than on COGNOS, the source of the other three impacts. Work zone closures are broken down by specific lane closure or number of lanes closed (single lane closure – unknown, left lane closed, etc.), whereas the COGNOS lane closures are grouped by full, partial or none.

By far, the most impactful lane closure type was *all lanes closed* as measured by 75th percentile, which was 31.2%. While *various lane closures* had the highest max value (1,052%), the 75th percentile is only 6.38%. *All lanes closed* also has the highest mean value of 18.2% increase in mean travel time. When averaging each single-lane closure type (*single lane traffic, single lane closure – unknown, alternating single lane closure*, and *left lane closed*), there is a small increase in mean travel time of 1.88%.

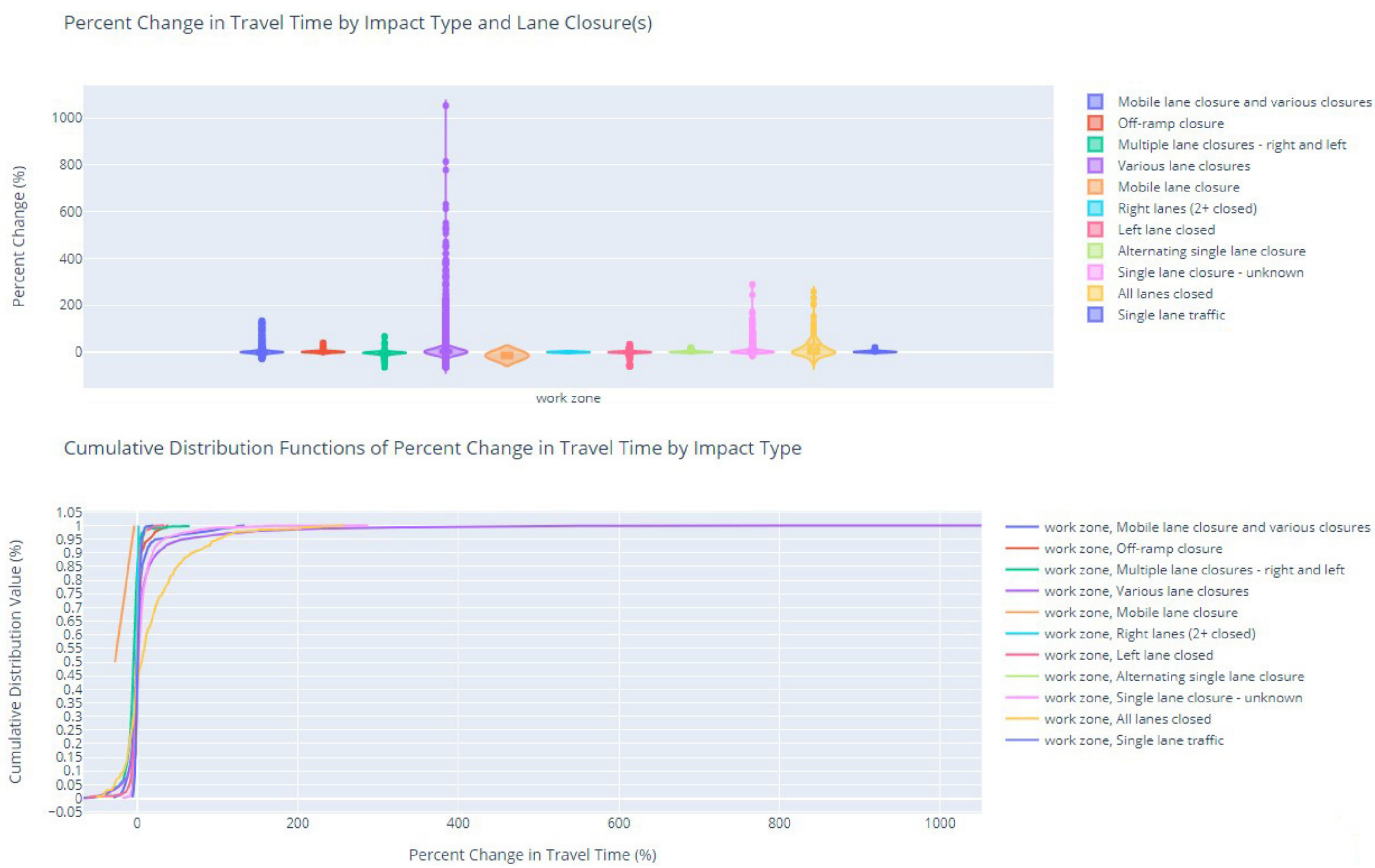



**Figure 26:** *Travel Time Reliability by Work Zone Closure Type.*

### Table 6: Summary Statistics on Travel Time Reliability by Work Zone Closure Type

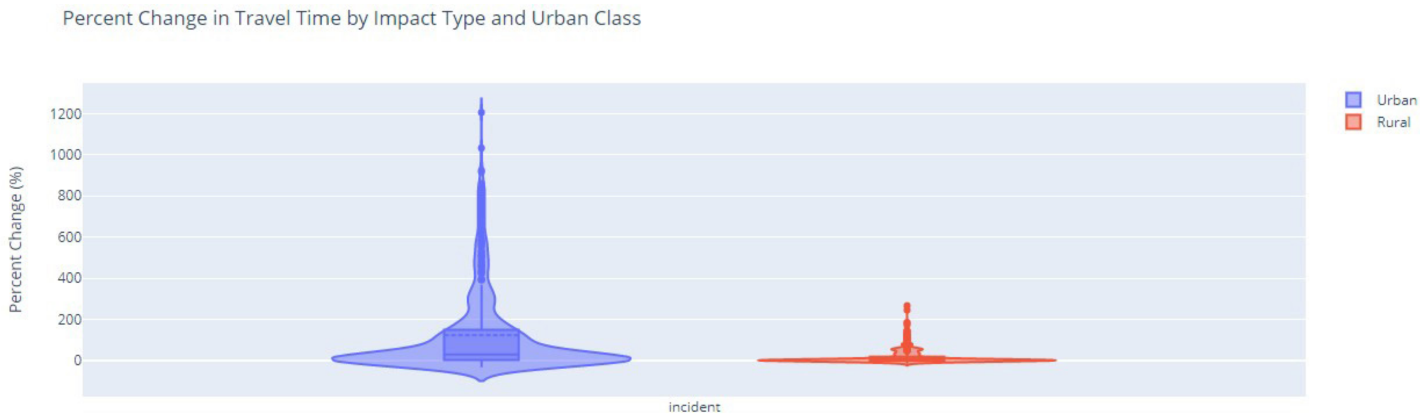
| | Mobile Lane Closure & Various Closures | Off-Ramp Closure | Multiple Lane Closures | Various Lane Closures | Mobile Lane Closure | Right Lanes (2+ Closed) |
|---|---|---|---|---|---|---|
| **Mean** | 2.90 | 2.31 | -5.2 | 10.23 | -15.29 | -0.31 |
| **SD** | 20.24 | 7.44 | 10.27 | 52.97 | 17.01 | 1.80 |
| **Min** | -29.51 | -6.33 | -65.56 | -66.68 | -27.32 | -2.30 |
| **25% (Q1)** | -4.35 | -1.03 | -7.72 | -2.46 | -21.30 | -1.34 |
| **Median** | -0.36 | 0.52 | -4.01 | 0.70 | -15.29 | -0.45 |
| **75% (Q3)** | 3.14 | 3.26 | -1.12 | 6.38 | -9.27 | 0.58 |
| **Max** | 134.13 | 39.05 | 65.16 | 1052.00 | -3.26 | 1.95 |

