

**COMMUTER MOBILITY VS. WORK-ZONE SAFETY:
AN EMPIRICAL STUDY USING DATA
MINING OF ANONYMOUS USER GENERATED
TRAVEL DATA**

PROJECT REPORT

by

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Sponsorship:
PacTrans
Oregon State University

for

Pacific Northwest Transportation Consortium (PacTrans)
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In cooperation with US Department of Transportation-Research and Innovative Technology
Administration (RITA)



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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle		5. Report Date	
		6. Performing Organization Code	
7. Author(s)		8. Performing Organization Report No.	
9. Performing Organization Name and Address		10. Work Unit No. (TRAVIS)	
PacTrans Pacific Northwest Transportation Consortium University Transportation Center for Region 10 University of Washington More Hall 112 Seattle, WA 98195-2700			
		11. Contract or Grant No.	
12. Sponsoring Organization Name and Address		13. Type of Report and Period Covered	
United States of America Department of Transportation Research and Innovative Technology Administration			
		14. Sponsoring Agency Code	
15. Supplementary Notes			
Report uploaded at www.pacTrans.org			
16. Abstract			
<p>The two primary considerations for highway work-zones are its effect on commuter mobility and worker safety which are often spoken of together. However, it must be noted that they conflict with each other. This research aims to study this generally inverse relationship and develop a Decision Support System (DSS) for work-zone traffic control for state DOTs and contractors to determine the most effective traffic control and work-zone operation plans by evaluating their effects on the mobility of the traveling public. Work-zone information about safety devices (e.g., cones and barrels) from traffic control plans will be collected. Also, mobility through work-zones will be measured by periodic sampling of anonymized crowd-sourced data from publicly available mobile mapping services. This information will be used along with survey responses from workers and commuters to determine optimal traffic control strategies that maximize worker safety while still minimizing the adverse effects on commuter mobility. Results obtained from the perception survey data, quantitative mobility data and work-zone data helped create a Decision Support System that utilizes an index numbering process to augment user's decisions when selecting work-zone variables relatively balanced in safety and mobility.</p>			
17. Key Words		18. Distribution Statement	
Work-zone, safety, mobility, survey, worker, commuter		No restrictions.	
19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.		NA

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Executive Summary

This report outlines information on research focused on improving the safety of workers and commuters on work-zones, while still ensuring the mobility of commuters. The two primary considerations for highway work-zones are its effect on commuter mobility and worker safety which are often spoken of together. However, it must be noted that they often conflict with each other. For example, traffic control plans that reduce travel speed in work-zones improve both commuter and worker safety but adversely affect commuter mobility. Thus, transportation agencies require work-zones to be active only in times of low traffic (i.e. nighttime and weekends) to minimize its impact on the public's mobility.

This research aims to study this inverse relationship and develop a Decision Support System (DSS) for work-zone traffic control for state DOTs and contractors to determine the most effective traffic control and work-zone operation plans by evaluating their effects on the mobility of the traveling public. Work-zone information about safety devices (e.g., cones and barrels) from traffic control plans will be collected. Also, mobility through work-zones will be measured as the difference between vehicular travel speed and posted speed limits along a work-zone route. This information will be obtained by periodic sampling of anonymized crowd-sourced data from publicly available mobile mapping services. This information will be used along with survey responses from workers and commuters to determine optimal traffic control strategies that maximize worker safety while still minimizing the adverse effects on commuter mobility.

Results obtained from the perception survey data, quantitative mobility data and work-zone data were used to create the Decision Support System. It is expected that these results, along with the created DSS will provide an adequate means for construction professionals to design a work-zone layout with variables that optimize safety and mobility on jobsites.

Chapter 1: Introduction

In recent years there has been an increase in the construction work on highways to replace older road networks across the United States. This frequency is attributable to the fact that a lot of the United States highway systems are reaching their 30-40 year service lives and therefore require maintenance, preservation, and rehabilitation (Oh, Kim, & Park, 2011). Ultimately, these efforts aim to improve transportation infrastructure quality for the betterment of the travelling public and pedestrians during commutes. However, even with their goal of improving driving conditions, construction projects cause traffic congestion. A traffic delay study conducted by the Oak Ridge National Laboratory identified that work-zone activities in particular create 24% of nonrecurring traffic delays on freeways (Chin et al. 2004). The results of this study are detailed in Figure 1 below.

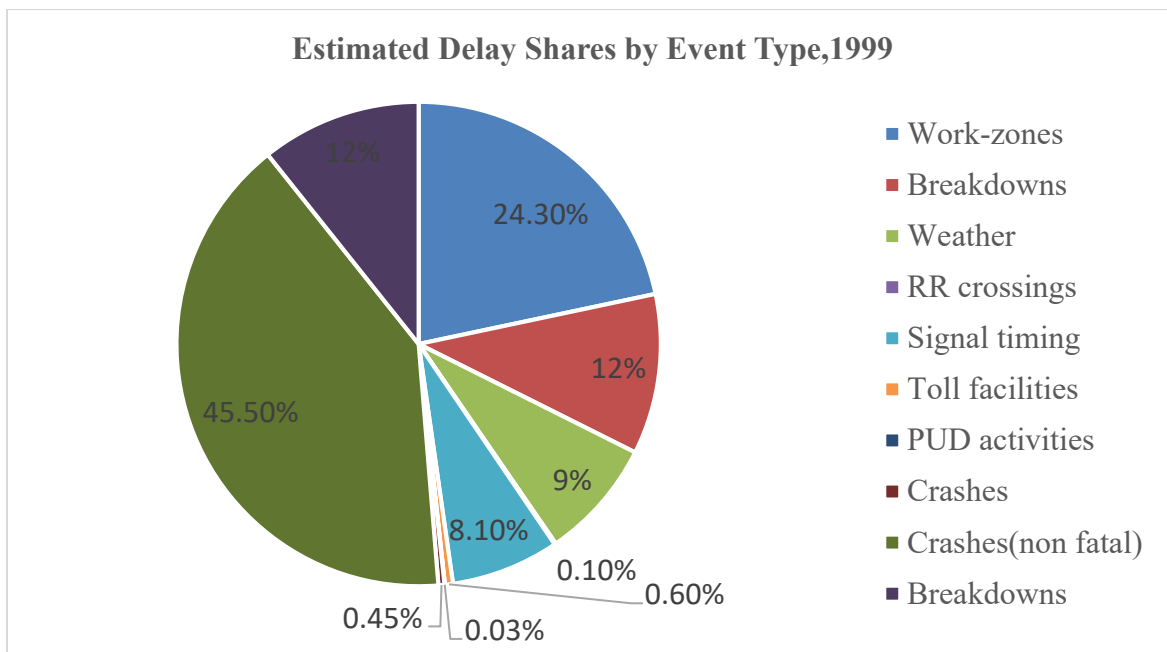


Figure 1: Delay Attributed to Work-zones and Various Other Transportation Activities

According to the findings in Figure 1, work-zone delays rank second only to non-fatal crashes in terms of being the source of delays for commuters. This large delay share by work-zones shows the pertinence of finding solutions that improve traffic flow through roadway jobsites.

From a time-wise perspective, a study by the Federal Highway Administration (2004) estimated that over 482 million hours of traffic delays per annum is caused by construction work. These delays can be psychologically draining to drivers and could increase driver frustration and aggression. Hennessy and Wiesenthal (1999) conducted a study where drivers were interviewed over the phone during high and low congestion traffic conditions (Hennessy & Wiesenthal 1999). A checklist was utilized to assess drivers stress level on a scale based on their responses to interview questions. Using this scale and a statistical analysis of each participant's average response, the researchers discovered that individuals commuting in high traffic density conditions had a higher state driver stress and aggression score. These results show how vehicular congestion has negative repercussions on driver mental state. From a monetary perspective, traffic delays also cause financial losses to commuters and communities. The annual cost of driving delays in the United States was quantified to be approximately \$48 billion, this price adds up to be about \$640 per driver (Arnott & Small 2012). This shows how traffic delays have significant fiscal impacts not only to individuals but to the country's economy as a whole.

Roadway work-zones activities also pose challenges to construction safety. Work-zone roadways are notorious for high incidence rates of fatality and injury per lane-mile of roadway when compared to non-work-zone roadways.

A study conducted by the FHWA, did a comparison between non-work-zone crashes and work-zone crashes from 2008 to 2015. Results from the study indicated that work-zone fatality crashes have a higher occurrence rate than non-work-zone crashes between the years 2008 to 2015. This elevated crash rate on work-zones can be attributed to the fact that in the U.S.A there's is an increase in the amount of commuters on roadways while the rate of new roadway miles created has been at a fairly constant rate since 1980 (FHWA 2014) .

1.1. Problem Statement & Research Goal

The research studies discussed in the previous section demonstrates that if the issues pertaining to commuter mobility and jobsite safety on work-zones are independently tackled, solutions can be found. However, the generally inverse relationship between these two elements results in a situation where improving one element leads to the detriment of the other (Abdelmohsen and El-Rayes 2018). For example to improve worker safety on a site, a construction manager might

utilize traffic control devices and practices that reduce vehicular travel speed through work-zones. While these practices might reduce crash/collusion incidences, it also results in a slower traffic flow around the site. This traffic slow-down could create vehicular congestion that negatively impacts commuter mobility. Inversely, a construction manager might try to please the public by creating a traffic control plan with more focus on commuter mobility. However this free flowing traffic regulation system may cause construction workers to have a greater exposure to high-speed live traffic during work hours. Exposing construction personnel to this risk increases the chances of them being struck by drivers.

The facts indicated in the preceding paragraph demonstrates that a balancing act is required for construction firms and state transportation agencies to ensure that roadway construction has minimal negative impacts to both the travelling public and construction employees. Therefore it the overall goal of this research to:

“To develop a Decision Support System (DSS) for state DOTs and contractors that helps augments the user decision making when determining the most effective traffic control and work-zone operation plans that balance safety and mobility.”

This research proposes to achieve this goal by meeting the following objectives:

1. Objective 1: Automatically quantify mobility of commuters through work-zones by establishing mobility metrics and collecting live anonymous user-generated traffic data
2. Objective 2: Quantify the safety of construction work-zones through a multi-step process of literature review, traffic control plan analysis, and survey data analysis metrics
3. Objective 3: Determine the relationship between safety and mobility on work-zones using the previously determined metrics.

Before detailing the methodology required to meet this study’s goals and objectives, extant literature will be reviewed to analyze recent research attempts that have tried to solve the work-zone mobility-safety relationship problem. Gaps in existing knowledge are identified and this study’s point of departure is extensively detailed.

1.2. Current Work-Zone Safety-Mobility Optimization Methods

Analyzing the relationship between safety and mobility metrics provides a more generalized perspective on how work-zones impact motorists and construction workers. Some research has been already done on the safety vs mobility relationship for work-zones.

A study by El-Rayes et al. in 2014 , conducted research to find the impact of safety and traffic control measures in improving safety and mobility on work-zones (El-Rayes et al. 2014). To accomplish this, the researcher conducted a national survey. These surveys were sent out to 100 DOT engineers to gather their opinions on the effectiveness of traffic control devices on work-zones. Their findings help determine the importance of flaggers and spotters in different construction scenarios.

Abdelmouhsen and El-Rayes in 2018 created a multi-objective model that sought to improve highway work-zone layout design by identifying layout features that help improve work-zone safety and mobility (Abdelmouhsen & El-Rayes, 2018). They were able to accomplish this through the use of genetic algorithms. The overall goal of their model was to minimize work zone risks and minimize work-zone related traffic delays. Results from their study revealed that the key decision variables for optimal safety-mobility balance on work zones were (1) Work-zone speed limit (2) Construction start time (3) Shoulder use (4) Lateral clearance (5) Work zone segment length (6) Traffic control measures and (7) Work-zone access and egress methods..

Ding et al. (2013) sought to determine and analyze key factors of work-zone safety and mobility. Their research, which was set in China had the overall goal of identifying these key factors to improve work-zone management practices for highway construction in their country. Micro-simulation modeling was used in this research to garner results. Findings upon research conclusion revealed that speed limit value on the work-zone had the greatest influence on on-site safety and mobility. (Ding et al. 2013).

1.3. Identification of Gaps in Research

The studies mentioned above have positively contributed to finding a solution to the safety-mobility relationship problem on highway work-zones. However, certain limitations are present in their employed methodologies.

Genetic algorithms for work-zone optimization as used in the research of Abdelmouhsen and El-Rayes was able to yield results. However this study is limited due to the fact that genetic algorithms belong to non-deterministic class of algorithms. Consequently, the optimal solution derived from this process may differ every instance that the algorithm is run for the very same input data.

Microsimulations based optimizations like the one used by Ding et al. 2013, have some limitations. This due to the fact that microsimulations constrains research veracity. This is because microsimulations produce results influenced by assumptions different from real-world observations.

