SUSTAINABLE ROUTING GUIDANCE FOR A ROAD NETWORK WITH WORK ZONES DURING THE CONNECTED AND AUTOMATED VEHICLES ERA

by

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A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science

Lyles School of Civil Engineering

West Lafayette, Indiana

December 2020

THE PURDUE UNIVERSITY GRADUATE SCHOOL

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This thesis is dedicated to my beloved husband, Mojtaba,

For his endless love, support, understanding, and encouragement during the challenges of graduate school and life. I am truly thankful for having you in my life and by my side. This work is also dedicated to my dear parents who have raised me to be the person I am today.

ACKNOWLEDGMENTS

I would like to express my deep and sincere gratitude to my academic advisor, Dr. Labi, for providing me with his invaluable guidance throughout this research. His vision, motivation, sincerity and support have deeply inspired me. He has taught me the methodology to carry out and present the research clearly. It was a great privilege and honor to study and work under his guidance. I would also like to express my gratitude to my committee members, Dr. Tarko and Dr. Cai for support and giving me the opportunity to improve my research upon their helpful comments. I am sure I can always benefit from what I have learned from them throughout my research career. Last but not least, I would like to express my gratitude to Jenny Ricksy, Graduate Program Administer in Lyles School of Civil Engineering, for her endless kindness and support for always being there for me and resolving the issues I was facing during the pandemic. This work was supported partially by Purdue University's Center for Connected and Automated Transportation (CCAT), a part of the larger CCAT consortium, a USDOT Region 5 University Transportation Center funded by the USDOT Award #69A3551747105.

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LIST OF ABBREVIATIONS

Acronym	**Definition**
AASHTO	American Association of State Highway and Transportation Officials
AV	Automated Vehicles
AGC	Associated General Contractors of America’s
CAV	Connected and Automated Vehicles
CMEM	Comprehensive Modal Emissions Model
CWZ	Construction Work Zone
DOTs	Departments of Transportation
GHG	Greenhouse Gas
FHWA	Federal Highway Administration
INDOT	Indiana Department of Transportation
NE	Nash Equilibrium
UE	User Equilibrium
VOT	Value of Time
SO	System Optimal
NE	Nash Equilibrium