| | Left Lane Closed | Alternating Single Lane Closure | Single Lane Closure - Unknown | All Lanes Closed | Single Lane Traffic |
|---|---|---|---|---|---|
| **Mean** | -1.08 | 0.75 | 6.99 | 18.18 | 1.16 |
| **SD** | 7.05 | 3.36 | 19.63 | 43.23 | 3.24 |
| **Min** | -61.72 | -6.37 | -17.24 | -50.62 | -5.40 |
| **25% (Q1)** | -2.77 | -1.34 | -1.19 | -6.36 | -0.95 |
| **Median** | -0.66 | 0.15 | 1.71 | 6.45 | 0.76 |
| **75% (Q3)** | 1.54 | 2.14 | 7.68 | 31.23 | 2.95 |
| **Max** | 33.75 | 20.13 | 287.95 | 258.02 | 20.53 |

# 5.3. Incidents

## Incidents by Urban/Rural Classification

Of all the impact types *incidents* produced the largest impact to travel time reliability. By far, urban incidents caused a greater change to travel time than their rural counterparts as measured by any value included in the table. It is worth noting that rural incidents still caused a large increase in travel time, and are on par with work zones.



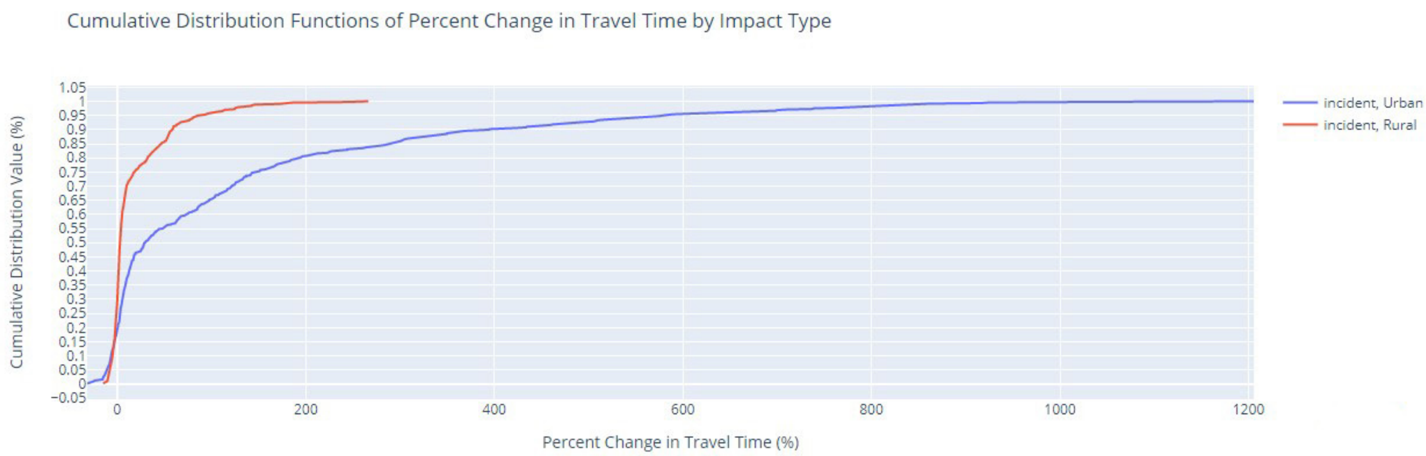




**Figure 27:** *Travel Time Reliability by Incidents and Urban/Rural Classification.*

### Table 7: Summary Statistics on Travel Time Reliability by Incidents and Urban/Rural Classification

| | Urban | Rural |
|---|---|---|
| **Mean** | 123.63 | 17.55 |
| **SD** | 200.44 | 36.31 |
| **Min** | -31.71 | -14.77 |
| **25% (Q1)** | 3.16 | -0.39 |
| **Median** | 29.68 | 2.98 |
| **75% (Q3)** | 148.62 | 18.44 |
| **Max** | 1205.76 | 266.60 |

### Incidents by Sub Type

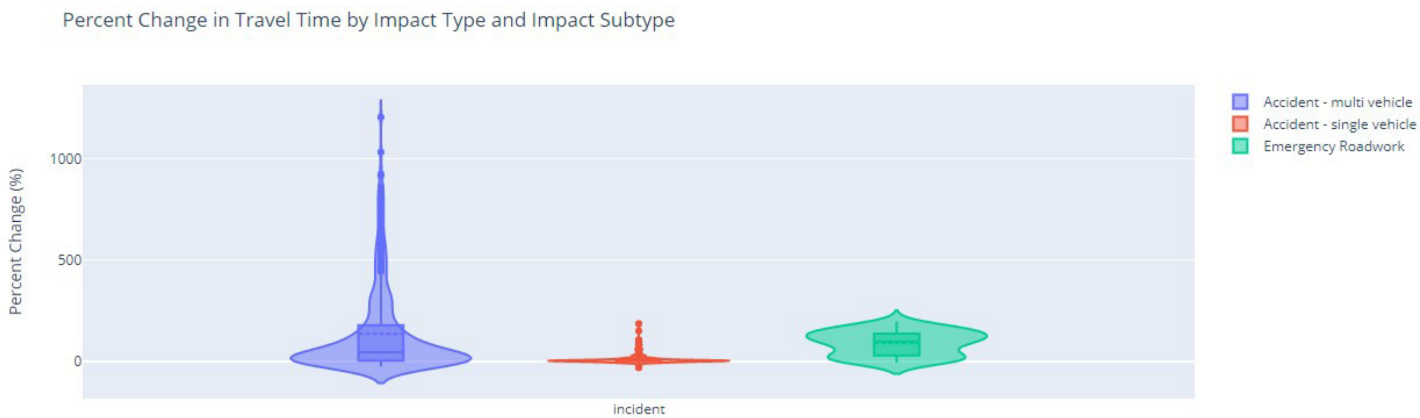
When we broke out incidents by subtype, there were three very differently shaped violin plots and CDFs. Examining the violin plots in **Figure 28**, notice how the widest part for *accident–multi-vehicle* and *accident–single vehicle* are near the bottom of the plot (0% change). This differs from Emergency Roadwork which has the widest part of the violin further from the x-axis. Similarly, if we look at the CDFs, *single* and *multi–accidents* are standard sigmoid (s-shaped) curves while *emergency roadwork* is much more linear[6]. From these shapes we can determine the travel time reliability.

Let us compare in more detail two subtypes, *accident–single vehicle* (red) and *emergency roadwork* (green). Both have similar maximum percent change in travel time, which means that the worst-case, travel-time scenario for both subtypes are nearly the same, at approximately a 200% increase. Despite this, from their shapes we know that *emergency roadwork* caused worse travel time reliability, but there is only one notable *emergency roadwork* event this is based on.

