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FREEWAY WORK ZONE: CURRENT TRENDS AND FUTURE NEEDS

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Abstract: Work zones are recognized as a significant source of freeway incidents as they involve frequent lane closures and lane merges that last for different periods of time. Work zones generate road user delays, traffic incidents, safety hazards, and vehicle emissions. This article presents a comprehensive literature review of the mobility, safety, driver behaviour, and cost and planning aspects of state of the art work zones. Over 100 publications, including research papers, master thesis, and dissertations were reviewed in order to understand the spread of work zone applications. Mobility and safety have become important measures that are used to optimize the performance of work zones by minimizing delay and traffic collisions. Work zone configuration plays a major role in all aspects of work zones while capacity reduction and speed limits are critical issues for mobility. The review revealed that safety is mostly modeled and predicted using collision data as the main factor. The impact of nighttime safety attracted less research attention. Cutting-edge smart work zone concepts have emerged as a key component in most of the phases of work zone studies. Driver behaviour is explored as one of the main considerations that affects the entire work zone aspects. In this article, the important elements of each publication are tabulated to give the reader quick access to the relevant references. Apart from the existing approaches, the design variables, limitations, and future research needs are listed separately for prospective users. It is our hope that this paper will serve as a quick freeway work zone reference and a guide for potential researchers and practitioners.

1 Introduction

Highway work zones have been an area of major concern for decision makers and researchers when conducting multiple activities on road networks, including construction and maintenance. Many work zone studies have been published. These studies examine different work zone aspects such as mobility, safety, driver behaviour, and planning. Work zones are nationally recognized as a significant source of highway incidents as they involve frequent lane closures and lane merges that last for different periods of time according to the type of construction or maintenance and their intensity. These scenarios generate road user delays, traffic incidents, safety hazards and vehicle emissions. The Highway Capacity Manual (HCM 2010) defines a work zone as "a segment of highway in which maintenance and construction operations reduce the number of lanes available to traffic or affect the operational characteristics of the traffic flowing through the segment".

The past few decades have seen major improvements in work zone analysis with the adoption of cutting-edge science and technology. A review of the work zone literature revealed that the majority of the research contributions have been in the areas of mobility and safety. Driver behaviour, planning and cost represented only 8% of the research contributions to work zone analysis. The publications reviewed included 70 journals, 14 MASc theses and 16 PhD dissertations. Many of these papers were published in

highly reputable international journals. Despite the large number of work zone studies, the exposure is not comprehensive and only gives a picture of work zone application site. The references are summarized in a tabular form under each of the area sub-headings with a synopsis for readers. The limitations of the existing approaches and future needs are also briefly mentioned for prospective users.

2 Analysis of Work Zone Applications

The following subsections review different work zone applications. All of these applications have been classified into four major areas: (a) Mobility (b) Safety (c) Driver Behaviour and (d) Cost and Planning. Each section describes one of these major areas and contains tables that list all of the reviewed studies published in this area.

2.1 Mobility Applications

Son (1999) incorporated fluid approximations to establish a queueing model for the average delay of lane closures on two-lane highways. Fluid approximations and stochastic models were originally developed by Newell in 1969. Turley (2002) presented a Generalized Linear Model (GLM) for speed by evaluating the Arrow-Panel Caution Displays. An online algorithm for variable speed limit control in work zones was introduced by Kang et al. (2004). The proposed model and algorithm optimize the speed-limit based on the evolution of dynamic traffic conditions and macroscopic traffic characteristics. Chin (2004) developed a moving slot model and framework for operational strategies for slot/lane assignment rules. This model is used to manage highway space for interactions between the entrance and exit processes in order to maximize capacity while accounting for vehicle maneuvers. Kang (2006) developed an advanced Dynamic Lane Merge (DLM) control model and operational algorithm as well as a dynamic Variable Speed Limit (VSL) model and operational algorithm. The optimization took into account the interactions between the speed, flow and work zone capacity.

