IDENTIFYING RELATIONSHIPS BETWEEN SAFETY AND CONGESTION IN A CONNECTED VEHICLE ENVIRONMENT

Final Report

Southeastern Transportation Center

Adam Kirk
MARCH 2019

US Department of Transportation grant
Problem Statement
The US Department of Transportation has advised planning agencies to begin considering how their local transportation systems will function in a connected vehicle environment. Connected vehicles promise to revolutionize modes of travel and will be a major — if not the major — technological development that shapes the infrastructure, policy, and practices of state agencies. Connected vehicle systems will enable improved management of transportation networks through the procurement, analysis, and distribution of real-time information. Most efforts in the realm of connected vehicle technologies to date have focused on improved operations. However, managing safety performance has largely been reactive, with a focus on increasing responsiveness to incidents rather than crash prevention. This is largely due to the random nature of crashes, but also the limited development of safety models that typically examine static variables such as roadway geometry and average daily traffic (ADT), which do not include temporal effects such as congestion or weather-related variables. With connected vehicle infrastructure, significantly more data on vehicle operations are available, and it is possible to explore the spatial and temporal dimensions of safety performance from data generated by vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) in real time. This opens up abundant opportunities to identify locations where there is a high probability of crashes. The need exists for a strategic framework that not only aims to detect and alleviate congestion, but also attempts to estimate potential crash risk at the network scale using the extensive data gathered within a connected vehicle environment. Although we are just stepping into the connected vehicle environment, we must take the initial steps to understand how these data may be used to enhance current understanding of congestion and safety performance. This report proposes that active datasets from V2V and V2I can be integrated with a crash database and congestion-monitoring index using a composite index of the two. This will facilitate the identification of high-risk locations.

Research Objectives
The objective of this research is to leverage existing V2I datasets to link data on high-resolution traffic performance and weather information to safety performance data. This resulting dataset can then be used to identify weather, geometric, and operational conditions that may increase the probability of crashes. By identifying potential high-crash conditions, future efforts can pinpoint alternative operational control strategies that mitigate adverse conditions or send advisory information to drivers, provide alternative routing, or call for alternative vehicle operating characteristics — such as following distances — in a fully connected V2V environment.
Literature Review
Transportation agencies have unprecedented access to fine-grained traffic data. Sources of these data are numerous, including sensors embedded in infrastructure, instrumented vehicles, intelligent transportation systems, GPS-enabled smartphones, and V2V and V2I technologies, among others. While processing and evaluating massive quantities of data has proven challenging, agencies are nonetheless benefitting from new techniques for analyzing and visualizing spatial and temporal variations in congestion and crashes that would have been impossible with coarse-resolution data. Along with improving our understanding of how congestion influences crash frequencies and severity, agencies are using big data and novel computational methodologies to inform safety improvement plans, guide investment decisions, and develop new performance management techniques to assess real-time and historical system performance. This brief literature review highlights recent work how big data (collected via probes, smartphones, and other means) has been put to use by transportation agencies, the effects of congestion on crash rates and severity, and traffic control measures which aim to mitigation congestion and enhance safety.

Probe Source Data and Its Uses
Hanbali and Fornal’s (1997) work serves as an early example of using performance measures to document congestion and safety improvements resulting from the use of advanced traffic management systems. Following award of a grant to reduce congestion, mitigate queue length, and lower crash frequencies at an intersection complex, the city of Milwaukee, Wisconsin installed a closed-loop, traffic-responsive signal system. Design of the system had to be such that detector data could indicate the level of congestion and differentiate normal queuing during uncongested periods from queuing during congested conditions. Before-and-after data were collected to evaluate the project’s effectiveness. Analysis found that the traffic-responsive signal control system alleviated to varying degrees congestion during peak periods along the intersection legs. Mean average vehicle occupancy went down following installation of the new system as well. Importantly, the adjusted frequency of crashes at intersections attributable to congestion fell, and there were no observed increases in crashes at signalized intersections adjacent to where the traffic-responsive system had been implemented. However, while the number of congested-related mid-block crashes declined across the study area, researchers found small increases in mid-block crashes along some intersection approaches. Nonetheless, the authors conclude traffic-responsive control systems are agile and able to respond quickly following the emergence of congestion, but that adaptive signal control — then unavailable — held considerable promise.