Perception surveys were the only methods utilized in the study by El-Rayes et al. 2014, to define the safety-mobility relationship between multiple variables on a work-zone. In this research methodology, the researchers were prudent in gathering opinions from a knowledgeable population sample (DOT engineers). However, this type of research is limited because it relied solely on user perception to qualify the value of safety and mobility for each work-zone variable. This sole dependence on subjective data might provide results heavily skewed from real-world observations.

1.4. Point of Departure

This research intends to address all of the identified gaps in literature. Unlike certain previous studies, genetic algorithms are not used during the data analysis and decision support creation stage of this thesis. This was done to prevent the optimization solution variation problem that is observed in genetic algorithm based models. Also, no microscopic simulation or macroscopic simulation optimization methods were adopted in the system. Not using these type of optimization methodology would minimize the need for assumption during model development. This will reduce the possibility of experimental results being different from real-world observations.

Perception surveys, work-zone data and user generated traffic information would be used in this research to establish the safety-mobility relationship among work-zone layout variables. Combining both subjective and objective data collection approaches will provide more well-

rounded and accurate results. This is in contrast to other state of the art research that use only subjective perception surveys to validate their findings.

Finally, the utilization of user generated mapping data will provide a novel approach to gather mobility information on work sites. Current state of the art technology demands the use of spot sensors to get accurate vehicular mobility results. However installation of these spot sensors is obtrusive and difficult to maintain. Additionally newer sensor technologies like microwave sensors, infrared sensors and video sensors are expensive, highly sensitive to weather or have difficulty tracking stationary motorist. Employing user generated traffic applications to collect mobility data combines the convenience of simulation models with the accuracy of spot sensors. By utilizing crowd sourcing as an innovative means of collecting mobility data, this research is parsing “big data” in real time from thousands of travelers. This obviates the need for on-site personnel and sensor systems, thereby making the proposed methodology scalable and easily replicable for a large number and type of roadways projects.

Chapter 2: Literature Review

This section details the literature review conducted to gather requisite information on the relationship between work-zone safety and mobility. This review was conducted by analyzing data from research articles and from key transportation manuals like the Manual on Uniform Traffic Control (MUTCD) and the Oregon Traffic Control Plans Design Manual devices (OTCPDM) (King et al. 2019). To perform a thorough review, the following topics will be covered in this section:

- 1) **Work-zone Layout:** This subsection provides a general overview of what work-zones are and the key components that form their make-up.
- 2) **Work-zone Transportation Management Practice:** This subsection identifies and reviews widely used work-zone transportation management methods and traffic control devices.
- 3) **Work-zone Safety:** This subsection helps define what safety is on work-zones and determining key metrics/measurements of safety. This will be accomplished by examining extant literature
- 4) **Mobility on Work-zones:** This subsection defines what mobility is on a work-zone and determining key metrics/measurements of mobility. Additionally, the novel mobility data collection method to be used in this particular research will be discussed in detail.
- 5) **Current Work-zone Safety-Mobility Optimization Methods:** In this subsection, current methods used to improve the safety-mobility relationship on work-zone are analyzed. The merits of these methods are also discussed.
- 6) **Identification of Gaps in Current Research:** In this subsection gaps in the state of the art technologies and research used to balance work-zone safety-mobility relationship are analyzed.
- 7) **Thesis Point of Departure:** This section discusses how this thesis research attempts to resolve the limitations of current methodologies.
- 8) **Literature Review Summary:** This brief subsection serves as a summary of everything discussed in the literature review chapter of this thesis.

2.1 Work-zone Layout

The success of a roadway construction project is tied to the overall design of its work-zone layout. A properly designed work-zone layout and traffic control plan improves the effectiveness of production by construction workers, improves safety, and also minimizes congestion around the site. Efficient traffic flow management can be accomplished by creating a layout that is not overly crowded with traffic control devices and that also provides a distinct buffer between live motorist traffic and construction work activity areas.

According to the Oregon Traffic Control Plans Design Manual, work-zones are typically made up of four areas (King et al. 2019). These areas include (1) Advance Warning Area (2) Transition area (3) Activity Area (4) Termination Area. These work-zone components are detailed in Figure 2.

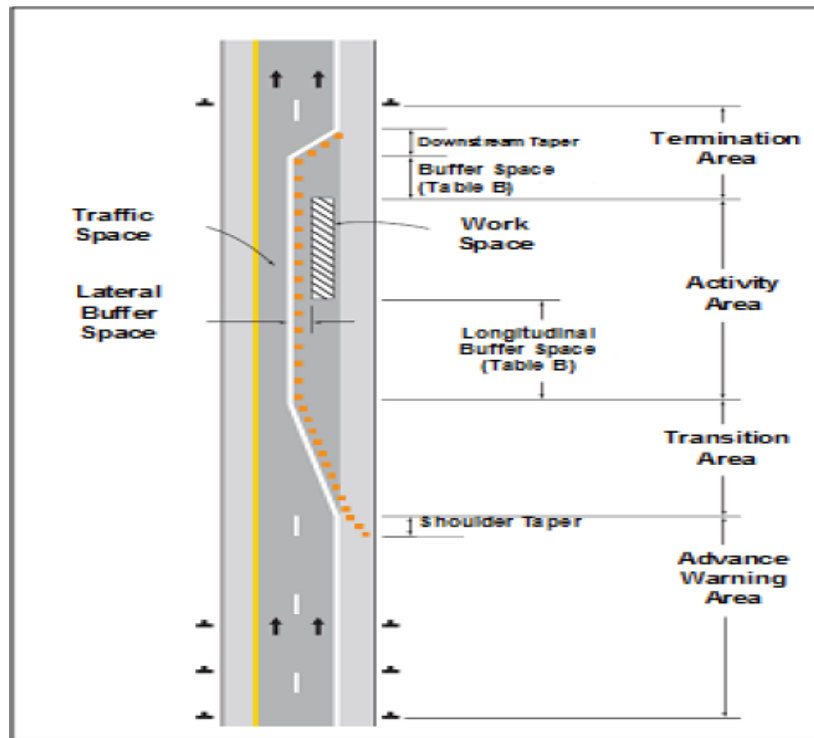


Figure 2: Major Components of Work-zones (FHWA 2014)

Apart from the components detailed in Figure 2, other work-zone components exist but are usually more project specific (King et al. 2019). These may include layout sections like tapers, detours and diversions.

2.1.1. Advance Warning Area

This is the area where the motorist or pedestrians first recognize a work-zone during their approach. Typically this section has advanced warning signs to notify the road user. These warning areas should extend between 450m to 800m depending on the type of roadway (FHWA 2014)

2.1.2. Transition Area

The transition area is the location on the work-zone where road users are directed out of their normal travel path through the use of channelization devices (FHWA 2014). Based on previous studies the transition area is the location with the highest incidence of work-zone crashes.

Therefore it is important that particular attention is given to this section during the work-zone layout design process.

2.1.3. Activity Area

This area is where all the activities on the work-zone take place. This area is comprised of the work space, the buffer space and the traffic space. The work space is where construction activities are undertaken. This section is either mobile or stationary depending on the type of work or construction progress (Elghamrawy 2011).

The buffer spaces are used to separate commuters from construction work. These buffer spaces are classified as either longitudinal buffers or lateral buffers. A longitudinal buffer is designed to provide motorists time to recover from driving mistakes before reaching the work area. A lateral buffer is simply a space between traffic lane and the edge of work area (OTCPDM 2015). Finally the traffic space refers to the space in the activity area where motorists traverse.

2.1.4. Termination Area

The termination area is the section of the work-zone that returns road users to their originally intended path of travel. This section should have the last traffic control devices and have no construction equipment (Elghamrawy 2011). This reduction in potential crash objects makes the termination area the work-zone section with the least amount of crashes.

2.1.5. Other Work-zone Components

Detours are typically used to provide an alternative travel route for commuters, that is outside project limits (OTCPDM 2015). This is done in situations where it is more prudent to separate traffic from the work area. Often this is due to heightened safety risk to commuters or workers because of the nature of a construction project. Diversions are used to move traffic from one part of the existing roadway in the work-zone to another part.

Tapers typically direct traffic from one path to another through the use of channelizing devices. There are 5 types of tapers that are used on work-zones. These include the merging tapers, shifting taper, shoulder taper, downstream taper, one-lane two-way traffic taper. Figure 3 shows images of these tapers on work zones.

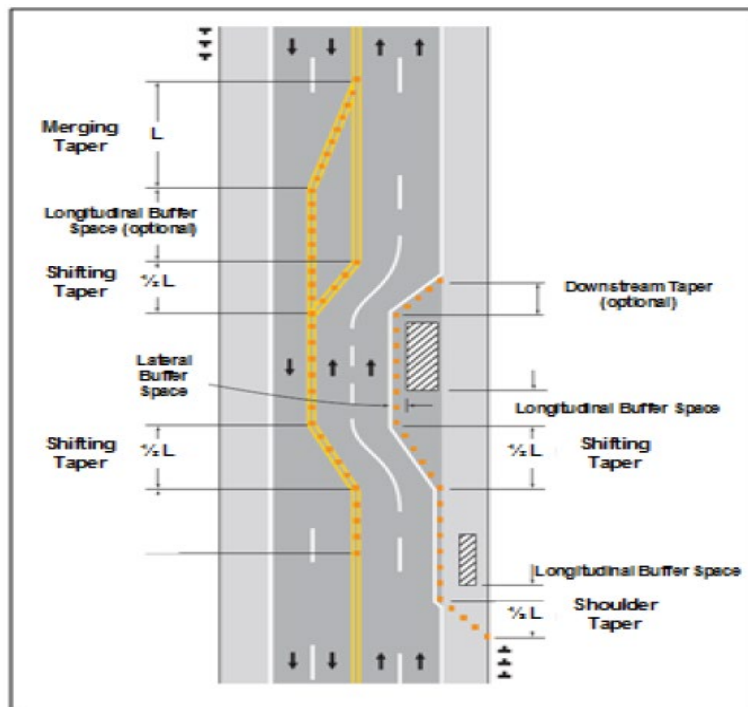


Figure 3: Work-zone Tapers & Buffers (MUTCD 2009)

2.2 Work-zone Transportation Management

The closer a work-zone is to an active roadway, the more it requires the implementation of appropriate transportation management practices to provide flow continuity to motorists. Factors such as road user condition, duration of operation and type of roadway also affect the type of management practice used on a work-zone (Elghamrawy 2011).

Within the construction industry transportation management practices can be broken down into three components (1) traffic control plan (2) public information plan (3) transportation operation plan (FHWA 2014)

This particular research study will focus only on analysing traffic control plans for data gathering due to the fact that these elements will help effectively determine the variables on site pertinent to mobility and safety.

Traffic Control Plans

Traffic control plans (TCP's) are layout designs that show the distribution of traffic control devices across the work-zone. A good TCP should focus on: (1) construction procedures (2) traffic demand (3) work-zone traffic control (4) specific work-zone strategy (Bryden & Mace 2002).

The temporary traffic control devices found in a TCP are implements that are used on work-zones to regulate, warn and guide traffic (MUTCD 2009). On the other hand, traffic control procedures are strategies used on the work-zone sites that are used to improve safety and mobility on a job-site (i.e. Lane closure)

Within the context of this thesis research, traffic control devices and traffic control procedures were arranged into 4 categories based on their functionality.

1. Speed Reduction and Traffic Redirection: These are devices and management practices that influence the direction of approaching live traffic as well as reduce their approach speed (i.e. speed capture cameras, pilot cars, medians, on-site law enforcement).

2. **Intrusion Prevention and Channelization:** These are devices and management practices that aim to hinder the intentional or nonintentional encroachment of high risk areas of the work sites by motorists (barriers, cones etc.).
3. **Proximity Alert:** These are technology and management practices that utilize audio communication and visual cues to warn workers that a vehicle might be encroaching their work space before the action even occurs.
4. **Visibility Improvement:** These are work-zone designs, devices and safety management practices that properly illuminate the work space at night and improve the visibility of workers to the driving public or any machine operator on the jobsite (i.e. Electric lamps, reflective personal protective equipment etc.).

Apart from traffic control devices other elements can play a key role in adequately regulating live traffic and promoting safety on a construction site. This may include safety personnel like flaggers, the use of personal protective equipment by workers and even practices like lane closure.

2.3 Safety on Work-zones

Determining the pertinent safety issues on work-zones requires the definition of what safety is and the identification of key metrics. Safety can be described as minimizing the potential occurrence of hazards that affect road users and highway workers within the confines of a work-zone and adjacent roads (FHWA 2014).

The process of measuring safety is typically done in research by gathering incidental data and perception surveys. Adopting this practice provides a means of garnering information about safety hazards on worksites while also collating the opinions of the workers that are exposed to these risks. Within the context of this particular research, the author used perception surveys to gather safety data. These metrics are affected by the physical structure of a work-zone and all temporary traffic control devices utilized on site (Chen and Tarko 2014)

The relationship between safety and highway work-zones has been investigated in a number of studies. In 1990 Gerber and Woo conducted research to understand the accident characteristics at work-zones located in urban areas (Gerber and Woo 1990). The goal of the research was to assess the ability of traffic control around work-zones to reduce accident occurrence rates.