Kang and Chang (2006) proposed a speed control strategy called the Time-of-Day Speed Limit (TOD SL). This strategy enables researchers and designers to establish optimal real-time speed limits by maximizing the use of available historical data. Kim (2008) investigated the upstream traffic characteristics of a work zone and developed a mechanistic model of capacity based on merging behaviour. This model estimates work zone capacity according to the lane closure configuration and traffic conditions such as heavy vehicle percentage, merging patterns, merging time and the queue discharge flow rate. Radwan et al. (2011) evaluated the operational effectiveness of the Simplified Dynamic Lane Merge Systems (SDLMS) i.e. Early Merge and Late Merge in the presence of VSL. The simulation results revealed that a late merge, with or without VSL, produced higher mean throughputs for all adherence levels (compliance rates) of motorists. Kurker (2013) evaluated a Dynamic Traffic Assignment (DTA) system equipped with Early Merge, Late Merge and Fixed Cycle Work Zone Signal Merge Control (FCWZSMC) using VISSIM simulations. He also developed guidelines for the selection of merge concepts according to the traffic flow. FCWZSMC was recommended for multiple lane closures and high traffic flows.

Du and Chien (2014) developed guidelines for the use of the road shoulder to increase the capacity in work zones. Patil (2015) evaluated the use of Portable Traffic Signal (PTS) systems in long rural two-lane highway work zones. This study compared three different conditions for the control of one-lane traffic involving the deployment of flagger and PTS system combinations in conjunction with pilot car operations. A PTS unit without flagger operation was recommended to control one-lane traffic for long rural two-lane highway work zones. Yeom (2015) developed capacity and Free Flow Speed (FFS) models which were calibrated using three sources (field, sensor and literature achieves). The introduced capacity model may be amalgamated into the next issue of the Highway Capacity Manual (HCM). Abdelmohsen (2016) conducted studies involving a large number of parameters to obtain more realistic scenarios. The primary focus of the model was minimizing traffic delay, however, the model also made contributions to the area of cost and safety. Table 1 presents the references involving work zone mobility.

Table 1: Mobility references on the mobility aspect

No	Sample References	Type	Country*	Analytical Tools Used
1	Turley (2002)	Journal	USA	Regression Analysis, Statistical Analysis
2	Liu et al. (2017)	Journal	China, USA	Statistical Analysis
3	Bie et al. (2016)	Journal	Canada	Regression Analysis, Statistical Analysis
4	Chung (2011)	Journal	Korea	Statistical Analysis
5	Radwan et al. (2011)	Journal	USA	Statistical Analysis
6	Zheng et al. (2011)	Journal	SWZ, NLD	Fuzzy Logic Artificial Neural Networks
7	Zhu (2015)	MASc	USA	Regression Analysis, Sensitivity Analysis
8	Abdelmohsen (2016)	PhD	USA	Non-Dominated Sorting Genetic Algorithm
9	Patil (2015)	MASc	USA	Statistical Analysis
10	Yeom (2015)	PhD	USA	Regression Analysis, Statistical Analysis
11	Kim (2008)	PhD	USA	Probability Analysis
12	Kang (2006)	PhD	USA	Extended Kalman Filtering (EKF) Algorithm
13	Qu (2014)	PhD	USA	Genetic Algorithm, Statistical Analysis
14	Li (2008)	MASc	USA	Statistical Analysis, Cost-Benefit Analysis
15	Chin (2004)	PhD	USA	Probability Analysis
16	Zhang (2016)	MASc	USA	Agent-Based Dynamic Traffic Assignment
17	Du and Chien (2014)	Journal	USA, China	Statistical Analysis, Sensitivity Analysis
18	Kang and Chang (2006)	Journal	USA	Min-Max Optimization Criterion
19	Ahmed et al. (2016)	Journal	UAE, USA	Statistical Analysis
20	Ng (2012)	Journal	USA	Integer Linear Programs
21	Kang et al. (2004)	Journal	USA	Lindo-API Linear Optimization Program
22	Isaiah (2014)	MASc	USA	Qualitative Analysis, Citable Test Analysis
23	Son (1999)	Journal	Korea	Statistical Analysis
24	Kurker et al (2014)	Report	USA	Statistical Analysis, Sensitivity Analysis
25	Kurker (2013)	MASc	USA	Statistical Analysis
26	Ding et al. (2013)	Journal	China, USA	Regression Analysis
27	Weng and Meng (2011a)	Journal	Singapore	Decision Tree-Based Approach