State transportation agencies are leveraging increasingly sophisticated data collection and monitoring techniques to understand traffic flows, facilitate rapid incident management, and make short- and long-term investment decisions about projects that will bring the greatest systemwide benefits. The Maryland State Highway Administration (SHA) has introduced new policies, programs, and projects which aim to mitigate recurring and nonrecurring congestion (Wolniak and Mahapatra 2014). At the core of its efforts is a performance-based approach intended to bolster the quality and reliability of the state’s highway system. To evaluate mobility and congestion, and identify strategies for streamlining traffic flow, there is a statewide program in place that collects public traffic data for all public roadways. These data are supplemented with data from INRIX, a vendor which markets real-time and historical traffic speed data collected from over 100 million vehicles across the United States. Data from INRIX were used to calculate the travel time index and planning time index to quantify congestion. The results were compiled in tabular and visual formats, with both indices revealing issues with reliability and congestion are most pronounced in the Baltimore-Washington metro area. Further analysis estimated costs incurred due to congestion in 2010 were $1.27 billion. Based on insights it has garnered from analysis of probe data and other data sources, SHA has addressed congestion through techniques such as low-cost intersection improvement projects, signal system optimization, and signal prioritization for public transit. Furthermore, the SHA Coordinated Highways Action Response Team (CHART) is focused on improving operations of the state’s highway system through communication, system integration, incident response and management, and advanced traffic management system, among others. INRIX traffic probe data are used to post travel time
or toll information on dynamic message signs located throughout Maryland. The state’s work on congestion mitigation demonstrates the value of real-time data for pinpointing roadway segments vulnerable to bottlenecks and routine and non-recurring congestion — and applying that information to solve urgent traffic management problems.

Spurred in part by mandates contained in recent federal legislation, state transportation agencies are turning to performance management to improve the operation of highway systems. The Pennsylvania Department of Transportation (DOT) licenses real-time and historical probe data from INRIX to monitor traffic conditions and identify areas that can be improved. Mathew et al. (2017) describe a project that leveraged INRIX data to develop three performance metrics for a performance dashboard. The first of these, a travel time comparison tool, lets users compare travel times on 138 super-critical corridors; users can specify a before-and-after time range of their choice. The tool generates a cumulative frequency diagram, which depicts all estimated travel times for selected periods on a single chart. One potential use of this tool is comparing travel times before and after a signal retiming project. The arterial ranking tool captures the median and interquartile range of normalized travel times. It is ideally suited for eliciting performance comparisons between several corridors in a county or region. It ranks corridors according to both the median travel time and travel time reliability. As with the travel time comparison tool, users can specify date ranges for analysis. The final dashboard tool is a travel delay monitor tool, which produces time-series plots of selected corridors illustrating the cumulative miles operating at different speeds during a specified period. More basically, the tool helps users visualize the locations on a corridor where traffic flow is occurring within various speed categories. Subsequent analysis of several corridors in the Philadelphia region where the Pennsylvania DOT invested in signal retiming and deploying adaptive control identified user benefits on four of the five corridors under study, resulting in a total savings of $32 million.

The United States DOT’s Safety Data Initiative (SDI) has as its goal the integration of transportation data and big data to improve safety analysis, forge better visualizations of traffic conditions and incidents, and assist policymakers with decision making. Flynn et al. (2018) discuss Phase 1 of a pilot project in which crowdsourced Waze data were used to develop models capable of estimating the number, pattern, and severity of crashes (those severe enough to warrant a police report) in approximately real time throughout a large area. Researchers leveraged random forests, developing models with six months of data from the state of Maryland. They demonstrated the feasibility of integrating disparate sources of transportation data and that Waze data are suitable for producing Electronic Data Transfer-level crash count estimates. The greatest volume of Waze data is available during the day on higher functional classification roadways. Because of abundant data, researchers expect model estimates based on crowdsourced data during these periods will most closely reflect the actual distribution of crashes. Conversely, models will tend to perform less well during periods or in situations where crowdsourced data are scarce (e.g., early morning hours, rural areas that have few Waze users). A potential benefit of this approach is that Waze data contain more crashes than are generally found in crash report data — for example, minor crashes after which police officers are not summoned by those who were involved. Phase 2 work of the SDI pilot will attempt to identify applications with the crash estimation models. Researchers envision using models to detect anomalous crash patterns and evaluate traffic safety indicators (e.g., incident duration, secondary crashes) across states.