The shape of the red violin plot indicates a very reliable travel time. Comparatively, the blue plot is much more indicative of high travel time variability. In conclusion, our data suggest that travel times remain significantly more reliable in single vehicle accidents, making the red, single vehicle violin plot a great example of consistent travel times displayed visually. We can roughly quantify this idea using the Standard Deviation (SD) in the table below. There we see a value of 209.2 for *multi-vehicle* and 22.7 for *single vehicle*. When examining SD, the higher the value the more spread-out the data is, thus leading to less travel time reliability. Conversely, the smaller the SD, the more reliable the travel time is.

In **Figure 28** we see both the blue and red lines roughly trace out a sigmoid (s-shaped curve). A line that ascends vertically more quickly is indicative of a more reliable the travel time. Notice how the blue, *multi-vehicle accidents* line has a shorter vertical section that quickly starts stretching out horizontally to high travel times. This indicates that only a few drivers experienced significant increases to their travel time, while most only felt a moderate increase.

*[6]A sigmoid (S) shaped CDF, in general, is related to the Gaussian (normal) distribution while a linear CDF is related to a uniform distribution. These two distributions differ in many ways, one way is how the two extremes (minimum and maximum) have much smaller values in a normal distribution verse a uniform where the values are evenly distributed across all values.*



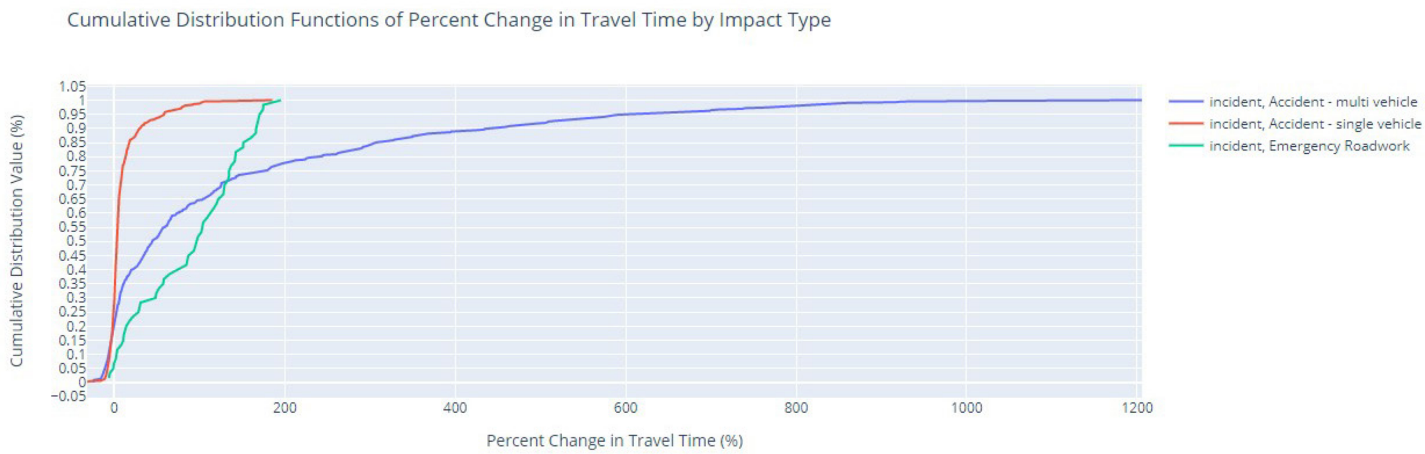




**Figure 28:** *Travel Time Reliability by Incident Sub Type.*

## Table 8: Summary Statistics on Travel Time Reliability by Incident Sub Type

| | Accident - Multi Vehicle | Accident - Single Vehicle | Emergency Roadwork |
|---|---|---|---|
| **Mean** | 135.45 | 9.50 | 88.63 |
| **SD** | 209.21 | 22.69 | 59.75 |
| **Min** | -25.65 | -31.71 | -6.05 |
| **25% (Q1)** | 2.54 | -0.55 | 29.27 |
| **Median** | 44.87 | 2.87 | 97.86 |
| **75% (Q3)** | 176.07 | 9.61 | 135.30 |
| **Max** | 1205.76 | 185.29 | 195.78 |

### Incidents by Closure Type

Next, we broke out incident events by lane closure types. Using the summary statistics (mean, Q1, and Q3), it's clear that the most impactful lane closure type is *no closure* followed by *partial closure*. Yet, the single highest time variation happened during a *partial closure*, where one event affected travel time by over 1200%. Maximum travel time is not the only factor in travel time reliability; previously we explored standard deviation as a means of quantifying travel time reliability. When comparing by SD in the tables, *no information* is the most reliable with 45.1 while the least reliable is *partial closure* with a SD of 184.7. In a previous section we discussed the effect of limited data and its incompatibility when making comparisons. We have a similar situation here with *no closure* where the few events are causing certain summary statistics to swell while other shrink. Like we've done previously, no significant conclusions were able to be drawn for *no closure*, and their results have not been considered for further comparisons.