***** USA – United State of America UAE – United Arab Emirates SWZ- Switzerland NLD – Netherland

2.2 Safety Applications

Chambless et al. (2002) determined the important characteristics that were over-represented in work zone crashes. These included severity, driver characteristics, location and misjudgement. This study involved a large crash dataset from Alabama, Michigan and Tennessee. Schrock and Ullman (2003) conducted research on the spacing of law enforcement pullout areas in highway work zones. They concluded that the spacing for law enforcement pullout areas should be 2 to 3 miles and no longer than 3 miles for alternative work zones with closed emergency shoulders. They also identified the speed reduction potential of fluorescent orange sheeting, innovative message signs and changeable message signs with radar. Li (2007) proposed 4 Crash Severity Index (CSI) models including 2 Driver-Independent

(DI-CSI) models and 2 Driver-Dependent (DD-CSI) models. The DI-CSI models estimate driving risk levels in work zones by incorporating travel conditions without human factors. The DD-CSI models estimate driving risk levels in work zones by assessing driver factors such as demographic characteristics and driver error.

Li and Bai (2008) conducted a study to identify the deficiencies of current Temporary Traffic Control (TTC) measures. Chen (2008) developed a crash prediction model using regression analysis. The results revealed that the construction type was a significant factor in work zone crashes. Chen (2008) also developed a VISSIM model and did a conflict analysis based on the simulation results. Table 2 presents the references involving work zone safety.

Table 2: Safety references on the safety aspect

No	Sample References	Type	Country	Analytical Tools Used
1	Qi and Zhao (2017)	Journal	USA	Statistical Analysis
2	Li and Bai 2008(a)	Journal	USA	Regression Analysis, Statistical Analysis
3	Mathes (2012)	MASc	USA	Regression Analysis, Statistical Analysis
4	Abdelmohsen (2016)	PhD	USA	Optimization - NSGA2, Statistical Analysis
5	Chen (2008)	PhD	USA	Regression Analysis, Statistical Analysis
6	Chambless et al. (2002)	Journal	USA	Graphical & Statistical Analysis
7	Elghamrawy (2011)	PhD	USA	Optimization, Statistical & Sensitivity Analysis
8	Nannapaneni (2011), Miatudila (2016)	PhD	USA	Statistical Analysis
9	Li (2007)	PhD	USA	Statistical Analysis, Regression Analysis
10	Wong (2009)	MASc	USA	Cost-Benefit & Regression Analysis
11	Bai et al. (2010)	Journal	USA	Statistical Analysis
12	Li and Bai (2009)	Journal	USA	Statistical Analysis, Regression Analysis
13	Phanomchoeng et al. (2010)	Journal	USA	Sound Wave Mechanics, Graphical Analysis
14	Schrock and Ullman (2003)	Journal	USA	Delphi Method, Graphical Analysis
15	Kurker et al. (2014)	Report	USA	Statistical Analysis, Sensitivity Analysis
16	Ding et al. (2013)	Journal	China	Regression Analysis
17	Meng et al. (2010)	Journal	Singapore	Quantitative Risk Assessment Model

Wong (2009) introduced a Risk Index (RI) to measure the level of injury risk in work zone. Wong conducted extensive studies of the safety benefits of ArmorGuard^{TM} barriers and concluded that these barriers could be used to assure worker safety in work zones. Elghamrawy (2011) conducted field experiments to evaluate the effectiveness of temporary rumble strips prior to and at the edge of work zones by analyzing the sound levels generated by the tires. Nannapaneni (2011) used questionnaires and field tests to evaluate the effect of Steady Burn Lights (SBLs) on channelizing drums vs crash occurrence at night. The results revealed that SBLs on drums increased the occurrence of risky driver behaviour and higher speeds. Mathes (2012) introduced the job site line of communication model to assure the safety of workers.