Accomplishing this required the creation of regression models relating to the accident rates before and during a project with control devices. The results from the study indicated that the major influencing factor on accident rates during roadway construction is the accident rate just before the construction time frame.

Similar research was conducted by Rista et al. in 2017. The safety impacts of varied temporary traffic control strategies on roadways was examined by the authors. Specifically, they utilized certain statistical analyses to scrutinize crash trends and evaluate work-zone safety control strategies pertaining to shoulder closures, single-double-lane closures and lane shifts. Results from the experiments indicated large occurrence rates of vehicular accident with traffic control procedures that used single lane closures and required lane shifts.

2.4 Mobility on Work-zones

Mobility is defined as the measured quantity of velocity by motorists during the introduction of a work-zone along a particular route FHWA (2004). According to the FHWA (2004), performance metrics that can be used for assessing mobility may include any of the following:

- 1) Speed: The summation of the instantaneous or spot measured speeds at a specific location of vehicles divided by the number of vehicles observed (MUTCD, 2009).
- 2) Delay: Any additional travel time deviating from the averaged baseline speeds that a driver, pedestrian or passenger experiences during commute on a particular roadway. (Highway Capacity Manual, 2010)
- 3) Travel Time: A specified period of time spent travelling from one point to another.
- 4) Queue Length: This refers to the measurement of the number of vehicles forming a line on a stretch of roadway due to increased traffic volume (MUTCD 2009).
- 5) Queue Duration: It refers to the amount of time that a queue length lasts due to increased traffic volume (Ulman 2011).

For the purpose of this research the author will utilize speed as the measurement of mobility. The author theorizes that the aforementioned metric of mobility is significantly affected by identified variables on a work-zone like lane closure and traffic control device distribution. (Abdelmohsen and El-Rayes 2017 Elghamrawy 2011, Du and Chien 2014; FHWA 2014).

Literature by several other authors have delved into the relationship between work-zone and traffic mobility. A research article written by Du and Chien (2014), discussed an analytical model used to optimize work-zone length based on time varied traffic volume. By testing their model in a New Jersey case study, the researchers were able to create a framework that utilized roadway shoulders to increase traffic mobility. Investigation into traffic congestion induced by work-zones was also conducted by Fei et al. (2016). A cellular automata model was proposed that took into account driving behavior and acceleration rates of vehicles during the approach, bypassing and departure of a work-zone on a highway. Their traffic simulation program was made realistic through the use of certain randomization factors during its development. Upon concluding their investigations, the researchers were able to find out that the probability of a driver merging into an unblocked driving lane decreases when traffic density increases due to work-zone obstruction.

2.4.1. Traditional Traffic Mobility Data Acquisition Methods

Conducting traffic flow assessments requires the use of tools that allow motorist mobility measurement. Typically tools such as spot sensors and simulations are used to get quantifiable data that can be analyzed. However utilizing these data acquisition methodologies has its drawbacks. This section highlights the following technologies:

1. Sensor Technology
2. Simulation Models

Both these technologies will be reviewed and their functionalities discussed.

2.4.1.1 Sensors Technology

Sensor technology has been one of the primary practices used in transportation management and incident trend analysis to determine traffic density on roadways. However these technologies typically utilize obtrusive installation techniques and are hard to maintain. For example, widely used sensors like the inductive loop detector (ILD's) require the cutting /drilling into pavements during installation. (Atluri et al. 2007). Numerous research attempts have also been made to improve the functionality of ILD's through the creation of improved algorithms (Sun & Ritchie 1999 and Coifman 2001). Unfortunately these improvements do not negate the fact that these

sensors get easily damaged and repair work requires the shutting down of traffic lanes (which further decreases commuter mobility).

Video sensors have also been used as a means of continuously monitoring traffic flow. Methodology to detect incidents using videos requires an accurate estimate of traffic patterns. However the ability to determine the accuracy degrades due to external factors that affect video quality. For example, inaccurate traffic analysis can occur due to adverse weather conditions, light glares/reflection, low visibility time of day. Additionally, even with the availability of good quality videos, significant time consuming post-processing analyses is needed before yielding usable information (Edara & Cottrell 2007).

Other traffic sensor technologies have also been coming to prominence in the field of transportation engineering. Non-intrusive sensing technologies like infrared, acoustic and ultrasonic sensors are gaining popularity due to the fact that they obviate the need for intrusive installation practices. However, most of these technologies are either too expensive or extremely sensitive to weather (Alturi et al. 2007). Microwave radars have also been used as traffic detecting sensor technology. Microwave sensors work by utilizing devices that operate at electromagnetic field frequencies starting from 300 MHz to the terahertz range (Polivka 2007). This technology shows great promise, but has difficulties tracking motorist that are stationary or slow moving (Zhang et al. 2004).

2.4.1.2 Simulation Models

Simulation models also provide a means of analyzing vehicular mobility trends to aid in traffic management. There are two main types of simulators that are utilized to achieve this end: macroscopic and microscopic.

Macroscopic simulators provide traffic description in ways that can be declared as global; principally, they are used to solve the tactical problems of strategic planning. (Buisson et al. 1996). Macroscopic simulators also present discrepancies when modelling interaction among motorists (el Hmam et al. 2006). Some examples of these simulators include NETFLO2, FREFLO etc. This technology however requires the use of assumptions when creating models. The use of assumptions cause deviations often times different from real world situations.

Microscopic simulators create models that analyze flow movements at only the vehicular level. Unlike macroscopic simulators they operate on a smaller scope and are mainly used to study drivers individual behavior (Krauß, 1998). According to El Hmam et al (2006) using these tools to simulate traffic flow causes significant data-processing resources to deal with inherent large data sets. Example of these simulators include Integration, Corsim, etc. Much like macroscopic simulators, microscopic simulators also require assumptions. These assumption cause deviations different from real-world observations.

2.4.2. Crowd Sourced Traffic Data

This research deviates from typical mobility studies by utilizing crowd sourced traffic data acquisition (specifically global positioning technology platforms). Global positioning technology seems to be the key to solving some of the current issues plaguing traditional methods of mobility data acquisition. The mainstream use of handheld devices in particular will prove to be very useful in shaping how satellite-based GPS systems can be leveraged in understanding, monitoring and analyzing traffic flow patterns near work-zones. Most smart mobile phones have receivers that correspond with positioning satellites to provide the user geospatial information needed for navigation.

Location service applications like Google Maps are immensely popular and are used on a daily basis by a large number of cell phone owners. Given this fact, a significant number of motorist can be represented using GPS data. Consequently a practical and highly dynamic traffic monitoring system can be created by collecting highway specific location data being transmitted from mobile devices and this data can be used to represent the amount of traffic on a roadways (Amin and Uddin, 2007)

Google Maps

Google Maps is an extension of the Google map feature that helps determine the live density of traffic and their flow rate over a given stretch of roadway. To produce this data, Google uses crowdsourcing from its android users. Each phone user can opt to turn on/off the tracking feature of their phone (Barth, 2014). When turned on there are two main methods that the location of individuals can be extracted to determine traffic flow. These two approaches include:

1. Tower Trilateration: This process is determines the absolute or relative location of points by the measurements of distances or through the use of geometry. Distances are determined by using the time delay each user experiences relative to at least three surrounding cell phone towers near their location.
2. Global Positioning System: Global Positioning Systems (GPS) are utilized to triangulate the geodetic location of several drivers on roadways by finding out the users exact coordinates. As the car moves, the coordinates change over a period of time of each user can be determined.

The combined tower trilateration and GPS geospatial data is used to analyze the speed of each individual motorist. The average of other user's velocity path is then calculated and this result is then plotted on a map displayed on the user's cellphone. Certain algorithms created by Google excludes frequent stopping vehicles (like post office trucks) that might alter the traffic data (Matthews, 2013). Once all these considerations have taken place, all the averaged velocity plots are then assigned different colors to show different traffic congestion levels.

For example, the Google Maps color codes for highway speeds are as follows:

1. Red Lines: Represent traffic velocities below 25 miles per hours
2. Yellow Lines: Represents traffic velocities 25 to 50 miles per hours
3. Blue/Green Lines: Represents traffic velocities 50 miles or more

Figure 4 shows all the different color markings on the google map API that denote different traffic congestion speeds.

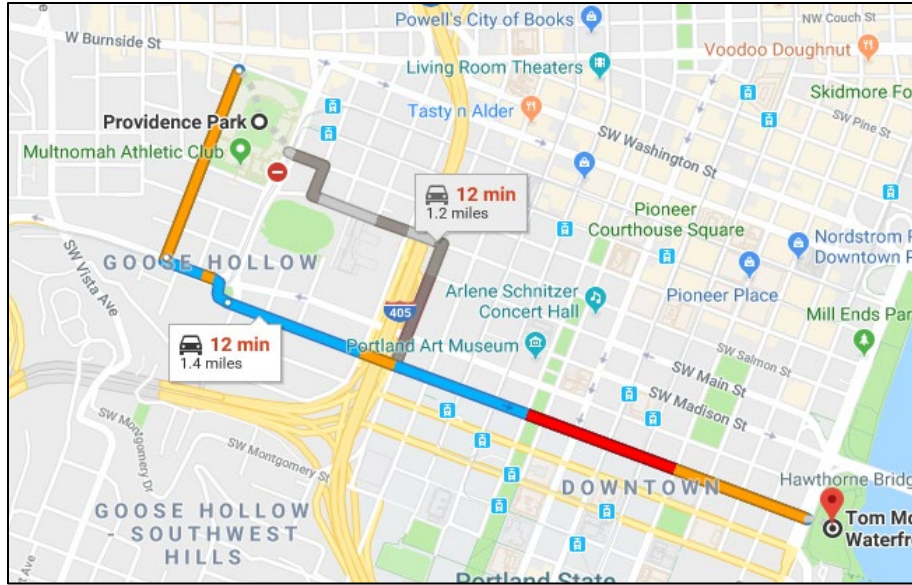


Figure 4: Display of Google Maps API with Live Traffic

All of these color schemes represent live data and can be used within the context of our particular research to show how the obstruction of work-zones affects commuter mobility.

Speed is the mobility metric that will be used in this research to quantify the mobility of traffic over a given area of roadway. This measurement provides a clear indication of the dynamic characteristics of traffic flow of motorists as they commute. According to the Manual of Uniform Traffic Control Devices (2009) average vehicular speed on a roadway is derived from the summation of spot measured speeds at a specific location, divided by number of vehicles observed. However this method of measuring speeds cannot be applied to GPS based traffic mobility measuring tools like Google Maps since their technology does not utilize any spot measuring equipment for determining speed. Consequently, new parameters as to what delineates the speed of a motorist needs to be expressed specifically for Google Maps. The answers to this question can be found in how speed is calculated when utilizing GPS/Cell tower trilateration. This can be surmised in the following calculation steps:

Step 1

The differences between latitudinal and longitudinal position of the motorist is calculated to determine the distances travelled (Pennau, 2014).

Using Haversine formula:

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos \phi_1 * \cos \phi_2 * \sin^2\left(\frac{\Delta\lambda}{2}\right)$$

$$c = 2 * \text{atan2}\left(\sqrt{a}, \sqrt{(1-a)}\right)$$

$$d = R * c$$

Where:

Φ = Latitude coordinates

λ = Longitude coordinates

R = Earth's radius (6, 371km)

d = *Distance on earth surface*

Step 2

The internal clock of the GPS receiver (in this case the user's phone) synchronizes with the atomic clock on the GPS satellite. This atomic clock has the capability of providing extremely accurate time measurements of the user. Therefore to determine how long it takes a user to travel from one point to another, the difference between two timestamps at those points need to be calculated. This can be represented in the following formula:

$$T_i - T_f = \Delta T$$

Where:

T_i = Initial time

T_f = Final time

ΔT = Time difference

d = *Distance on earth surface*

Step 3

Determining the speed of each individual user can be obtained by using the following formula:

$$\text{Individual Velocity (v)} = \frac{d}{\Delta T}$$

Where:

T_i = Initial time stamp measurement

T_f = Final times stamp measurement

ΔT =Difference between initial and final time stamp

Step 4

The average of the velocity of all available cell phone users is gathered through crowd sourcing to give the general speed of vehicles moving on the roadway.

$$\text{Total Averaged Velocity (TAV)} = \frac{v_1 + v_2 + v_3 + \dots + v_n}{n}$$

Where:

v = Individual Velocity

d = Initial time stamp measurement

T_f = Final times stamp measurement

ΔT =Difference between initial and final time stamp

Based on the information indicated in the steps above, speed in Google Maps is expressed as the value of the total averaged velocity of crowdsourced vehicles based on their calculated coordinate distance on the earth's surface and the time stamp differences from an initial location point to a final location point.