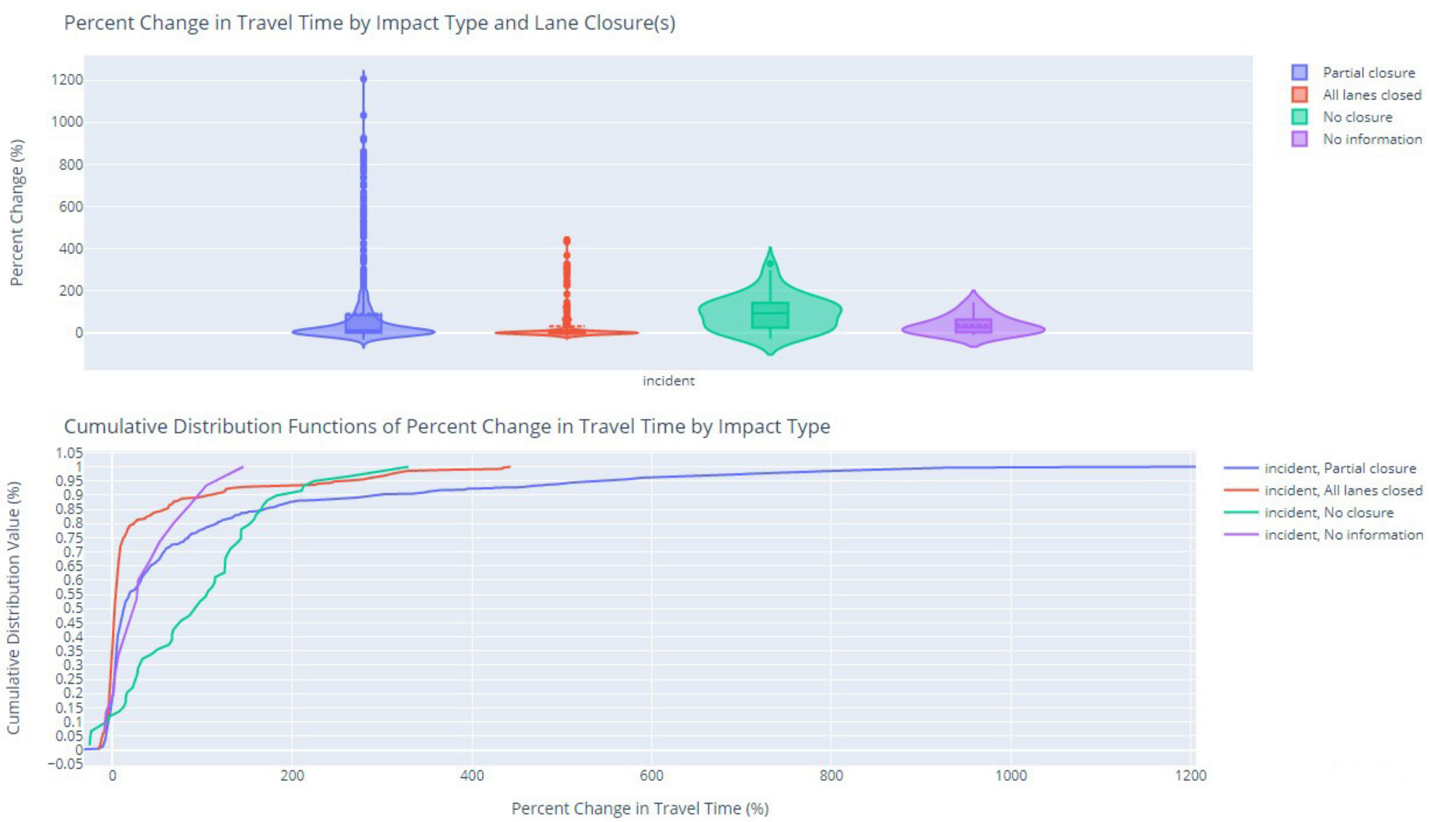



**Figure 29:** *Travel Time Reliability by Incident Closure Type.*

### Table 9: Summary Statistics on Travel Time Reliability by Incident Closure Type

| | Partial Closure | All Lanes Closed | No Closure | No Information |
|---|---|---|---|---|
| **Mean** | 91.51 | 31.96 | 94.42 | 38.52 |
| **SD** | 184.69 | 83.18 | 81.38 | 45.08 |
| **Min** | -31.71 | -16.10 | -25.65 | -9.14 |
| **25% (Q1)** | 1.69 | -1.84 | 26.37 | 4.42 |
| **Median** | 12.57 | 2.27 | 94.16 | 26.69 |
| **75% (Q3)** | 83.75 | 12.54 | 142.72 | 59.96 |
| **Max** | 1205.76 | 443.10 | 329.31 | 145.36 |

# 5.4. Weather Events

## Weather Events by Urban/Rural Classification

In **Figure 30**, weather events on urban corridors show a statistically significant increase in travel time. While the rural corridors appear to have a higher max value (183.2%) the 75th percentile on urban corridors is higher – 6.6% to 3.4%. The more horizontal the *urban* CDF is, less reliable travel times, which is quantified using the summary statistics shown in Table ??. Additionally, the urban corridors SD is 16.2% while rural is 10.6% – further indicating that weather events on urban corridors cause more travel time unreliability than rural corridors.

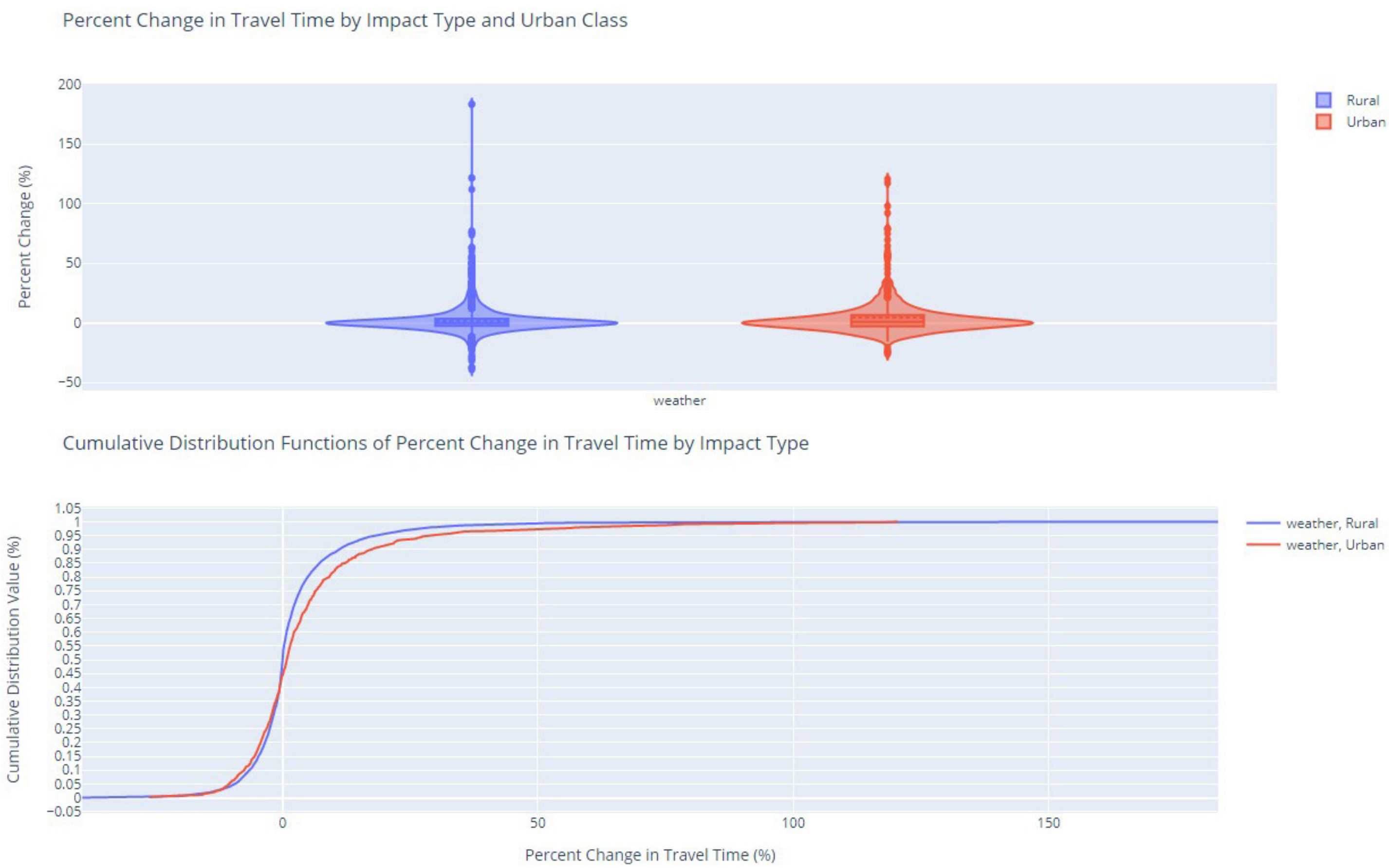



**Figure 30:** *Travel Time Reliability by Weather Event and Urban/Rural Classification.*

### Table 10: Summary Statistics on Travel Time Reliability by Weather Event and Urban/Rural Classification

| | Rural | Urban |
|---|---|---|
| **Mean** | 1.70 | 4.41 |
| **SD** | 10.62 | 16.17 |
| **Min** | -39.20 | -26.15 |
| **25% (Q1)** | -2.48 | -3.05 |
| **Median** | 0.00 | 0.87 |
| **75% (Q3)** | 3.37 | 6.55 |
| **Max** | 183.19 | 120.48 |

## Weather Events by Sub Type

Breaking down the weather events by subtype produces some interesting results. In particular, *blizzard* and *snow* show some portion of their data as a negative change travel time. A negative change means that travel times during were shorter than they are historically. For every subtype there is a notable presence of a negative percent change in travel time. This can be quantified using the table below. Examining the Q1 (25th percentile) row shows that, for example, *snow* travel times were -4.7% for 25% of travel times recorded.