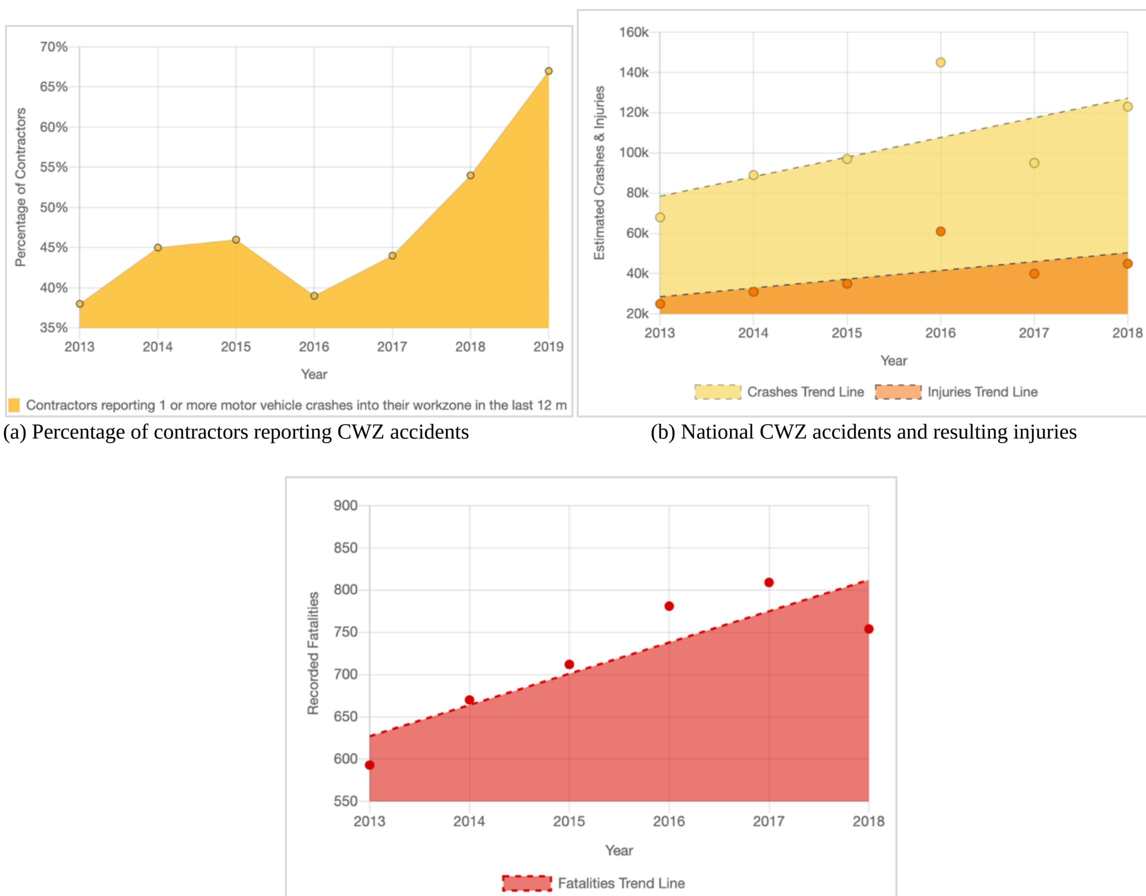
ABSTRACT

Emerging technologies in transportation engineering including connected and automated vehicles (CAVs) exhibit much potential to solve a variety of persistent problems that have impaired the safety and mobility performance of transportation systems. A well-known context of such problems is the construction work zone where agencies have grappled with solutions that range from no closure, partial closure to full closure of road sections during construction, rehabilitation, or maintenance work. Road agencies also seek to develop and implement such workzone plans in a manner that does not unduly jeopardize the economic, social and environmental resources of the road users and the community where the workzone is located. In order to ensure that these three components of sustainable development are attained during road construction workzone management, road agencies seek to develop and implement tools that they can use to guide road users in a network to minimize overall delay, emissions, and fuel consumption. This thesis examines this specific context of highway administration. The thesis developed detour routing guidance for the road users in a road network with work zones in case of full closure, in a manner that is consistent with sustainable development. The research did this for the Automated vehicles (this unlikely scenario is merely considered to demonstrate the potential of connectivity in the network) and the era of connected and automated vehicles. In doing this, the thesis identified the potential benefits that CAV technology can offer in sustainable systemwide management of road work zones. The thesis considered the following sustainability-related evaluation criteria: economic (accessibility to businesses, user costs of fuel consumption, and user costs of travel delay; social (rapid access by emergency services such as ambulance); and environmental (noise pollution and Greenhouse Gas (GHG) emissions). The routing optimization was modeled as a linear programming problem and numerical experiments were carried out. The road network of Sioux Falls city was used to demonstrate the study results. The results suggest that the developed optimal sustainable routing scheme yielded significant improvement in terms of the sustainability criteria while maintaining the acceptable levels of service The results also provided insights on the prospective benefits of routing schemes developed via system optimal management (achieved through centrally-guided detour movements that is facilitated by CAV technology) vis-à-vis user equilibrium management, specifically, Nash Equilibrium.

CHAPTER 1. INTRODUCTION

1.1 Background

Construction work zones (CWZ) are becoming more problematic compared to a decade ago in terms of safety and mobility, and this has posed a serious challenge for the construction agency, contractors, the community, and road users. According to the Associated General Contractors of America (AGC)'s 2019 nationwide study on highway CWZ's safety, 67% of highway construction contractors reported CWZ intrusions. Of these, 62% involved project delays, 28% worker injuries, 8% worker fatalities, 70% public injuries, and 28% public fatalities [1]. The AGC's 2019 study also revealed that 73% of contractors reported a greater risk of highway CWZ accidents now compared to some past years (Figure 1-1).