2.5 Current Work-Zone Safety-Mobility Optimization Methods

Analyzing the relationship between safety and mobility metrics provides a more generalized perspective on how work-zones impact motorists and construction workers. Some research has been done on the safety vs mobility relationship for work-zones. However, only a few of these studies sought to develop models that optimized work-zone planning to maximize safety and mobility.

A study by El-Rayes et al. in 2014 , conducted research to find the impact of safety and traffic control measures in improving safety and mobility on work-zones (El-Rayes et al. 2014). To accomplish this, the researcher conducted a national survey. These surveys were sent out to 100

DOT engineers to gather their opinions on the effectiveness of traffic control devices on work-zones. Their findings help determine the importance of flaggers and spotters in different construction scenarios.

Abdelmouhsen and El-Rayes in 2018 created a multi-objective model that sought to improve highway work-zone layout design by identifying layout features that help improve work-zone safety and mobility (Abdelmouhsen & El-Rayes, 2018). They were able to accomplish this through the use of genetic algorithms. These algorithms, inspired by the process of natural selection used a population candidate of solutions to perform optimization to meet their multiple objectives. The overall goal of their model was to minimize work zone risks and minimize work-zone related traffic delays. Results from their study revealed that the key decision variables for optimal safety-mobility balance on work zones were (1) Work-zone speed limit (2) Construction start time (3) Shoulder use (4) Lateral clearance (5) Work zone segment length (6) Traffic control measures and (7) Work-zone access and egress methods..

Ding et al. (2013) sought to determine and analyze key factors of work-zone safety and mobility. Their research, which was set in China had the overall goal of identifying these key factors to improve work-zone management practices for highway construction in their country. Micro-simulation modeling was used in this research to garner results. Findings upon research conclusion revealed that speed limit value on the work-zone had the greatest influence on on-site safety and mobility. (Ding et al. 2013).

Models have also been developed to optimize work-zone factors like length, start time and traffic control devices. This was accomplished using cost objective functions that convert the safety and mobility objectives of the identified work-zone factors into equivalent costs (Meng & Weng 2013).

2.6 Identification of Gaps in Research

The studies mentioned above have contributed to helping to find a solution to the safety-mobility relationship problem on highway work-zones. However, certain limitations are present in their employed methodologies.

Genetic algorithms for work-zone optimization as used in the research of Abdelmouhsen and El-Rayes was able to yield results. However this study is limited due to the fact that genetic algorithms belong to non-deterministic class of algorithms. Consequently, the optimal solution derived from this process may differ every instance that the algorithm is run for the very same input data.

Microsimulations based optimizations like the one used by Ding et al. 2013, have some limitations. This due to the fact that microsimulations constrains research veracity. This is because microsimulations produce results influenced by assumptions different from real-world observations.

Perception surveys were the only methods utilized in the study by El-Rayes et al. 2014, to define the safety-mobility relationship between multiple variables on a work-zone. In this research methodology, the researchers were prudent in gathering opinions from a knowledgeable population sample (DOT engineers). However, this type of research is limited because it relied solely on user perception to qualify the value of safety and mobility for each work-zone variable. This over-dependence on subjective data might provide results heavily skewed from real-world observations.

Finally, cost based objective function models like those done by Meng & Weng (2013) are great ways to understand the safety-mobility relationship through a fiscal approach. However these studies are too focused on monetary evaluations and fail to quantify important work-zone variables like speed limit, traffic control measures and shoulder use.

2.7 Thesis Point of Departure

This research intends to address all of the identified gaps in literature. Unlike certain previous studies, genetic algorithms are not used during the data analysis and decision support creation stage of this thesis. This was done to prevent the optimization solution variation problem that is observed in genetic algorithm based models. Also, no microscopic simulation or macroscopic simulation optimization methods were adopted in the system. Not using these type of optimization methodology would minimize the need for assumption during model development.

This will reduce the possibility of experimental results being different from real-world observations.

Perception surveys, work-zone data and user generated traffic information would be used in this research to establish the safety-mobility relationship among work-zone layout variables.

Combining both subjective and objective data collection approaches will provide more well-rounded and accurate results. This is in contrast to other state of the art research that use only subjective perception surveys to validate their findings.

Finally, the utilization of user generated data will provide a novel approach to gather mobility information on work sites. Current state of the art technology demands the use of spot sensors to get accurate vehicular mobility results. However installation of these spot sensors is obtrusive and difficult to maintain. Additionally newer sensor technologies like microwave sensors, infrared sensors and video sensors are expensive, highly sensitive to weather or have difficulty tracking stationary motorist. Employing user generated traffic applications to collect mobility data combines the convenience of simulation models with the accuracy of spot sensors. By utilizing crowd sourcing as an innovative means of collecting mobility data, this research is parsing “big data” in real time from thousands of travelers. This obviates the need for on-site personnel and sensor systems, thereby making the proposed methodology scalable and easily replicable for a large number and type of roadways projects.

2.8 Literature Review Summary

The main goal of this study is to create a decision support (DSS) for state DOTs and contractors to determine the most effective traffic control and work-zone operation plans by evaluating their effects on the mobility and safety on work-zones. This framework will use data collected from perception surveys, work-zones and user generated traffic information to identify worksites variables. In order to meet the goal of creating a Decision Support System this research has the following objectives:

- 1) Objective 1: Automatically quantify mobility of commuters through work-zones by establishing mobility metrics and collecting live anonymous user-generated traffic data

- 2) Objective 2: Quantify the safety of construction work-zones through a multi-step process of literature review, traffic control plan analysis, and survey data analysis metrics
- 3) Objective 3: Determine the relationship between safety and mobility on work-zones using the previously determined metrics.

Details on how these objectives and overall goal was reached will be discussed in the proceeding methodology chapter.

Chapter 3: Methodology

As mentioned previously, the objective of the present study is to develop and propose a DSS that helps augments a user’s decision making and helps them select work-zone variables that are relatively balanced in safety and mobility. A methodology comprised of data collection, data analysis and results gathering was required to attain the goals of this study. Figure 5 displayed on the next page provides an overview of the methodology that was used.

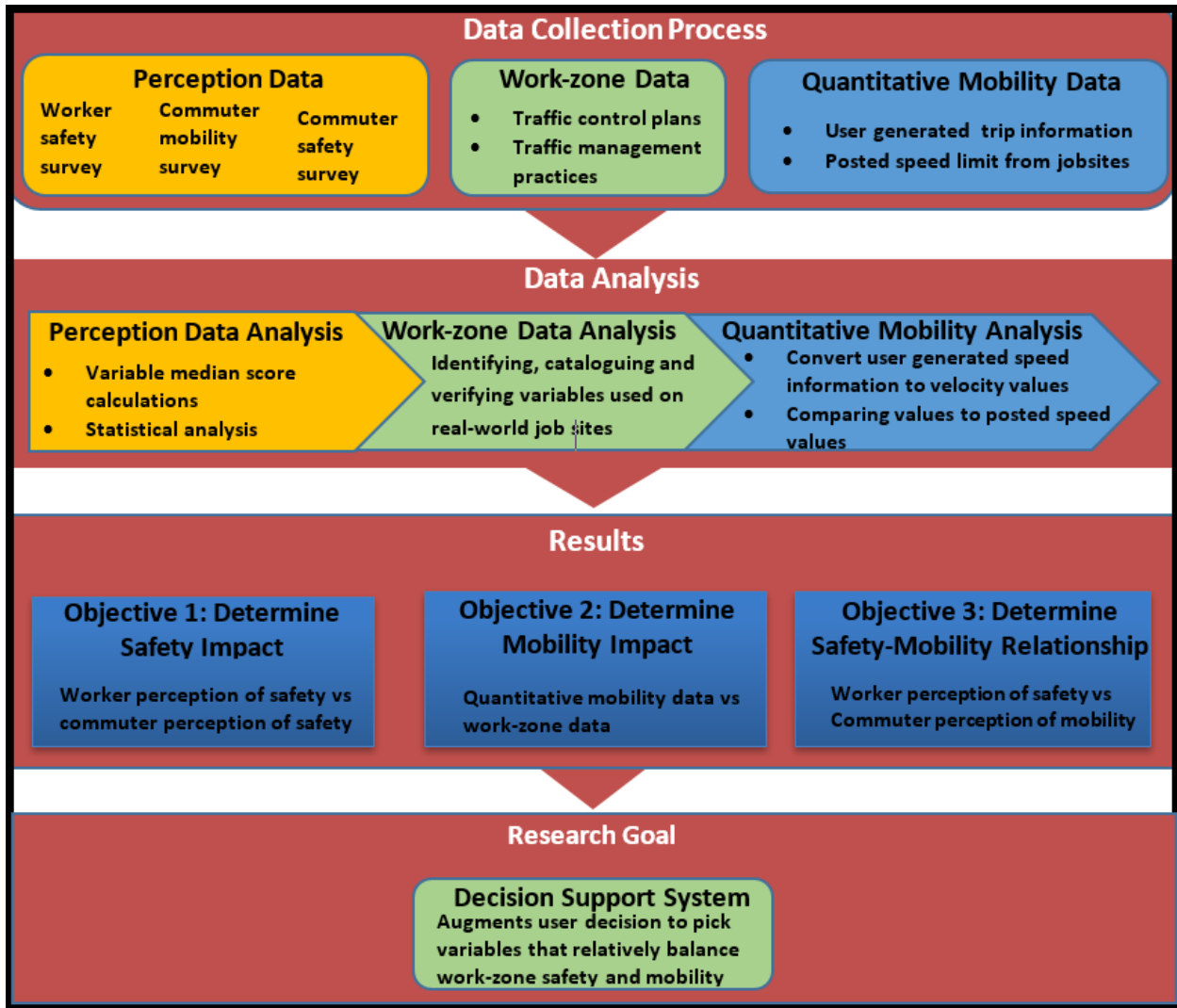


Figure 5: Research Methodology

3.1. Data Collection

Large datasets were generated in the study given the fact that a significant portion of the research requires data gathering from user generated cellular sources. Survey responses and work-zone data cataloging also produced a significant amount of data.

Perception data was the first data type collected in the study. Surveys were sent out to construction workers and commuters to understand the perception of safety and mobility on construction sites by affected population samples. The worker survey was sent to 198 individuals and had a response rate of 22.2% (44 individuals). The survey was designed to ascertain the perception of safety on roadway construction sites by construction professionals. Specifically, questions were asked about the impact of 41 safety-specific work-zone variables grouped into four types. The main body of the survey was created on a six point Likert scale in which contributors would indicate if a certain work-zone parameter made them feel: (1) Highly unsafe (2) Unsafe (3) No effect (4) Safe (5) Highly safe (0) Not applicable. The survey was distributed throughout the Pacific Northwestern region of the United States to individuals with varying roles and experience level within the construction industry to obtain a more representative sampling of work-zone perception of safety in the construction industry. The commuter survey was sent out to the driving public to gather their opinions and experiences on traffic flow and safety around work-zones. The survey was distributed through the use of a content advertising service provided by a social media platform (Facebook). In total, the survey was sent to over 5854 individuals and had a response rate of 1.9% (115 people). To ensure that participant responses were based on relevant personal experience, the survey was designed to filter out individuals without driving experience. The survey relied on drivers opinions to extract results on how visible work-zone characteristics affect commuter's perception of mobility and safety. Consequently, each question for every variable on the survey was repeated twice. Commuters were asked about how each variable influenced their mobility in the first instance and how it influenced their safety in the second instance. A six point Likert scale was utilized to access respondent's perceptions of safety or mobility for each variable.

Quantitative Mobility data was gathered by using the Google Traffic application to gather user generated trip information from motorists. The steps for analyzing this data required the analysis

of vehicular speed along selected routes. To this end, 29 job site across the state of Oregon were used as research samples. These jobsites were chosen after correspondence with officials from the Oregon Department of Transportation (ODOT) to determine their suitability. Some of the criteria used to ascertain jobsite suitability included (1) Work activity status (2) Commuter activity near site (3) availability of traffic control plans. Next, a web scripting language was used to create a code that enabled screen capture of the mapping application every four minutes. Accurate periodic sampling of live traffic for each job site was actualized by refreshing the mapping application. The origin and destination of drivers route was selected by referencing location information in the traffic control plans for each work zones. Using this information the user trip could be set on the right roadway that ran through the work-zone. A screen image capture software was then used to track and store the information after each refresh cycle. This screen capture software (IrfanView) generated a jpeg file database for each work-zone. The four minute cycle image capture process was conducted for 24 hours per jobsite. This yielded a total of 360 images for each work-zone location. Upon conclusion of this phase of the research's methodology, about 10,440 total images were collected for all 29 work-zone sites.

Work-zone data was gotten from the 29 real-world construction sites by sending requests out to administrative personnel on these sites to provide traffic control plans or any relevant documents that detailed transportation management procedures. These documents were then reviewed and all work-zone layout variables were identified and catalogued. This information were compared to the speed data observed on each sites. Observations from these comparisons revealed key work-zone variables that influence quantitative mobility.

1.2 Data Analysis

After the data had been collected, it was analyzed to understand safety, mobility and the safety-mobility relationship on work-zones. This meant that each data type had to be analyzed individually and then compared to other collected data types.