The FHWA is encouraging transportation agencies to use automated traffic signal performance measures (ATSPMs) to assist with signal retiming. Generally, agencies retime signals on fixed intervals of three to five years; in the past, engineers have lacked objective performance measures to guide retiming. Instead, motorist feedback has been a primary influence on retiming. ATSPMs give practitioners a foundation to retime signals, but as Day et al. (2018) observe, contextualizing performance measurement data has been a challenge. While vast amounts of data have been generated, users have been reliant on their knowledge of a system to discern whether particular values reflect good or poor operations. Users have also called for aggregation methods that offer them a straightforward way to appraise system performance. To address
these shortcomings, Day et al. lay out a method for evaluating corridor performance using high-resolution data from ATSPM systems. The method generates an overall score for each corridor, which is the lowest score of five sub-scores: communication, detection, safety, capacity, allocation, and progression. Day et al. justify the selection of the lowest score as being representative of corridor performance by arguing that it highlights pronounced system deficiencies — averaging sub scores would provide a smoother average that conceals areas in which performance is below standards. This method was then used to assess the performance of eight signalized arterials in the state of Indiana. Overall scores for the corridors evaluated ranged from C to F. Because the paper is intended as a conceptual exercise, the authors do not put forward definite guidelines for scoring thresholds and interpretation of grades. Nonetheless, the method may prove instructive for agencies seeking to get a better handle on ATSPM data.

**Impact of Congestion on Crashes**

Researchers have frequently conjectured that a relationship exists between congestion level and type and crash type and severity — specifically, that more congestion leads to higher crash rates, although crashes tend to be less severe in these situations. Studies that have looked into the links between flow regime and crash type and severity have generally been grouped into two categories: those which use aggregated data over long periods to compare crash rates and congestion levels and those which rely on data aggregated across shorter intervals (e.g., five minutes). Attempting to gain clarity on this issue, Talebpour et al. (2012) discuss a cognitive risk-based microscopic simulation model to unpack the relationship between traffic conditions and the risks perceived by drivers embedded in a traffic steam. The sequential risk-taking, car-following model factors in lane changing and incidents. Simulation results found at lower traffic densities, driving risk is elevated because even minimal contact between vehicles can produce severe damage. Reducing flow rate lowers the risk until an inflection point is reached, where more sustained interactions among drivers increases risk. The research team also compared the safety implications of high reductions in speed occurring along a short road segment to smaller reductions in speed across a long roadway segment. Modeling suggested that high speed reductions against the backdrop of a short road segments has a more significant impact on the risk experienced by drivers; the attendant effects will also propagate to downstream flow.