Note that we made a decision to remove *hail* from the final results because the results appeared unreasonable, as all travel time measurements were shorter than the historical average. The cause for this was a small sample of *hail* travel time measurements and an inability to capture a reasonable baseline period.

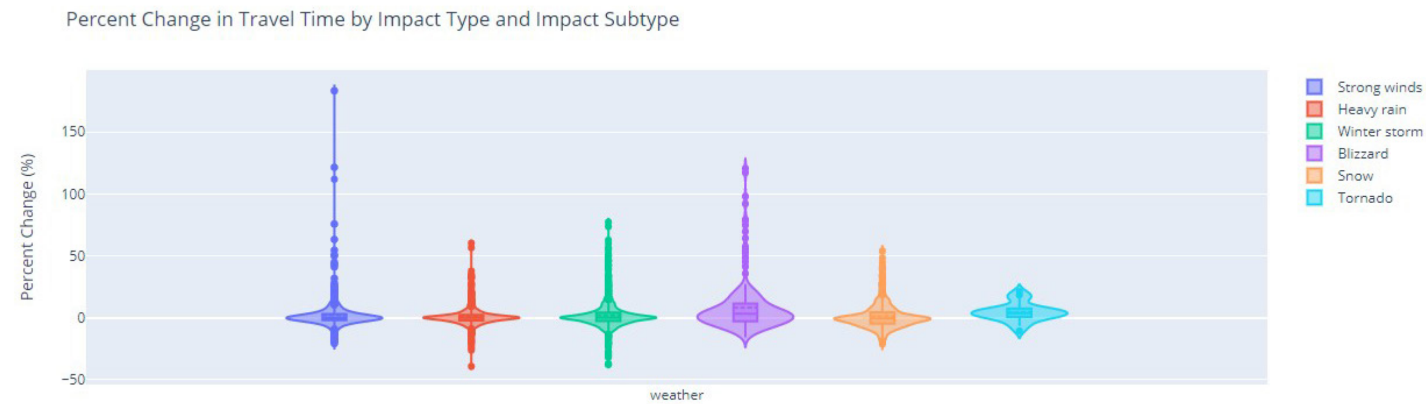




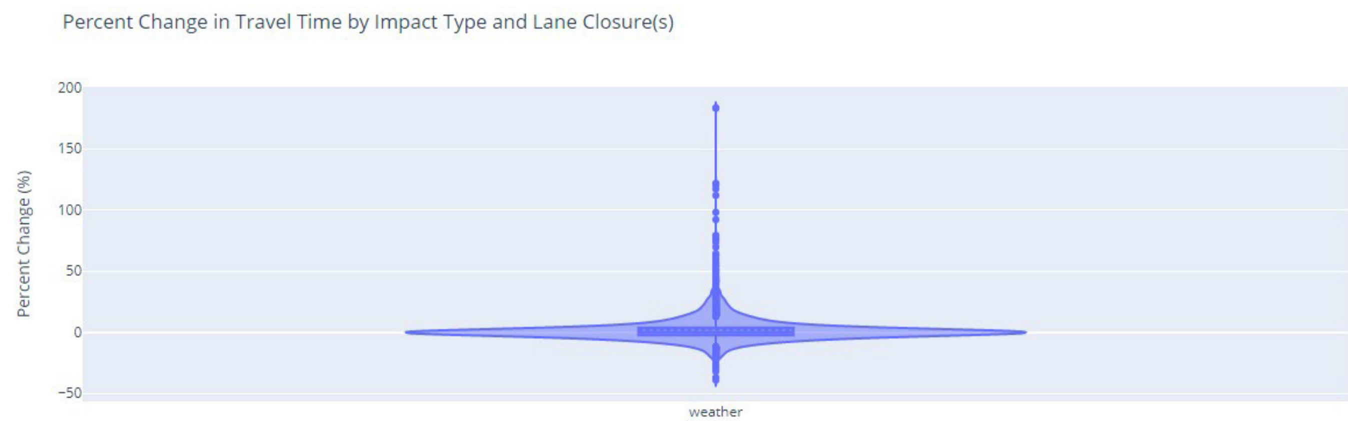
**Figure 31:** *Travel Time Reliability by Weather Event Sub Type.*

### Table 11: Summary Statistics on Travel Time Reliability by Weather Event Sub Type

| | Strong Winds | Heavy Rain | Winter Storm | Blizzard | Snow | Tornado |
|---|---|---|---|---|---|---|
| **Mean** | 2.19 | 0.80 | 2.07 | 8.21 | 1.18 | 4.51 |
| **SD** | 12.95 | 7.19 | 10.66 | 20.80 | 10.18 | 7.40 |
| **Min** | -20.74 | -39.20 | -37.59 | -15.75 | -21.20 | -10.59 |
| **25% (Q1)** | -1.82 | -2.14 | -2.74 | -2.90 | -4.71 | 0.54 |
| **Median** | 0.02 | 0.00 | 0.11 | 3.21 | -0.42 | 3.80 |
| **75% (Q3)** | 2.93 | 2.34 | 4.21 | 11.48 | 4.46 | 7.18 |
| **Max** | 183.19 | 60.20 | 77.15 | 120.48 | 53.92 | 21.14 |

## Weather Events by Closure Type

The various methods used to obtain weather events – which include COGNOS and Weather Underground - excluded any information on lane closure type Nevertheless, we can still compare the summary statistics listed below with others studied in this report. A mean of 1.99% and a Q3 of 3.68% ranks very well, resulting in a reliable travel time. When compared to the *none* baseline impact type, there is only a 0.12% difference in mean and a 0.45% difference in Q3 (75th percentile). In essence, travel time reliability during weather events is about as reliable as normal, baseline conditions.