The perception data obtained from the surveys were analyzed through (1) Median calculations (2) Statistical analysis. Median score value for each survey variable (based on participant responses) were calculated to represent the respective population sample perception. Median was chosen as the calculation method since it is the best measure of central tendency for Likert scale

based survey data (Gambatese, Karakhan, & Simmons 2019). As opposed to mean calculations, the median is less likely to be influenced by potential outliers. Statistical analysis (Mann-Whitney U test) was then done to compare worker perception of safety survey results and the commuter perception of safety survey results. The commuter perception of mobility results didn't undergo statistical analysis since it was on a different perception scale to the others.

Quantitative mobility data obtained from the Google Maps image screen for the 29 jobsites also required analysis. Completing this analytical process required the conversion of the image data into quantifiable numerical vehicular speed data. . To this end a code was scripted by the author that counted the pixel quantity of each of the different color-coded speeds observed on every jobsite screen capture image. The scripted code was ran and pixel reading of the quantity of the three Google Maps vehicular speed color categories (blue/green, red and yellow) was actualized. Figure 6 and Figure 7 shows an example of image capture and pixel counting for one of the 29 job sites.

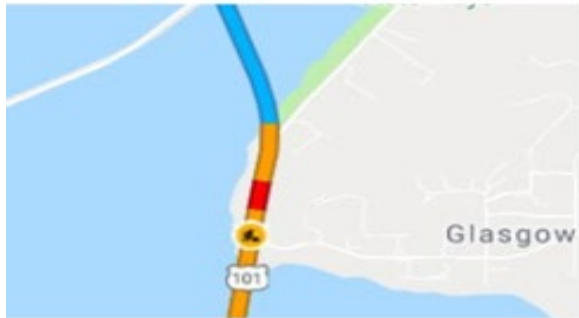


Figure 6: Screenshot of Work-zone Site

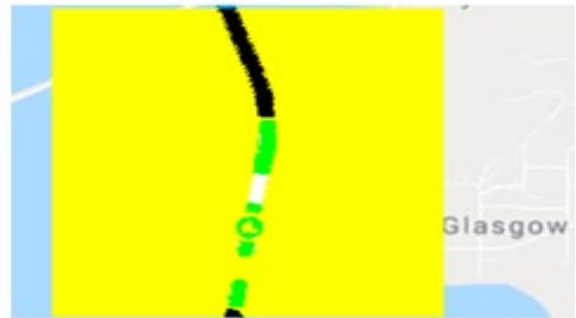


Figure 7: Screenshot During Pixel Counting

After the pixels had been identified the code crafted by the researcher quantified the values of blue/green, yellow and red. These values were then exported to Microsoft Excel. Next, the color to speed parameters provided by the Google Maps application was used to calculate the average velocity on each site. The following formula was developed by the author to determine average velocity for each site:

$$\left[\frac{\sum_{i=1}^n BP_i}{BP+Y_P+RP} * \left(\frac{\max BS + \min BS}{2} \right) \right] + \left[\frac{\sum_{i=1}^n YP_i}{BP+Y_P+RP} * \left(\frac{\max YS + \min YS}{2} \right) \right] + \left[\frac{\sum_{i=1}^n RP_i}{BP+Y_P+RP} * \left(\frac{\max RS + \min RS}{2} \right) \right]$$

Where:

BP= Blue Pixels, max BS= maximum Blue speed, min BS= minimum Blue speed

YP = Yellow Pixels, max YS = maximum Yellow speed, min YS = minimum Yellow Speed

RP = Red Pixels, max RS= maximum Red speed, min RS= minimum Red speed

Formula 1 utilizes summation functions to add each pixel's measurements taken during each discrete instance of image capture on all the work-zone sites. A ratio of total pixel summation of one color type to overall total pixel is then formed. That result is multiplied by the average speed range for that color type (per the parameters provided by Google Maps). Next this result is added to the results of the other color code calculations. The final value derived from this process denotes the average speed observed on the work zone over a period of 24 hours. After calculating all the average vehicular speed for each job site, the posted speed needed to be obtained for delay to be calculated. Information about posted speed limits for each of the roadways was obtained by using the traffic control plans provided by construction administrators, Google Street View and Geographical Information System (GIS) resources. The Federal Highway administration defines roadway delay as "the difference between an ideal travel time and actual travel time". Therefore delay can be estimated by subtracting the hypothetical travel time at posted speed limit from the measured averaged travel time. Using this concept, delay within the context on this research can be defined as the vehicular speed variation observed when subtracting the optimal speed at posted speed limit from the measured average travel time. This is represented in the formula 2 detailed below:

$$V_d = S_a - S_p$$

Where:

V_d = Vehicular delay

S_a = Average speed

S_p = Posted speed

Work-zone data analysis was conducted once all of the layout variables utilized for each of the 29 job site had been identified and catalogued. The project managers for each of the job sites were contacted again. This was done to ensure that nothing was missed and all variables that were utilized on site were accounted for by the author. Any items that were missed were included to this inventory list and any items that were unintentionally added were removed.

Undergoing this verification process would help improve the accuracy of results once quantitative mobility to TCD variables comparisons were done.

Chapter 4: Analysis and Results

Results of the research was obtained therein after analyzing all collected data. The analysis consisted of first comparing the different variables by their effect on safety and mobility. This analysis enables the ranking of work-zone traffic control devices and transportation management practices that rank high in both safety and mobility concurrently. Additionally the Man-Whitney U test was conducted on the safety surveys to see the statistical relationships of variables when comparing their commuter vs workers perception of safety.

Finally, the quantitative mobility values calculated for each of the 29 jobsites were ranked based on Level of Service (LOS) traffic flow ratings. The work-zone traffic control devices and transportation management practices that significantly contributed to traffic flow were recognized. The objective measurement of these variables influence on mobility was then compared to their subjective mobility influence (provided by the commuter mobility survey).

A comparison was made between the commuter safety and worker safety surveys to measure safety on a work-zone. Details indicating the results obtained from survey comparisons and statistical analysis are detailed in the next few sections.

4.1. Survey Median Calculation

The median response score for each work-zone traffic control device and management practice was calculated. This provided distinct scores for each variable (one for commuter safety, one for worker safety and one for commuter mobility).

Variables were then then analyzed based on their pre-established categories. The categories were

1. **Speed Reduction & Traffic Redirection Variables:** These are work-zone traffic control devices and management practices that influence the direction of approaching live traffic as well as reducing their approach speed and through driving speed of drivers (i.e. speed capture cameras, pilot cars, medians, on-site law enforcement).
2. **Intrusion Prevention & Channelization Variables:** These are work-zone traffic control devices and management practices that aim to hinder the intentional or nonintentional encroachment of high risk areas of the work sites by motorists.

3. Proximity Alert Variables: These type of work-zone variables utilize audio communication and visual cues to warn workers that a vehicle might be encroaching their work space before the action even occurs.
4. Visibility Improvement Variables: These work-zone layout parameters detail work-zone designs and safety management practices that properly illuminated the work space at night and improved visibility of workers to the driving public or any machine operator on the jobsite (i.e. electric lamps, reflective personal protective equipment etc.)

Figure 8 shows the spread of median scores when comparing commuter perception of safety, worker perception of safety and commuter perceptions of mobility.

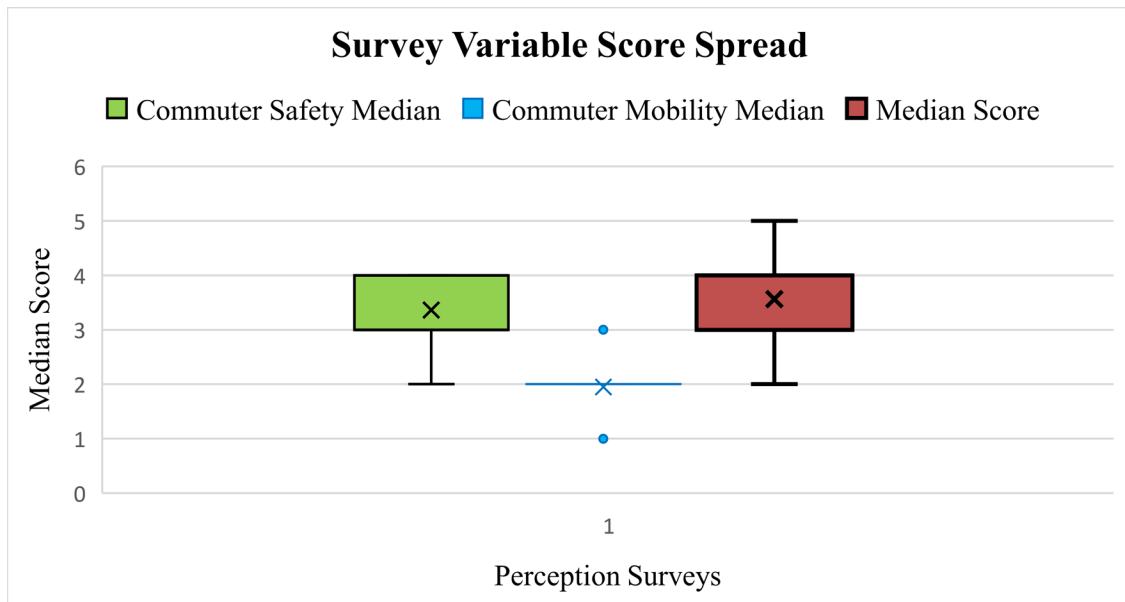


Figure 8: Median Safety Scores Spread for all surveys.

The box plot of Figure 8 shows that for commuter perception of safety, the lower quartile minimum value for safety is 2. The median score for all commuters is 3 and the upper quartile maximum score is 4. Worker perception of safety also had a lower quartile minimum value of 2. The median value for combined worker perception of safety is 4 and upper quartile maximum score is 5. For commuter perception of mobility, the lower quartile minimum value for mobility is 1. The median score for all commuters is 2 and the upper quartile maximum score is 3. Worker perception of safety also had a lower quartile minimum value of 2.

The spread of median values observed in Figure 5 suggests a general similarity when comparing worker perception of safety and commuter perception of safety. Conversely, there seems to be generally disparate relationship when comparing both safety survey results to the commuter perception of mobility results.

Results obtained from median calculations for each variable category are discussed in the next few subsections. Calculating the individual median scores for both population samples will provide values that can be compared and contrasted.

4.1.1. Speed Reduction & Traffic Redirection Variables Results

The speed reduction and traffic redirection work-zones variables categorized in the survey were then analyzed. The median work-zone variable was calculated for (1) worker perceptions of safety (2) commuter perception of safety (3) commuter perception of mobility. An analysis of these values revealed the following information:

1. Stationary police officers near work zone: This variable had a worker safety score of 4, commuter safety score of 5 and commuter mobility score of 2. These three scores relatively represent the greatest positive combination of safety and mobility in the speed reduction and traffic redirection category of variables. The high commuter and worker safety scores shows that the respondents perceive stationary police officers as having the greatest possible influence on job site safety. The mobility median score indicates that commutes perceive police officers as having some negative impact on mobility. However the 2 rating indicates that commuters view this negative impact as minimal
2. Road Shoulder Use: This variable had a worker safety score of 3, commuter safety score of 3 and commuter mobility score of 1. These three values represented the lowest safety-median combination. Worker and commuter median safety scores for this variable was 3. A value of 3 in the survey was described as “No effect”. Therefore a worker median value of 3 indicates that this population perceives road shoulders as having no effect on their perception of safety. However, the mobility median score of 1, is the lowest possible score on the survey Likert scale. This low score shows commuters perceive road shoulders as having a strongly negative impact on mobility.

Figure 9 displayed below indicates the results of obtained from all variables in the speed redirection and traffic redirection variables.