Engineers, planners, and other state transportation agency stakeholders have long recognized the importance of communicating information about current and historical traffic and incident management data to the public. One challenge of getting these data into the hands of consumers is selecting the appropriate mix of technologies to first collect the data and then derive appropriate measures from the data that accurately portray highway conditions. Point sensors, modeling, and statistical analyses have been primary tools to conduct performance monitoring. On the heels of a probe-based data collection initiative started by the I-95 Corridor Coalition in 2008, which relied on data from GPS-enabled vehicles and supplemental information provided by point-sensor technologies, Lund and Pack (2010) propose a dynamic, web-based congestion and incident scanner tool for evaluating congestion performance measurements. Many previous efforts to visualize traffic monitoring data gravitated toward the use of performance dashboards, which typically house graphs, tables, and regional maps. To produce more meaningful and intuitive visualizations, researchers and practitioners have turned to contour-line mapping. The system Lund and Pack talk about use the latter approach to help users identify where and when congestion has or is likely to occur as well as incidents or construction events correlated with different spatial patterns of traffic flow. With respect to the web-based tool’s interface, users can select one date or a date range and choose how to aggregate data into time bins as well as a preferred speed measure. Users can also modify the colors used in the congestion visualizations and adjust how results are displayed. On the contour-line maps the x-axis represents the time of day and y-axis the distance along the selected road segment (Figure 1). The maps also display atop the congestion visualization interactive icons which users can click on to acquire incident data (e.g., incident type, place of occurrence, number of lane closures). Although Google Maps and Waze can be useful for real-time data, the web-based tool Lund and Pack...
Various methods of analyzing traffic flow, congestion, and safety pull from data collected by point sensors such as loops and radars. In some cases, vehicles outfitted with instruments have been used to study variability in traffic conditions. However, the use of sensors and instrumented vehicles are not appropriate for all contexts (especially urban settings) and are not equipped to generate data at the spatial and temporal resolutions needed to fully comprehend how different traffic flow characteristics relate to collision frequency and severity. To address this challenge, Stipancic et al. (2017) use GPS data collected via smartphones to correlate quantitative measures of congestion, speed, and speed uniformity with historical collision frequency and severity data at the network scale. Drawing from a sample of approximately 40,000 trips representing the behavior of 5,000 drivers, they focus analysis on Quebec City, Quebec. Map matching was first used to filter raw GPS data and eliminate positional variability; filtered data were then joined to original data set. Surrogate safety measures calculated using the final dataset included the Congestion Index, average speed, and speed uniformity. Facilities were grouped based on their functional classification — freeway, primary, secondary, tertiary, and residential. Researchers found a positive correlation between the Congestion Index and crash frequency at the link and intersection levels for all functional classifications. The most robust correlation was between average speed crash frequency. The correlation was negative and consistent across all functional classes. Speed uniformity had a positive correlation with crash frequency.
and exhibited a statistically significant relationship with increased crash severity, meaning greater variability in speed increases the number of crashes and results in more severe crashes.

**Traffic Control Measures for Reducing Congestion and Improving Safety**

Ukkusuri and Ramadurai (2009) conducted an exhaustive scan of current and emerging technologies focused on congestion reduction and management as well as safety and security systems, finding considerable promise in travel demand management strategies such as congestion pricing underwritten by dedicated short range communications (DSRC) or GPS; telecommuting; advanced signal management; performance metrics for freeways, arterials, and access management; improving transit services; transit signal priority; and advanced traveler information systems (including V2V and V2I system architectures) could mitigate congestion and potentially reduce the severity and frequency of crashes. Cutting-edge technologies exhibiting considerable promise included nanosensors (used to monitor infrastructure condition, identify bioterror agents, and monitor air quality), advanced transportation applications enabled by DSRC, faster and more efficient computing technologies, and new sensor technologies. Experts polled for the scan identified technologies they believed would be most transformative for congestion reduction—in order of their ranking: GPS and personal travel assistance, smart cards and RFID, collaborative technologies, adaptive ramp metering, and personal rapid transit.

A persistent challenge for researchers has been uncovering a definitive relationship between safety and congestion. Harwood et al. (2013), working in the context of urban freeways located in Seattle, Washington, and Minneapolis-St. Paul, Minnesota, used detector data collected at five-minute intervals, sought to explore safety–congestion relationships and use those to quantify the effects of safety and highway design treatments whose goal is to alleviate nonrecurrent congestion and increase travel-time reliability. Using data from each city, level of service (LOS) was calculated after aggregating data into 15-minute intervals. Although LOS typically ranges from A to F, researchers used a modified classification that included 18 categories instead of six. They evaluated average crash rates within each of the 18 LOS categories, finding a U-shaped relationship whereby crash rates are slightly higher at the lowest LOS than at minimum crash rates, while crash rates at higher LOS are much higher than the minimum crash rate. Regression analysis identified several equations practitioners can use when they are estimating the safety benefits (total crashes per million vehicle miles traveled [MVMT], fatal and injury crashes per MVMT, and property damage only crashes per MVMT) of mitigating congestion on freeways.