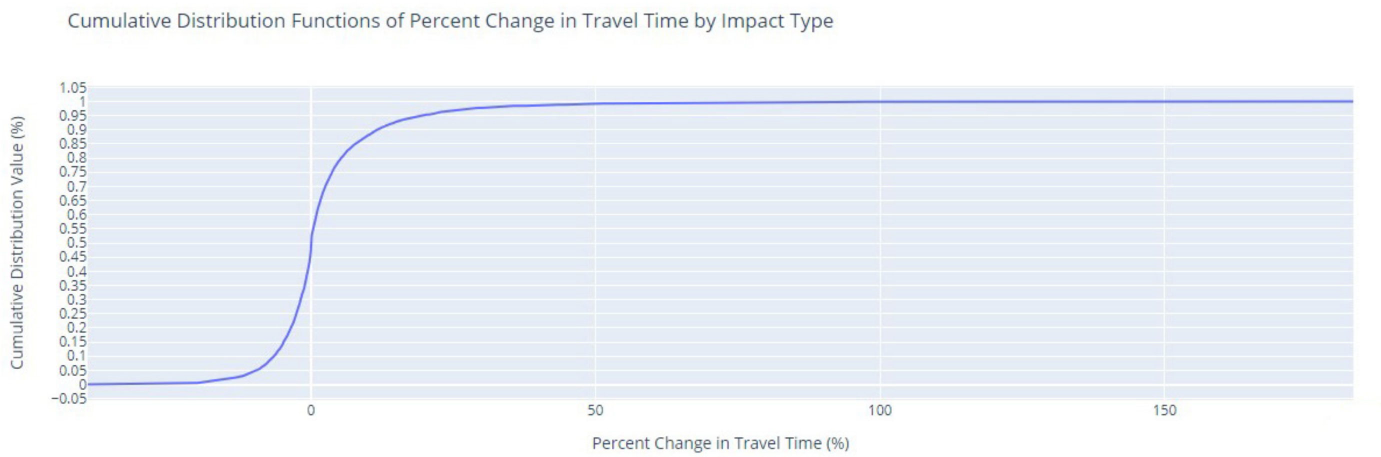




**Figure 32:** *Travel Time Reliability by Weather Event Closure Type.*

### Table 12: Summary Statistics on Travel Time Reliability by Weather Event Closure Type

| | No Closure |
|---|---|
| **Mean** | 1.99 |
| **SD** | 11.36 |
| **Min** | -39.20 |
| **25% (Q1)** | -2.53 |
| **Median** | 0.00 |
| **75% (Q3)** | 3.68 |
| **Max** | 183.19 |

# 5.5. Special Events

## Special Events by Urban/Rural Classification

The last impact type we investigated was *special events*. When we separate special events by urban and rural corridors, we see two similarly shaped violins. These represent relatively reliable travel times despite both having a chance of producing a +400% increase in travel time. Compared to weather events, there was only a small increase in average travel time; the average change in travel time for special events is only 4.6% while weather events are 2.0%. Even though this results in more than a two-fold increase in travel time change from weather events to special events, this only amounts to a 90 second difference in a one-hour drive.