Ding et al. (2013) assessed the safety of work zones by looking at the length of the transition area and the speed limit values. Kurker et al. (2014) used his work zone VISSIM model vehicle trajectories in FHWA's Surrogate Safety Assessment Model (SSAM) to conduct the traffic conflict assessment to

quantify the safety. Abdelmohsen (2016) developed a model to minimize the occurrence of work zone crashes using multi-objective optimization techniques. Miatudila (2016) introduced multinomial logit models to analyze crash severity and countermeasures to mitigate crash occurrence. Qi and Zhao (2017) presented an interesting signalized lane control strategy and cycle lengths to minimize conflicts related to lane merge and rear-end collisions on freeways.

2.3 Driver Behaviour Applications

Whitmire (2007) investigated the effectiveness of in-vehicle information technologies. The results indicated that audio information requires less reaction time than visual information. Heaslip et al. (2011) evaluated the effectiveness of selected work zone guidelines published by FHWA for older drivers and pedestrians. Adeli (2014) evaluated driver speed variations according to speed limits and road work signs. The results revealed that drivers generally complied with the speed limit. The results also revealed that age, road familiarity and experience had a noteworthy impact on speed limit compliance. Zehtabi (2014) conducted a study on driver perception of surroundings in work zones. The prospect-theory and Genetic Algorithm (GA) were used to develop the longitudinal acceleration model. The variables taken in to account were the work zone length, TTC barrier types, intensity and speed. Moradpour et al. (2015) compared the Conventional Lane Merge (CLM) configurations used in MUTCD and the Missouri Department of Transportation (MoDOT) configurations according to TTC and demographical influence. Table 3 presents the references involving driver behaviour in work zones.

Table 3: Driver behaviour references on the driver behaviour aspect

No	Sample References	Type	Country*	Analytical Tools Used
1	Hamdar et al. (2016)	Journal	USA, Lebanon	Optimization – Genetic Algorithm, Statistical Analysis
2	Heaslip et al. (2011)	Journal	USA	Statistical Analysis
3	Shakouri et al. (2016)	Journal	USA	NASA-TLX & Motion Sickness Assessment
4	Adeli (2014)	MASc	USA	Statistical Analysis
5	Nadathur and Narayanan (2016)	MASc	USA	Optimization – Solver
6	Zehtabi (2014)	MASc	USA	Optimization – Genetic Algorithm, Statistical Analysis
7	Moradpour et al. (2015)	Journal	USA	Statistical Analysis
8	Whitmire (2007)	PhD	USA	NASA-TLX & Motion Sickness, Statistical Analysis
9	Weng and Meng (2011b)	Journal	Singapore	Traffic Flow Fundamental Diagram

Shakouri et al. (2016) used questionnaires and driving simulator studies to examine driver merging behaviour in work zone configurations. A motion sickness assessment was also done for all of the participants in order to ensure confidence when taking the test. The findings supported previous research on the effects of work zone configurations and traffic density on performance variables and the subjective work load of drivers.

2.4 Planning Applications

Schonfeld et al. (2002) used a multi-objective optimization technique to develop a model to minimize total cost by optimizing work zone length and cycle times. Sukumaran et al. (2006) presented a model for the stochastic analysis of factors affecting work zone schedules using Monte-Carlo simulations and the Analytic Hierarchy Process (AHP). Tang and Chien (2008) also developed a model to schedule work zones by considering a discrete time-cost relation using a genetic algorithm optimization process. Kaewmoracharoen (2009) developed a work zone visualization model using 3-D models linked with scheduling data. He also examined the industrial influence on work zone visualization using a questionnaire. The results indicate that work zone visualization is a low cost communication technique that can also increase mobility. Table 4 presents the references involving work zone cost and planning.