Intelligent transportation systems (ITS) are a tool commonly employed by transportation agencies to relax the impacts of congestion, particularly in heavily trafficked urbanized areas. Beyond improvements in traffic, ITS can also bolster mobility, fuel efficiency, accessibility, operating, safety, and reduce atmospheric pollution (e.g., greenhouse gases, particulates). To understand the financial and environmental impacts of ITS deployment in the state of Florida, Erkan et al. (2013) adopted an economic input-output methodology. What differentiates this study from previous efforts to grasp the effects of ITS on the triple bottom line of sustainability is it analyzes economy-wide supply chains to look at how they reverberate beyond the proximate locations outside of where they are in use (i.e., both direct and indirect effects). The research team found that the most significant impact of congestion relief through ITS grew out of reductions in annual delays. Cost savings were also realized by reducing person and commercial vehicle hours, using less fuel, and cutbacks in imports (especially petroleum). There were pronounced environmental and ecological impacts as well, which manifested in the form of reduced energy use, less indirect water consumption, and fewer releases of toxic materials into the air.
Methodology
To quantify the impacts of congestion on crashes, we used the Kentucky Transportation Cabinet (KYTC) Real-Time Data Stream. KYTC Real Time Data are collected from eight different static and mobile data collection sources, including:

- KYMesonet Air Temps
- KYTC RWIS Pavement Temps
- CoCoRahs Precipitation
- HERE Traffic Speeds
- Twitter/Social Media
- Waze Crowd Sourcing
- AVL / Snow Plows
- SNIC Status List

All data sources are geo-located to Kentucky Highway information System (HIS) database. This integrates data with the Kentucky Highway system based on county, route and milepost data in addition to latitude and longitude coordinates. Additionally, metadata on date and time are recorded in as the system captures data.

The primary sources used for this analysis was Waze data and HERE travel speed data. Waze supplies two types of data to the Cabinet in real time:

- User-reported incidents, including:
  - Crashes, traffic jams, hazards, construction, potholes, roadkill, stopped vehicles, objects on road, missing signs.
  - System-generated traffic jams and link speeds identified by analyzing user GPS signals

HERE provides system-generated travel speed data from mobile GPS devices, including vehicle sensor data, smartphones, portable navigation devices (PNDs), road sensors, and connected vehicles. Because HERE data come from a number of sources, they are aggregated to predetermined segments on the roadway system. As a result, the resolution of travel speed data from HERE is lower than is available from Waze point data. Figure 3 shows real-time traffic data on the Waze platform around Lexington, Kentucky, on December 10, 2018. Waze users are identified by the vehicles icons and Waze jams are the yellow and red route indications.

![Figure 3 Waze Real-Time Data Map](image)
Figure 4 shows a time lapse development of a typical crash pattern. HERE speed data at the top indicate the speed reduction of the entire segment after a crash occurred around 05:00. The yellow and red dots represent the frequency of Waze user-reported incidents for jams and crashes, respectfully. Light blue and dark blue lines signify the average speed detected during the event, identified as a Waze Jam.
Figure 4 Waze and HERE Data output from KYTC Real-Time Data Visualization
KYTC has developed After Action Reports to summarize incidents reported by Waze users. The report depicted in Figure 5 shows the occurrence of incidents at two-minute intervals at a given road location. Several types of incidents can be reported, including road closures, crashes, and roadway hazards, including stopped vehicles or potholes. Jams and crashes are also reported (the primary focus of this research). This research addresses which comes first — the congestion or the crash. Previous analysis of probe-identified crash data showed that reported incident match closely with documented police crash reports (Flynn et al. 2018). Additionally, comparisons of Waze crash reports to 911 call center data undertaken by KYTC found that Waze identifies crashes 3-4 minutes faster than the reporting 911 call.