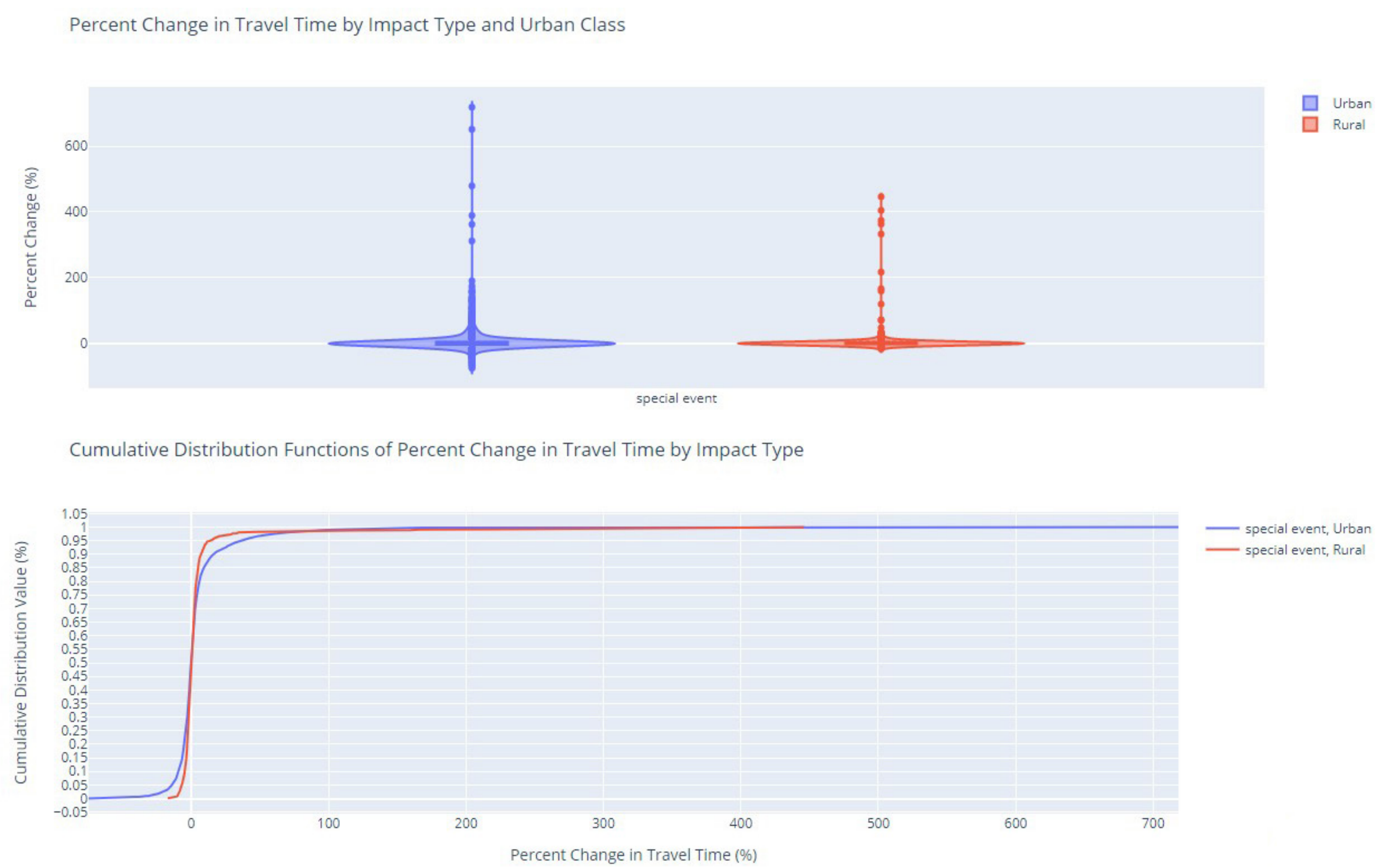


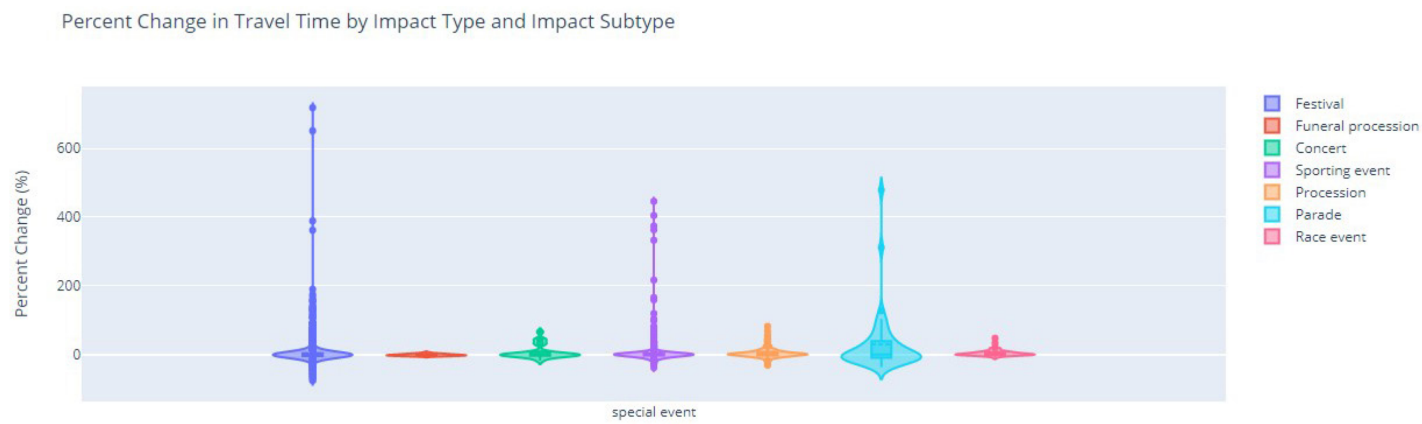

**Figure 33:** *Travel Time Reliability by Special Event and Urban/Rural Classification.*

### Table 13: Summary Statistics on Travel Time Reliability by Special Event and Urban/Rural Classification

| | Urban | Rural |
|---|---|---|
| **Mean** | 4.08 | 5.13 |
| **SD** | 29.36 | 37.47 |
| **Min** | -74.64 | -16.99 |
| **25% (Q1)** | -3.66 | -2.15 |
| **Median** | -0.04 | 0.00 |
| **75% (Q3)** | 4.23 | 2.63 |
| **Max** | 718.52 | 446.10 |

## Special Events by Sub Type

Looking at special events broken out by subtype we can see a variety of violin and CDF shapes. *Festivals*, in blue, may have had the highest potential travel time impact (max value), but it was not the most unreliable. The *parades* violin plot and CDF show the travel time reliability, and is *parades* have an SD four times higher than *festivals*. Continuing to examine the table, we see that the maximum travel time for *festivals* of 719% is greater than that of *parades* at 479%. Despite this when we look at SD *parades* are three times more unreliable than *festivals*. Conversely, *funeral processions* and *race events* were the two least impactful special event subtypes. These both have a worst-case travel time change of no more than a 50%.



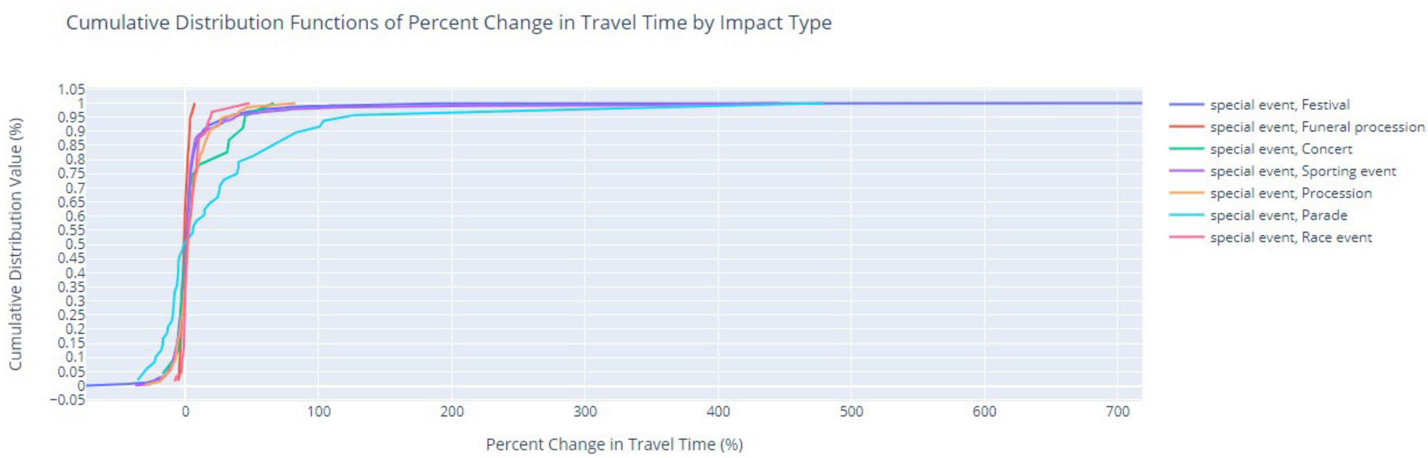




**Figure 34:** *Travel Time Reliability by Special Event Sub Type.*

### Table 14: Summary Statistics on Travel Time Reliability by Special Event Sub Type

| | Festival | Funeral Procession | Concert | Sporting Event | Procession | Parade | Race Event |
|---|---|---|---|---|---|---|---|
| **Mean** | 3.38 | -0.82 | 8.30 | 6.83 | 4.37 | 29.77 | 4.41 |
| **SD** | 28.04 | 2.83 | 20.59 | 41.87 | 13.91 | 87.34 | 8.89 |
| **Min** | -74.64 | -5.54 | -17.17 | -37.88 | -30.73 | -35.99 | -8.00 |
| **25% (Q1)** | -3.54 | -3.03 | -3.38 | -2.33 | -2.32 | -9.31 | -0.72 |
| **Median** | -0.30 | -1.27 | 1.33 | 0.42 | 1.79 | 0.20 | 1.20 |
| **75% (Q3)** | 3.54 | 1.03 | 7.38 | 3.22 | 8.12 | 38.69 | 7.18 |
| **Max** | 718.52 | 6.74 | 66.14 | 446.10 | 82.57 | 479.16 | 47.89 |

## Special Events by Closure Type

Lastly, we studied the difference between lane closure types, where the biggest change in travel time is caused by a *partial closure* with an average increase of 20.7%. Meanwhile, in *no closure* there was very little change to travel time for most vehicles. This is reflected in the CDFs (**Figure 35**) where the blue, *no closure* line climbs vertically close to the y-axis before extending horizontally near the 100% y-value. The next most impactful events were *planned closure* with a mean change of 11.6%, followed by *no information* with a mean of 8%. While *planned closure* had a high 75th percentile impact (18.3% versus 2.28% for *no closure*), it was a reliable change to travel time. Using SD to compare reliability, *planned closures* (21.7%) was nearly as reliable as *no closure* (20.3%). In this comparison, we discovered a 30-fold increase in mean change in travel time, as well as a 40-fold increase in the 75th percentile for *no information* over *no closure*.