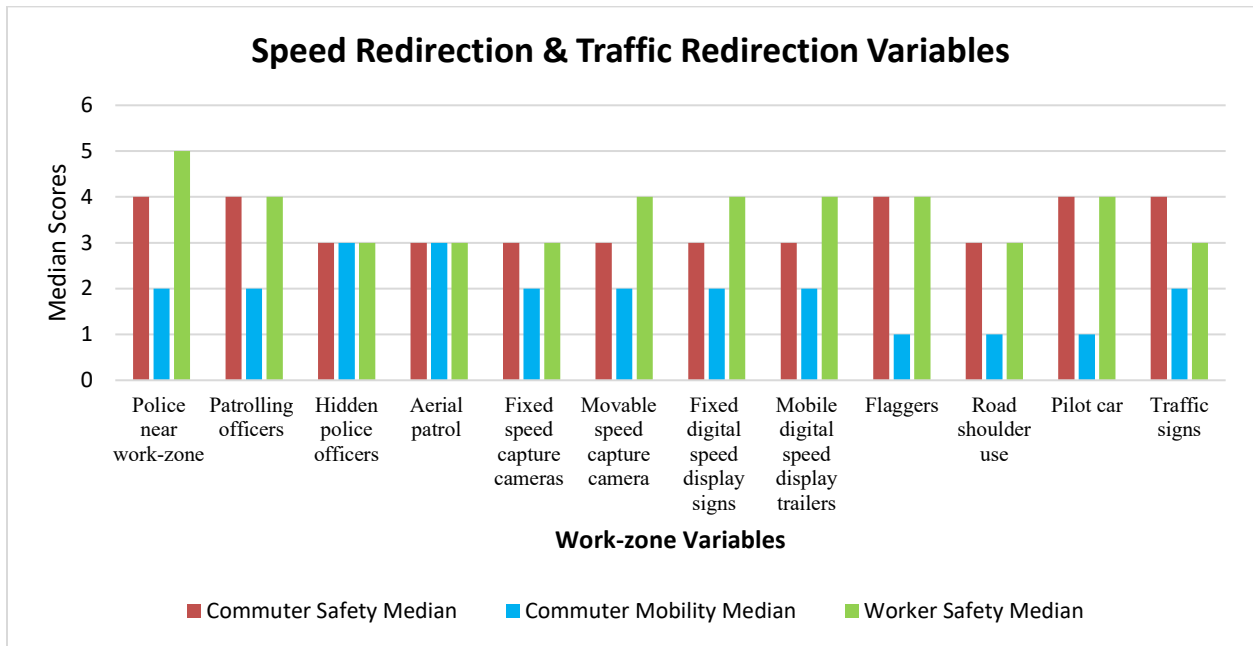


Figure 9: Speed Redirection & Traffic Redirection Variables Median Scores

4.1.2. Intrusion Prevention & Channelization Variables Results

Median analysis was also calculated for the intrusion prevention and channelization category of work-zone layout variables. Findings after data analysis revealed the following:

1. Concrete barrier and steel barrier variables had a commuter safety score of 4, worker safety score of 5 and commuter mobility score of 2. These three scores relatively represent the greatest positive combination of safety and mobility in the intrusion prevention and channelization variables. The high commuter and worker safety scores shows that the respondents perceive concrete barriers and steel barriers as having the greatest possible influence on job site safety. The mobility median score indicates that commuters perceive concrete and steel barriers as having some negative impact on mobility. However the 2 rating indicates that commuters view this negative impact as minimal.

2. Pavement edge drop-off had a commuter perception score of 2, work perception of safety score of 2 and commuter mobility perception score of 1. These three scores represent the lowest safety-mobility combination for variables in the intrusion prevention and channelization category.

Details of the results for all the intrusion prevention and channelization variables are displayed in figure 10 below.

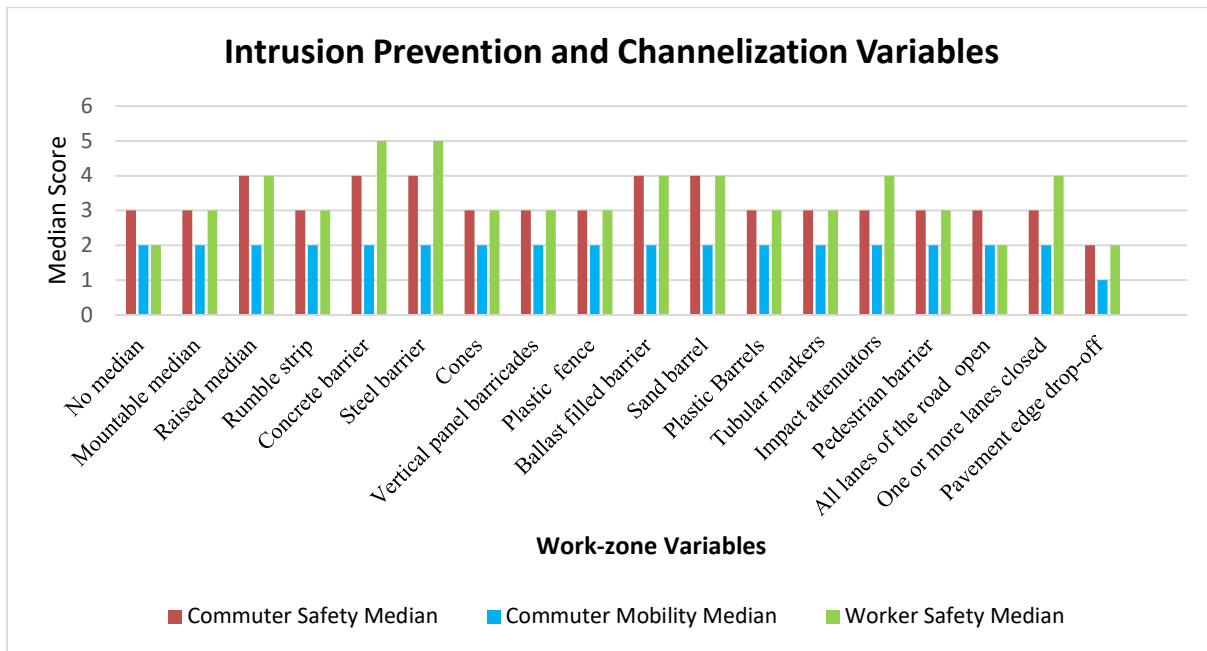


Figure 10: Intrusion Prevention and Channelization Variables Median Scores

4.1.3. Proximity Alert Variables Results

The third category is “Proximity alert devices”. This group was the smallest group with the fewest amount of layout variables. They typically were nascent technology introduced into the field of construction. Data extracted from this dataset and averaged median score for individual variables in both population was calculated. Results from data analysis revealed that revealed that:

1. On site spotters had commuter perception of safety score of 4, worker perception of safety score of 4 and commuter perception of mobility score of 2. The three scores represent the greatest positive safety-mobility rating in the proximity alert category of

variables. The commuter and worker scores of 4, indicated that on average both populations view spotters as having a great positive influence within this category of work zone traffic management variables.

2. Mobile phone alert systems had the lowest ranking with 3 points median score for all survey results. Mobile phone alert system scores indicated that survey participants perceived this work-zone variable to have minimal impact on safety.

Details indicated the results from the proximity alert variables are displayed in Figure 11.

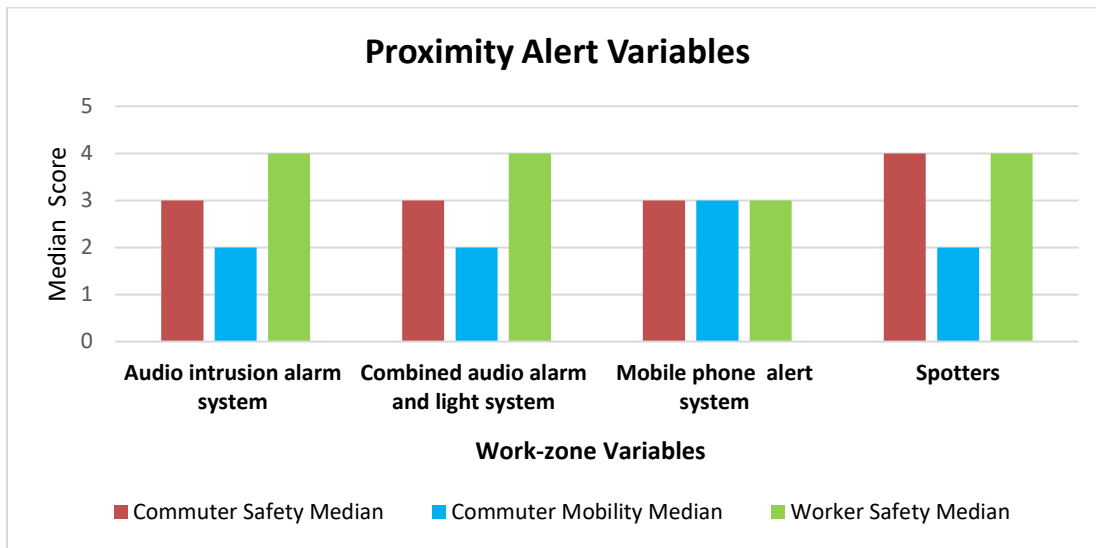


Figure 11: Proximity Alert Variables Median Scores

4.1.4. Visibility Improvement Variable Results

The fourth and final category of variables is “Visibility Improvement”. Once again median calculations were performed to get a single median score for each variable. The results revealed the following:

1. Helmet lights, flood lights, flashing warning lights and balloon lights had commuter perception of safety score of 4, worker perception of safety score of 4 and commuter perception of mobility score of 2. These finding revealed that the previously mention variables have the greatest positive safety-mobility ratings in the visibility improvement variables.

2. Electric lamps on the other hand had the lowest combined ratings with regards to jobsite safety-mobility improvement. Worker perception of safety was 3, commuter perception of safety was 3, commuter perception of mobility was 3 and commuter perception of mobility was 2.

Details on the median scores for all three populations for the visibility improvement category is visualized in Figure 12.

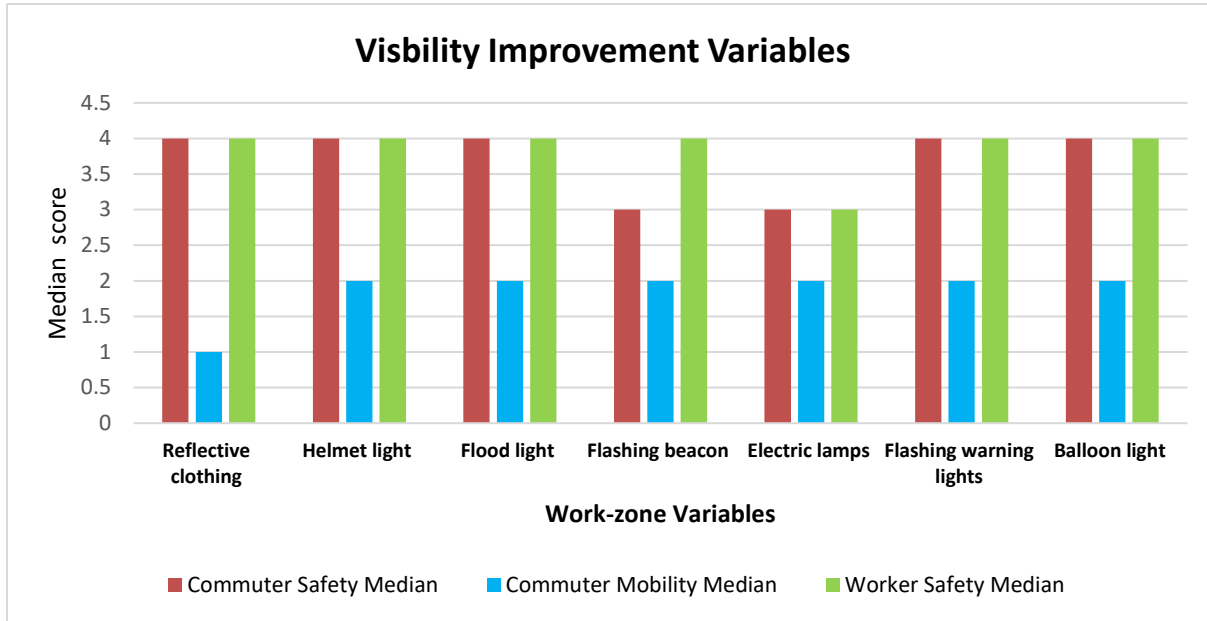


Figure 12: Visibility Improvement Variables Median Scores

4.2. Survey Statistical Analysis Results for Worker Safety vs Commuter Safety

Statistical analysis test was done to compare worker perception of safety to commuter perceptions of safety (since both of these surveys were measured on the same scale). Thusly, the Multiple Man-Whitney U statistical tests were conducted at 95% confidence intervals to establish the worker safety to commuter safety relationship. This test was conducted using a null hypothesis. This null hypothesis holds the idea that “There is no difference between worker perception of safety and commuter perception of safety”. Conducting a Man-Whitney U test provides a p-value that evaluates the null hypothesis. A p-value more than 0.05 means that a conclusion can’t be made that there is a statistically significant difference between worker safety and commuter safety median scores. On the other hand, a value less than 0.05 rejects the null hypothesis. A rejected null hypothesis means that a significant difference exists.

There were 41 work-zone traffic control and management variables that were analyzed. These measured components represented the dependent variable in the analysis. The sample population of commuter and worker represented the independent variable.

Results from the multiple Mann-Whitney U test revealed that 17 of the variables had a p-value score more than 0.05. These results showed evidence that for these 17 variables, statistically significant differences exist. Most of the variables with the smallest p-values fell into the “Intrusion prevention & Channelization” category of traffic control devices and practices. These included

1. Concrete barrier (p-value was 4.55E-10)
2. Steel barrier (p-value was 3.17E-07)
3. Impact attenuator (p-value was 3.69E-07)
4. Ballast filled barrier (p-value was 9.18E-04)

It can be surmised that these variables so strongly reject the null hypothesis due to significant variation in sample population perspective. For example, a worker who is constantly exposed to live vehicular traffic would feel very safe having sturdy protective structural devices like concrete barriers, steel barriers and impact attenuators on a work-zone. Conversely, drivers have less live traffic injury/death risk since they have more protection inside their cars. This situation might make drivers perceive the aforementioned work-zone devices as having less significant influence in improving their personal safety than workers.