Table 4: Planning references on planning aspect

No	Sample References	Type	Country	Analytical Tools Used
1	Abdelmohsen (2016)	PhD	USA	Optimization-NSGA2, Statistical Analysis
2	Schonfeld et al. (2002)	Journal	USA	Optimization , Sensitivity Analysis
3	Elghamrawy (2011), Qu (2014)	PhD	USA	Optimization – GA, Statistical & Sensitivity Analysis
4	Du and Chien (2014)	Journal	USA, China	Statistical Analysis, Sensitivity Analysis,
5	Tang and Chien (2008)	Journal	USA	Optimization – GA, Elitist Selection, Sensitivity Analysis
6	Sukumaran et al. (2006)(a)	Journal	USA	Monte Carlo Simulation, Statistical Analysis
7	Sukumaran et al. (2006)(b)	Journal	USA	Monte Carlo Simulation, Analytic Hierarchy Process (AHP)
8	Schonfeld et al. (2002)	Journal	USA	Optimization – Iteration, Sensitivity Analysis
9	Kaewmoracharoen (2009)	PhD	USA	Statistical Analysis
10	Yang (2010)	PhD	USA	Simulated Annealing, Statistical Analysis
11	Chou (2010)	PhD	USA	Simulation, Regression Analysis, Sensitivity Analysis
12	Qu (2014)	PhD	USA	Optimization – Genetic Algorithm, Sensitivity Analysis
13	Wiegand (2007)	MASc	USA	Statistical Analysis
14	Hajdin and Lindenmann (2007)	Journal	Switzerland	Optimization
15	Sukumaran et al. (2006)	Journal	USA	Monte Carlo Simulation, Statistical Analysis

Yang (2010) presented a framework and systematic methodology for optimizing critical work zone decisions by considering cost-effectiveness. Yang also developed analytical and simulation models using Two-Stage Modified Population-Based Simulated Annealing (2PBSA) to search for near-optimal solutions. Chou (2010) presented the Simulation Based Secondary Incident Filtering (SBSIF) methodology to evaluate proposed Traffic Incident Management (TIM) programs. Elghamrawy (2011) worked on developing an optimization model to minimize work zone costs involving construction costs, user delay costs and accident costs. Qu (2014) developed a work zone schedule model that considers work zone cost variables and incorporates Travel Time Reliability (TTR) measures. Du and Chien (2014) presented a model to optimize work zone length by considering the dynamic traffic volume and road capacity. They also created guidelines for the use of the road shoulder for various work zone scenarios. Abdelmohsen (2016) developed a multi-objective optimization model for work zone layouts to minimize construction costs. The study evaluated TTC measures and other work zone layout parameters including flaggers, spotters and TTC devices.

3 Design Variables and Limitations

The literature review revealed that a large variety of decision variables were taken into account when studying all of the aspects related to work zones. The most common decision variables for mobility studies included work zone configurations, AADT, speed, design speed, delay, volume, lane capacity, head-way distance, head-way times, directional split, vehicle length, weather, lighting, vehicle classifications, heavy vehicle percentage, VSL, road class, position of closed lane and length of ramp. Aside from traffic flow characteristics, fatal and crash data, crash characteristics, TTC types, VMSs, Intelligent Transportation Systems (ITS) technologies, regulations and policies, work zone layout details, work zone types, traffic control type, road surface, gender, age, time, day, type of collision, accident location, light and weather were the most common decision variables for safety studies. TTC barrier types, work zone intensity, age, education level, income, car ownership, driving experience, driving stress and human related factors, acceleration, braking and lane position were the most common decision

variables in driver behaviour studies. Agency cost (maintenance, traffic mitigation, equipment/labour idling, routine maintenance) and user cost (delay, vehicle operating, expected accident cost) were the most significant decision variables cost and planning studies.

Beyond the remarkable applications reviewed in this paper, there were also limitations. Most of the researchers listed the limitations of their studies. Real time high precision data acquisition, data screening, accessibility to emergency responders, oversaturated flow conditions, heavy truck impact, access & egress methods and lane merge position (left to right or right to left) were some of the highlighted limitations in the mobility studies. The unavailability of crash data, less information in crash inventories, validation of the proposed models, influence of different channelizing devices, driver cognitive process (gap acceptance, environment), nighttime luminance (brightness) requirements and the effect of the property damage only crash type were some of the highlighted limitations in the safety studies. Fewer participants and a lack of proper demographical representation for driving simulators, the adoption of advanced data collection technologies, practices in autonomous vehicles, and improvements to the car-following theory were some of the key limitations pertaining to driver behaviour studies. The enhancement of the robustness of the developed models, emission and fuel consumption aspects through simulation results, test the convergence of optimization and relationship between maintenance cost and project duration cost were some of the noteworthy limitations in the planning and cost studies.