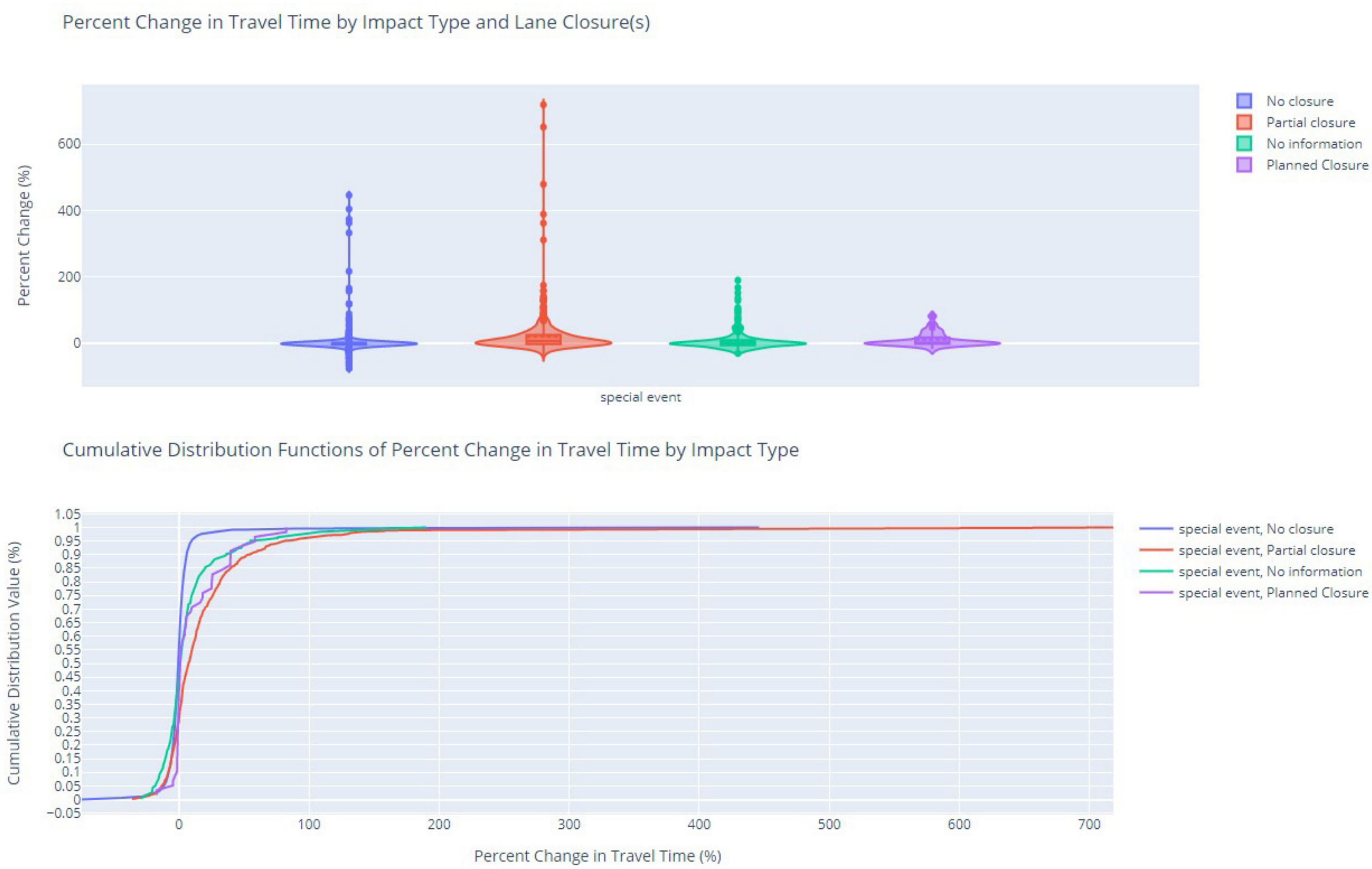



**Figure 35:** *Travel Time Reliability by Special Event Closure Type.*

**Table 15: Summary Statistics on Travel Time Reliability by Special Event Closure Type**

| | No Closure | Partial Closure | No Information | Planned Closure |
|---|---|---|---|---|
| **Mean** | 0.31 | 20.69 | 8.00 | 11.58 |
| **SD** | 20.28 | 57.62 | 28.77 | 21.73 |
| **Min** | -74.64 | -35.99 | -29.67 | -17.06 |
| **25% (Q1)** | -3.49 | -1.83 | -5.25 | -0.91 |
| **Median** | -0.58 | 7.26 | 1.30 | 1.01 |
| **75% (Q3)** | 2.28 | 25.88 | 9.93 | 18.25 |
| **Max** | 446.10 | 718.52 | 190.22 | 82.57 |

## 5.6. Conclusions

After studying a wide variety of impact types, subtypes, closure types, and urban classifications, we found that the *multi-vehicle accidents* were the most impactful events. With a 75th percentile of 176.1% and an SD of 209.2%, there were no event types, subtypes, or closure types that came close to the unreliability of *multi-vehicle accidents*. Weather resulted in the most reliable travel times. In particular, *heavy rain* showed the smallest change to travel time of the *weather* events with a 75th percentile of 2.3% and an SD of 7.2%.

The metrics used to determine travel time reliability are not only robust but have also been proven in other fields of study. In particular, the 75th percentile, SD, CDFs, and violin plots provided our team with a full picture from which to study, discuss, and draw meaningful conclusions from.

# 6. Conclusions, Recommendations and Next Steps

## 6.1. Conclusions

Using the SHRP2 L02 methodology, a TTRMS was created to join travel time data with information on work zones, incidents, special events and weather events. The tool's purpose is to automate merging these disparate data sources to produce "cleaned" data, provide a means to inspect the event, and upload the events to a database where they can be accessed using an interactive dashboard.

The TTRMS is comprised of four modules: a data cleaner, database, query tool, and a dashboard. The data cleaner joins travel time data with information on congestion events to be used for analysis. It generates travel time plots and travel time CDFs for the user to understand the travel time impacts of a single event before it is uploaded. This data is then uploaded to a large database. The summary charts tool provides a number of variables the user can select to view distribution plots. The user can then conduct an analysis to see how incident travel times are distributed between urban and rural interstates, or any other combination. The tool has currently processed 120 events to date. This provides users with a substantial database that can be used to understand the travel time impacts of work zones, incidents, weather events and special events. The database can be downloaded into a spreadsheet using the TTRMS database queries tool, and interacted with using the dashboard. The tool is also meant for users to study additional events and continue to grow the database.

The SHRP2 L05 product is a guide to integrate travel time reliability measures (from the TTRMS or other systems) into planning and programming decisions. It explains how reliability measures can be used in capital projects such as STIPs to fund operations-focused projects. Using TT-PDFs, we can derive various travel time reliability metrics such as PTI and median travel time. The measure used in reporting depends on the audience, and it is valuable to summarize performance measures so they can be clearly communicated to decision makers. If decision makers can understand sources of variability and how responses impact travel conditions, the planning process can then take advantage of a more holistic picture of congestion problems and prioritize projects that are more valuable investments.

As a research project, the TTRMS established a methodology that can be easily replicated and implemented on a much larger scale for analyzing the travel time reliability impacts of non-recurring congestion. Navjoy is currently working with CDOT to integrate the TTRMS data model into the Real-Time Data Hub.

## 6.2. Recommendations

Our recommendations for developing a TTRMS are:

- Inventory all possible data sources early on, and then weigh the pros, cons, and level of effort for each.
- Take a "crawl, walk, run" approach to development: focus on one pilot corridor for one congestion source first, then build the database and additional congestion sources.
- Understand the level of accuracy for data sources because data that has already undergone a quality assurance/quality control process will be easier to work with.
- Provide intuitive outputs that are easy to understand for different audiences. For example, simple travel time charts may be easier to communicate to non-transportation audiences.
- Use modern and flexible tools such as remote database storage and API access when possible.

## 6.3. Next Steps

The next steps for the TTRMS are to

- use the TTRMS database to better understand how travel times are impacted by work zones, incidents, weather events and special events,
- continue to process new events with the tool, and
- continue to build the database.

Ultimately, this tool provides a framework and process for merging congestion data with travel time data using the available information. In the future, this framework will be useful to develop tools using newer and more standardized data as CDOT continues to invest.

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