The other 24 variables (out of 41) showed evidence that a statistical significant difference can't be made between worker safety and commuter safety. These variables had p-values greater than 0.05. The devices with the greatest p-values included

1. Fixed digital speed display signs (p-value was 0.9175)
2. Steady burning electric lamp (p-value was 0.8744)
3. Aerial patrol devices (0.878)

The three variables listed above are not typically placed in roadway lanes during construction activities. Hence they have minimal contact with the driving public and provide minimal

structural protection that workers would deem as safe. It could be surmised that for this reason, both sample populations did not have any strongly deviating opinions on these devices.

4.3. Quantitative Mobility & Work-zone Data

Determining the decision variables that had relatively significant or insignificant influence of commuter maneuverability on work-zones required an analysis of both quantitative mobility results and mobility perception survey results. This analysis would require a method of converting both measurements into values that can be measured and compared on the same scale.

To determine what constitutes as acceptable or unacceptable delay on roadways it was pertinent to find a means to rank the delay data based on established measures of traffic flow. To this end Level of Service (LOS) measures were utilized for each work-zone, based on their roadway type, posted speed limit and observed average vehicular speeds.

Level of Service (LOS) according to the highway capacity manual can be described as a qualitative measure of motor vehicle traffic service at roadways and intersections with regards to a number of factors including speed, travel time, safety, driving comfort, freedom to maneuver and operating costs (Manual 1965) . For the purpose of this research the speed aspect of LOS was concentrated on. Using parameters provided by the Transportation Research board, the speeds observed at each of the 29 work-zone sites were categorized based on the information in Table 1, Table 2 and Table 3

Table 1: HCM Level of Service Criteria for Basic Freeway Sections

Level of Service Ranking	70 mph Posted Speed	65 mph Posted Speed	60 mph Posted Speed
	Motorist speed (mph)	Motorist speed (mph)	Motorist speed (mph)
A	≥ 70	≥ 65	≥ 60
B	≥ 70	≥ 65	≥ 60
C	≥ 68.5	≥ 64.5	≥ 60
D	≥ 63	≥ 61	≥ 57
E	≥ 58	≥ 53	≥ 50
F	Variable	Variable	Variable

Table 1: HCM Level of Service Criteria for Multilane Highway Road

Level of Service Ranking	60 mph Posted Speed	55 mph Posted Speed	50 mph Posted Speed
	Motorist speed (mph)	Motorist speed (mph)	Motorist speed (mph)
A	≥ 60	≥ 55	≥ 50
B	≥ 60	≥ 55	≥ 50
C	≥ 59	≥ 54	≥ 50
D	≥ 51	≥ 53	≥ 49
E	≥ 55	≥ 51	≥ 47
F	≤ 55	≤ 55	≤ 47

Table 2: HCM Level of Service Criteria for Arterial Roads

Level of Service Ranking	45-35 mph Posted Speed	35-30 mph Posted Speed	35-25 mph Posted Speed
	Motorist speed (mph)	Motorist speed (mph)	Motorist speed (mph)
A	≥ 35	≥ 30	≥ 25
B	≥ 28	≥ 24	≥ 19
C	≥ 22	≥ 18	≥ 13
D	≥ 17	≥ 14	≥ 9
E	≥ 13	≥ 10	≥ 7
F	< 13	< 10	< 7

As indicated in Table 1, Table 2 and Table 3, the ranking of Level of Service is alphabetical from A to F based on variations from posted speed limits. According to the Highway Capacity Manual, driver experience for each of the Level of Service rating can be described as (HRB, 1965):

1. Level A: Free flow traffic without any congestion. Individual users experience minimal interactions with others in a traffic stream.

2. Level B: Stable flow of traffic. However road users experience some influence from others.
3. Level C: Flow starts getting more restricted and interactions with other motorists becomes more significant.
4. Level D: Congestion is observed at this stage and maneuverability starts to seriously diminish.
5. Level E: Unstable flow at or near road capacity levels. Drivers at this stage begin to experience heightened discomfort and frustration
6. Level F: Amount of traffic on road exceeds road capacity. Stop and go waves is prevalent and there is increased accident exposure.

Based on all of the criteria detailed above the following results were observed for the 29 job sites:

1. 10 of the work-zone sites can be categorized as level A
2. 1 of the work-zone site can be categorized as Level E
3. 18 of the work-zone site can be categorized as Level F.

The results indicated above showed that none of the work-zones fell under Level of Service B, C and D. Focusing on the 10 worksites with the highest LOS rating helped determine the work-zone layout variables that played key roles in fostering mobility. The frequency of variable presence (obtained from the work-zone data) on each site was used as a measure of its importance in maintaining traffic flow. Layout variables that occurred in at least 50% of the 10 work-zone sites were considered relevant. Results revealed that (1) Signs (2) Tubular Markers (3) Flaggers (4) Partial Lane closure, were the traffic management practices/devices mostly present. Figure 13 visualizes these findings.

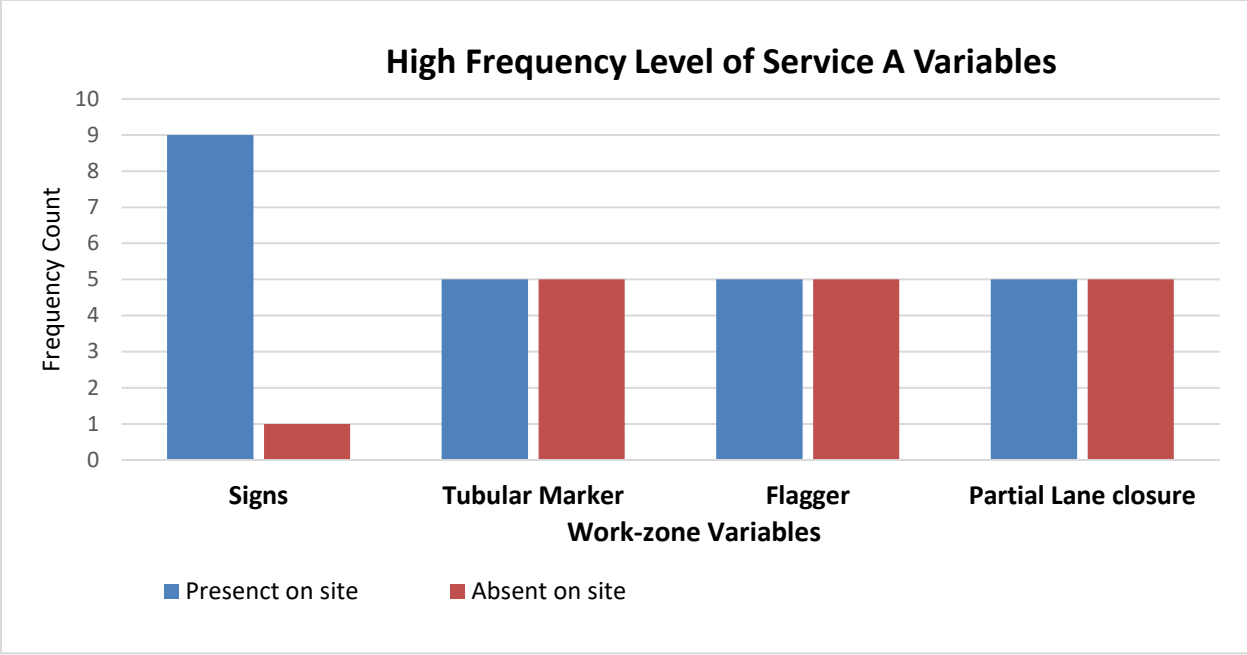


Figure 13: High Frequency Level of Service A Variables.

The column chart in Figure 13 indicates that signs had the highest presence frequency at 9 (out of 10 sites). Tubular markers, flaggers and partial lane closure all had a presence frequency of 5.

4.4. Research Validation & Limitations

An evaluation of the validation and limitations of the research was performed. Ascertaining the validity of a scientific study is an essential part of any research. It is important that validation is done through a meticulous, rigorous and objective process by the researchers. Within the field of construction, external, internal and construct validities are some applicable methods of authenticating research studies (Abowitz & Toole, 2010).

External validity can be described as the ability of findings of an experiment to be generalized beyond the sample studied (Karakhan & Gambatese, 2017). Within the context of this particular study, surveys were distributed to commuters and construction professionals within the Pacific Northwest region of the United States. This limitation in sample size was mostly due to budgetary constraints related to survey distribution and the time constraints required for research completion. However, despite this drawback, the sample size for construction workers can be described as representative of workers across the U. S. A. This is due to the fact there was great

sample diversity in participants. Construction individuals with varying levels of industry experience, age, work-zone layout knowledge and safety training participated in the research. Commuter surveys on the other hand were limited due to the fact that most of the participants were of an older generation.

Internal validity refers to the ability of a research study to show a causal link between its independent and dependent variables (Karakhan & Gambatese, 2017). An experiment passes this validation test if it has minimal confounding variable influence during the implementation phase of research. This particular study passes the internal validity test due to the fact that all participants were randomly assigned and there was limited preferential sampling.

Construct validity refers to the ability of the indicators in an experiment to establish the expected relationships among research concepts (Abowitz & Toole, 2010). This essentially means that this validity tries to ascertain if an experiment's data collection and analysis methodology effectively measures what it was designed for (Karakhan & Gambatese, 2017). The surveys used in this research pass some construct validity testing since care was taken to ensure that surveys were kept in simple understandable language to the participants. However there may be some limitation since there is a possibility that some individuals who are commuters may also work in the construction industry. The researcher didn't include questions in the commuter survey to filter out individuals in the construction industry. Therefore there is a possibility that there is cross representation in the two sample groups that are supposed to be categorically independent.

4.5. Decision Support System Formation & Utility

After the evaluation of research validations and limitations had been completed the Decision Support System (DSS) could be developed using the results obtained from the study. The framework for this Decision Support System was crafted to enable due consideration of both safety and mobility for workers and commuters when planning work-zone layouts.

The Decision Support System operates using a three-step approach. These approaches are

1. Decision variable selection.
2. Variable scoring.
3. Variable suitability assessment.

Figure 14 provides an overview of how these processes will work in the DSS.

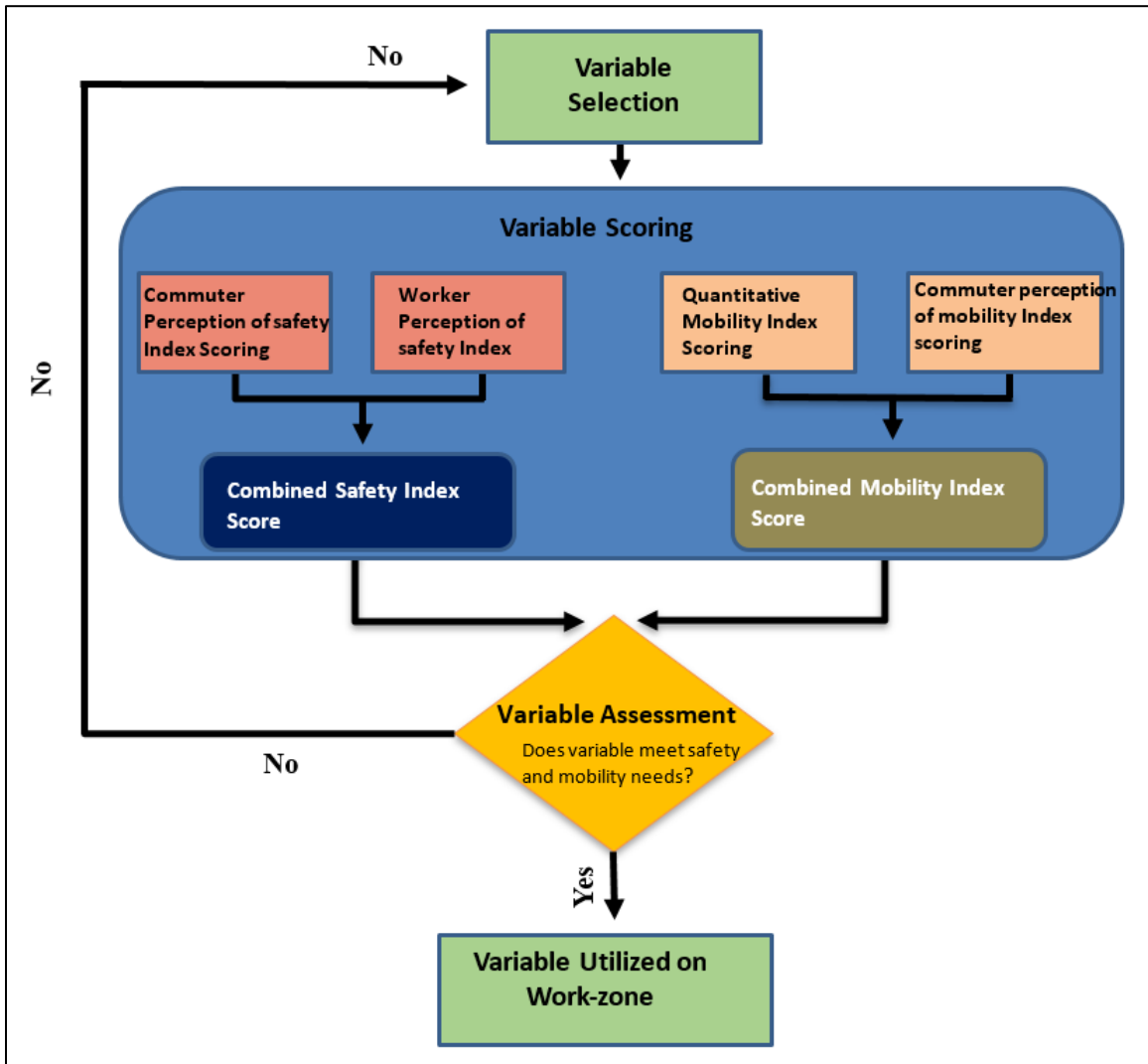


Figure 14: Decision Support System Framework

Further details of each of the operating phases of the Decision Support System are described in the proceeding subsections. Details are also provided how each operational phases was designed by the researcher.