4 Future Research

Mathematical theories such as the prospect theory can be used to approximate the human decision making process for the development of car following and lane merge models in work zones. The effect of horizontal and vertical alignment can be studied using microsimulation and the development of equations to estimate traffic flow parameters such as delay, capacity and average speed. It is critical to develop guidelines for the establishment of work zone speed limits and how speed reduction distribution regulate through up stream to merging area considering design speed of road, traffic flow data and work zone layout parameters. It would also be valuable to develop matrices to measure emissions due to work zones and minimization strategies involving the optimization of mobility. The application of multi-objective optimization concepts considering two or more parameters would be useful in order to generate the optimal trade-offs between them. The development of in-vehicle advanced warning systems using sophisticated ITS technologies which warn drivers of upcoming work zones is also inevitable. These technologies should provide advice on which lane to chose and which lane is closed in order to prevent aggressive maneuvering queue propagation. It is noteworthy that there were very few studies conducted on the joint merge concept. It would be valuable to analyze this concept and its applicability to selected highways in order to enhance mobility and safety in work zones.

Although there have been studies on the use of barriers at work zones, it is necessary to develop guidelines and recommendations for barrier types according to their benefits and applicability considering mobility and safety. As many studies have shown, the development of a work zone related standard crash database is paramount in order for researchers and policy makers to save more lives with more reliable countermeasures. There is also a need for more nighttime safety related studies involving things such as luminosity requirements for high visibility traffic control devices, signs and workers. The development of guidelines and criteria for the use of positive protection devices in work zones is also necessary in order to minimize safety hazards due to errant vehicles. Driving simulator studies with an increase in participants and more realistic conditions will lead to higher accuracy in the prediction of human behaviour in work zones. Guidelines can also be developed to plan and schedule work zones using optimization techniques. A review of the work zone literature also revealed a lack of research focused on Canadian work zones, especially regarding safety.

With the rapid advances in science and technology, the topic of “Autonomous Vehicles” is becoming more significant with each passing day. With the collaboration of intelligent transportation systems and cutting-edge mechatronic platforms, it will be necessary to study the behaviour of autonomous vehicles with the presence of smart work zones and the concepts already proposed. Microsimulation tools and driving simulators can be incorporated for research purposes. On the other hand, the development of concepts and guidelines for smart work zones that include sensor networks, real time data acquisition, data

warehousing, real time signalization and merge concepts (early merge and late merge), and the application of positive protection devices with high accuracy will be important for future work zone research.

5 Conclusions

This article reviewed different aspects of work zone applications such as mobility, safety, driver behaviour, cost and planning. Work zones are a significant source of freeway accidents, generating road user delays, traffic incidents, safety hazards and vehicle emissions. Work zone mobility and safety were the mostly conducted research studies among the literature reviewed which were penetrated in to the subareas of capacity optimization, delay minimization and safety assurance. Work zone configuration played a major role in all aspect and cutting-edge smart work zone concepts were applied in many phases of work zone studies. Demographical and psychological phenomenon were thoroughly examined whereas modern technology mostly involves driver behavioural measures. Finally, optimal planning and cost minimization strategies were proposed to incorporate in reliable scheduling and refined policies in states and agencies to present more effective and user ready work zone environment. It is important to mention that a limited number of studies and a brief summary of variables, limitations and future research needs were described in this paper due to space constraints. In this review, the important elements of each publication were tabulated to give the reader quick access to the relevant references. Apart from the existing approaches, the design variables, limitations, and future research needs are listed separately for prospective users. It is our hope that this paper will serve as a quick freeway work zone reference and a guide for potential researches and practitioners.

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