Figure 5 Waze After Action Report
To evaluate the relationship between crashes and congestion, we reviewed crashes that took place over a one-month in Lexington, Kentucky, on KY Route 4 (New Circle Road). KY 4 is a loop road that encircles the inner metropolitan core (Figure 6). Most of the road is a limited access freeway, however, on the north side of the city, it operates as a city arterial with at-grade intersections and partial access control. During the month examined, 24 crashes were identified from KYTC After Action Reports.

Three primary crash–congestion patterns were identified within the study period. The first crash–congestion pattern is free flowing traffic conditions followed by a crash and congestion (Type 1). Figure 7 exemplifies the appearance of this crash type in a KYTC After Action Report. As evident in the graph, speeds are slow at 15:00. A jam is reported at 15:04, followed report of a major crash at 15:06. The crash is repeatedly reported through 16:54, at which point traffic speeds begin to recover and the jam dissipates.
The second type of crash–congestion relationship is a crash that occurs after the initial report of jams and/or decreased speed (Type 2). Figure 8 shows the typical development of this crash type. Beginning at 07:30, traffic speeds decrease in conjunction with the morning rush hour. At 07:54 the Waze system detects a jam with low speeds. At 08:12, a Waze user reports a jam. At 08:48, a crash is reported. Traffic speeds recover after the crash is cleared at 09:20.
The third reported pattern is the presence of a reported incident on a roadway — not identified as a jam (Type 3). These typically include seemingly benign incidents such as potholes or vehicles on shoulders, followed by a crash and congestion. Figure 9 captures one example of this crash type. As indicated in the figure, a vehicle on the shoulder is reported at 12:52, and again at 14:24. Fourteen (14) minutes later, a minor crash is reported in Waze. A jam is detected and reported at 15:26, followed by continued reports of a crash. The resulting congestion is likely due to first responders arriving on the scene and subsequent lane closures.

Appendix A contains After Action Reports for each of the 25 crashes included in this evaluation.
Of the 25 crashes reviewed, six were Type 1, three were Type 2, and the remaining 16 were Type 3. Of the 16 Type 3 crashes, seven (7) were only reported as hazards on the roadway, while the remaining nine (9) included reported hazards occurring in conjunction with a reported jam. An analysis of the time to crash was also evaluated from the first report of the identified hazard to the crash reporting. Overall, the average time to crash was relatively long — 68.3 minutes. The minimum time to crash was eight (8) minutes, and the maximum 126 minutes. Figure 10 shows the cumulative distribution of the time to crash for all accidents following hazards.
Figure 10 Cumulative Distribution of Time to Crash following Hazard

Over 81 percent of the crashes reported in the study period occurred over 40 minutes after the first reported hazardous condition. Over 50 percent of the crashes occurred following at least one hour after the incident was reported.

Discussion and Conclusions
The initial objective of this research was to identify the relationship between traffic congestion and crashes to identify potential operational improvement strategies to optimize system performance and improve safety. Due to additional information made available through real-time traffic condition reporting, we found that over 64 percent of the reported crashes reviewed as part of this study were correlated with reports of other roadway hazards. While these hazards resulted in congestion or jammed conditions, they do not appear to have been the result of over-capacity roadways or underperforming traffic control strategies. Rather they were the product of temporary blockages or slowdowns resulting from stopped vehicles on shoulders in the roadway and/or large potholes.

The surprising outcome of this work is the ability to quantify the time to crash from when an incident was first reported. The average time to a crash was over one hour, indicating the crashes are not generally the result of a vehicle suddenly pulling to the shoulder or slowing down, but the product of traffic flow around the hazardous condition. As congestion builds up, so too does the probability of a crash in the vicinity. This information may be used to help traffic management centers prioritize incident response to clear incident reports for conditions that may previously have been thought to not be priority incidents. However, knowing stopped vehicles may cause a crash within the next two hours could trigger a more rapid response and clearance of the hazard prior to a crash occurring.
References


Appendix A KYTC After Accident Reports for Evaluated Crashes
STC Research Report Safety–Congestion Relationships in a Connected Vehicle Environment