4.5.1. Variable Selection

This is the first stage of the decision support system. It is the user’s first exposure to the model and should be utilized when the individual is starting to design the layout of their roadway work-

zone. In this phase, the user selects all of the variables that they intend on using on their job site. Once these variables are selected the user may then proceed to the next phase of the Decision Support System.

4.5.2. Variable Scoring

This is the second phase of the Decision Support System. In this stage the user can ascertain how safe or mobile their selected decision variable is by using the results obtained by this research.

The researcher created a scoring index for all variables analyzed in this research to provide this functionality in the DSS. Creating this index meant that all the observed quantitative and qualitative results for the layout variables could be put on a singular scale of measurement.

In order for this to be accomplished, all the median Likert scores for each variable in the mobility and perception of safety surveys were converted to index scores using the formula detailed below:

$$IS = \frac{MS}{HS}$$

Where:

IS = Index Score

MS = Median Likert Score

HS = Highest Possible Likert Score

This formula essentially shows that the derived median score for each variable based on survey participant response is divided by the highest possible score pair variable (5). This means that the score for each variable varies between 0 and 1. A score of 0 means that a variable has the most negative influence on safety or mobility. Conversely, a score of 1 indicated that a variable had the greatest positive influence on safety or mobility possible.

The quantitative mobility data obtained from user generated trip information could not be converted to an index score in a straight-forward manner like the qualitative perception survey data. Accomplishing this first required the normalization of the calculated vehicular delays and

accelerations for each of the 29 work zone sites. This normalization would be tailored to make the quantitative mobility dataset similar to the perception surveys.

First, the Level of Service rating (A to F) for each delay type was numbered from 1 to 6. Next the highest Level of Service scale ranking (6) was divided by the highest possible Likert scale ranking (5). This gave a value of 1.2, which would be graduated across all Level of Service ratings. Hence the graduation for Level of Service becomes:

Table 4: Normalized Scores for Level of Service

Level of Service Rating	Normalized Score
A	7.2
B	6.0
C	4.8
D	3.6
E	2.4
F	1.2

Utilizing the traffic control plan database for the 29 sites, normalized scores were assigned to variables that had high presence on sites with corresponding alphabetic Level of Service rankings. At this point, each layout variable from the quantitative mobility data could be converted to an index score using the following formula:

$$IS = \frac{NS}{HS}$$

Where:

IS = Index Score

NS = Normalized Score

HS = Highest possible normalized Score

Like the perception survey formula, this formula essentially shows that the normalized score for each variable is divided by the highest possible normalized variable score (7.2). Essentially this meant that the highest possible score for each variable is 1 and the lowest 0.

4.5.3. Variable Assessment

After the user has received the index score for their selected decision variable, the next phase in the Decision Support System is variable assessment. In this final stage, the user evaluates the suitability of their chosen variable for their jobsite safety and mobility needs. A score of 1 denotes that a variable has the greatest positive influence on mobility or safety and a score of 0 indicates a variable has the least positive influence on mobility or safety.

The index scores of variables can be combined for a single overall safety or mobility score using the following formula:

$$\text{Combined Safety Index Score} = 1 - [(1 - \text{CPSS}) * (1 - \text{WPSS})]$$

Where:

CSIS = Commuter Perception of Safety Score

WSIS = Worker Perception of Safety Score

n = Number of variables

$$\text{Combined Mobility Index Score} = 1 - [(1 - \text{QMS}) * (1 - \text{CPSS})]$$

Where:

QMS = Quantitative Mobility Score

CPSS = Commuter Perception of Safety Score

The two formulas above are derived from recommended and tested procedures for combining crash reduction factors (Lacy, 2001).

4.5.4. Illustrative Example on Use of Decision Support System.

An illustrative example is provided below to show the steps that a user would have to take when determining the suitability of a work-zone variable for the safety and mobility needs of a jobsites. This example is detailed in 3 steps.

Step 1: The user decides at the variable selection phase to access the use of plastic barrels on a jobsite. They want to know how balanced in safety and mobility this device is if utilized on a jobsite.

Step 2: The user in this step decides to find out the index scores of the previously mentioned variable. There are four different index score types for each selected variable. These scores types are:

1. **Commuter Safety Score:** These score type shows the subjective safety rating of a work-zone variable by commuters driving through a work zone.
2. **Worker Safety Score:** This score type shows the subjective safety rating of a work-zone variable by construction professionals working on a job site.
3. **Quantitative Mobility Score:** This score shows the objective mobility rating of a work-zone variable present on a jobsite
4. **Commuter Mobility Score:** This score shows the subjective rating of a work-zone variable by commuters driving through a jobsite.

After consulting the index to view the score of the selected variable, the user discovers the following.

Table 5: Observed Index Scores

Variable	Commuter Safety Score	Worker Safety Score	Quantitative Mobility Score	Commuter Mobility Score
Plastic barrels	0.6	0.6	0.2	0.4

Step 3: The user can now assess the suitability of plastic barrels by inputting the index scores in the previously described combinative formula (refer to page 75). This provides the following results:

1. Plastic barrels combined **safety score** = $1 - [(1 - 0.6) * (1 - 0.6)] = \mathbf{0.84}$
2. Plastic barrels combined **mobility score** = $1 - [(1 - 0.2) * (1 - 0.4)] = \mathbf{0.52}$

Using the results above, the user can use their judgement to decide if using plastic barrels will meet their standards of overall safety and mobility for their work-zone. If not the user can use the Decision Support System to analyze another work-zone variable for its suitability.

Chapter 5: Conclusions and Recommendations

5.1. Summary of Research Process

The issues of safety and mobility on work-zones is a core problem that challenges the field of transportation engineering and the roadway construction industry. Previous studies have shown that these two concepts are generally inversely related to each other since improving safety on a jobsite diminishes on-site mobility (Abdelmohsen and El-Rayes, 2018). This demonstrates that need for a delicate balancing act by construction firms and state transportation agencies to ensure that roadway construction has minimal negative impacts to both the travelling public and construction employees. To this end, this research focused on collecting three types of data for analysis:

1. Perception data: This data typed was gotten from surveys given to workers and commuters. In these surveys commuters were asked their opinions on safety and mobility for certain work-zone variables. Workers on the other hand were asked about their perception on safety for certain work-zone variables.
2. Quantitative mobility data: This data set was derived through empirical methods. 29 real-world work-zone sites were identified and by using user generated traffic data, the average speeds of vehicles traversing those site in a 24 hour period was derived.
3. Work-zone data: This data was also obtained from the 29 job sites used in the research. All of the traffic control devices, and traffic management practices used on these sites were catalogued. This data was then compared to the quantitative mobility data set to identify the effect of real-world work-zone variables on real-world traffic mobility.

Finally, the calculated median values were calculated and converted to index values to uniform scale of measurements of safety and mobility on jobsites.

5.2. Summary of Research Findings.

Results of the research revealed several key findings regarding safety and mobility on construction jobsites. These findings are listed below.

1. For worker perception of safety, commuter perception of safety and commuter perception of mobility the following findings were observed:
 - i. Speed reduction and traffic redirection variables that ranked the highest based on median calculations and comparisons were stationary police officers near work-zones.
 - ii. Intrusion prevention and channelization variables that ranked the highest based on median calculations and comparisons were concrete barrier and steel barrier.
 - iii. Proximity alert variable that ranked the highest based on median calculations and comparisons was spotters.
 - iv. Visibility improvement variables that ranked the highest was reflective clothing, helmet lights, flood lights and balloon lights.
2. Results from statistical analysis were derived by comparing commuter safety perception and worker safety perception. Results revealed that 17 variables showed evidence of statistically significantly difference and 24 variables didn't show evidence of statistically significant difference. These statistical findings could be perceived as evidence that commuter and worker perception of safety for a majority of the variables were similar.
3. For quantitative mobility and work-zone data vs commuter perception of mobility, the primary finding observed was that the work-zone variables that had the best positive influence on mobility were signs, tubular markers, flaggers and partial lane closure.

5.3. Revisiting Research Goal and Objectives

The overall research goal of this study was to develop of a Decision Support System that helps identify work-zone layout variables with an acceptable relationship balance of safety and mobility. This goal was to be attained through the pursuit of three specific research objectives listed below, along with commentary on its accomplishment at the conclusion of research:

1. Objective 1: This object required the quantification of commuter mobility through work-zones by establishing mobility metrics and collecting live anonymous user-generated traffic data. Objective 1 was successfully accomplished and mobility metrics within the context of this research was defined from a qualitative perspective as measured average vehicular speed being subtracted by posted speed limit and compared to the Level of

Service rating for that road type. Qualitatively, mobility was defined as a value on a 5 point Likert scale survey, ranging from 1(slow down a lot) to 5(speed up a lot).

2. Objective 2: This objective required the quantification of construction work-zones through a multi-step process of literature review, traffic control plan analysis, and survey data analysis metrics. Objective 2 was successfully accomplished by taking into account commuter and workers perception of safety. Safety of each variable was measured as a value on a 5 point Likert scale survey, ranging from 1 (Highly Unsafe) to 5 (Highly Safe).
3. Objective 3: This objective required that the establishment of the relationship between safety and mobility on work-zones using the previously determined metrics. Objective 3 was met during the data analysis phase of this research. Through a series of median calculation, data ranking, statistical analysis, and visual comparisons relations of safety and mobility of variables was established.

The overall goal of the research was to develop a Decision Support System. By converting all collected data into indexed scores this Decision Support System was successfully created. The DSS has a simple format that guides the user to select the most suitable work-zone device or management practice for their prospective project. The indexed data scores proved useful since they serve as a unified metric to measure commuter perception of safety, worker perception of safety, quantitative mobility and commuter perception of mobility for each variable. Having these indexed scores provides a reference source that helps shape user choices within the framework of the Decision Support System.

5.4. Contributions of Research

Similar studies have been done to explore work-zone safety-mobility relationships and develop optimization models that aid in work-zone layout design. However these current state of the art research methods use methodology that significantly limit the accuracy of results and the scalability of developed Decision Support Systems and optimization models for work-zone safety and mobility improvement.

Perception surveys, work-zone data and user generated traffic information would be used in this research to establish the safety-mobility relationship among work-zone layout variables.

Combining both subjective and objective data collection approaches allows for more well-rounded methodological approach.

Additionally this study provided knowledge on how utilized crowd-sourced traffic mapping software can better streamline the mobility data collection process. This methodology unifies the ease of simulation models with the accuracy obtained from direct measurement of real-time travel data. Using this process is both cost effective and highly scalable.

Finally the Decision Support System developed in this research is very easy to understand and simple to use (refer to chapter 4.5.4 to see illustrative example of decision support system use). This convenience would be very beneficial to construction personnel involved in work zone layout design and the DSS index system provides an easy means for users to understand the safety and mobility effect of various traffic control devices and transportation management practices.

5.5. Future Work

There are numerous avenues for future work which can be explored to expand the overall significance of this research. The findings of this research will provide the foundation upon which further investigation into the work-zone effects can be pursued, such as considering crew productivity in addition to mobility and safety. Additionally the functionality of the Decision Support System created from this research can be further expanded upon. Computational models for estimating work-zone queue delay and traffic delay can be developed. Precedence for investigating this type of technology has already been set by research on neural networks, fuzzy logic, case based reasoning and object oriented programming. Utilizing these technologies in creating an intelligent DSS, would result in a user friendly interactive software designed to effectively find the balance between traffic mobility and worker safety on roadway work-zones. Consequently, such a tool would be beneficial in protecting worker well-being without sacrificing motorist mobility during construction operations.

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