(a) Percentage of contractors reporting CWZ accidents

(b) National CWZ accidents and resulting injuries

(c) National fatalities resulted from CWZ accidents over years

Figure 1-1 Work zone safety trends (AGC, 2019)

The CWZ liability issue has been a persistent cause for concern from the perspective of road agencies, construction companies, and the general public. This has motivated agencies to provide guidelines for highway project contractors for work zone management in ways that decrease the CWZ crash rate. One way to do this is to implement full road closure in CWZ [9]. Advantages of full road closure includes positive public sentiment, increased productivity, reduced project duration, increased safety in the closed link as a result of less exposure between the workers and motorists, and cost saving (some cases) [9]. However, full road closure has the potential to cause challenges for certain stakeholders [10] [11] by increasing the accident risk and public complaints in the detour routes. Moreover, the detour cost should be considered in a full road closure cost evaluation.

Recent surveys and interviews of personnel from the Indiana Department of Transportation (INDOT) engineers other DOTs, the Federal Highway Administration (FHWA), and the American Association of State Highway and Transportation Officials (AASHTO) showed that the main challenge of full road closure is assignment of a reasonable detour route that considers the different stakeholders and cost components [12]. Moreover, there exists anecdotal evidence that at areas where full closure is implemented without sufficient considerations, there can be serious disruptions to the social and economic welfare. For example, during the full-road closure of the state street with West Lafayette, Indiana, in 2015-16, a number of companies suffer profound economic losses due to lack of customer access and reduction in clientele, and in some cases, others became bankrupt [13]. As such, in addition to safety, several aspects related to overall sustainability need to be considered in CWZ work zone and detour planning [14]. That way, the various concerns of the different stakeholders can be adequately considered to achieve a sustainable work zone plan.

Attaining safe and sustainable routing in CWZ has always been an important goal for the planners and contractors. For example, considerations of route choice estimation, travel time reliability/delay assessment, alternate route assignment, local community complaints, and work zone scheduling were studied in the literature using either field observation or optimization tools [15] [16] [17] [18]. Also, several of them have been implemented in practice. However, these efforts appear to be insufficient and therefore the problems associated with CWZ still persist.

Fortunately, the advent of new technologies offer some promising solution to the mobility issues in CWZ. One of these promising technologies that has been vastly studied in these years, is the implementation of Connected and Automated Vehicles (CAV) in CWZ detour routing [19] [20] [21]. The connectivity aspect of CAVs can help the road agency develop a central source of collecting and analyzing real-time traveler movements on the network, and subsequently can provide system-optimal detour route guidance in a manner that accounts for the concerns of the various stakeholders in a sustainable manner.

However, investigation of the potential of CAVs to help address the CWZ problem must be preceded by an examination of the CAV market share growth. Based on the adoption of previous vehicle technologies (e.g., automatic transmission, airbags, vehicle navigation systems, and hybrid-electric drive), Litman forecasted that Automated Vehicles (AVs) will constitute around 50% of vehicle fleet, 90% of vehicle sales, and 65% of all vehicle travel by 2050 [22] [23]. As a result, it is generally logical to consider an automated fleet for the future of transportation systems. One of the advantages of the automation is that higher levels of automation have the potential to increase the capacity of the road by improving the traffic flow characteristics, which will be exploited in this study [24] [25].

Connected vehicles are vehicles that utilize any of a number of different communication technologies (also shown in Figure 1-2) to communicate with the driver, other vehicles on-road [V2V], roadside infrastructure [V2I], etc. This technology can be utilized to not only improve the vehicle's safety, but also to enhance its efficiency and commute time [26].

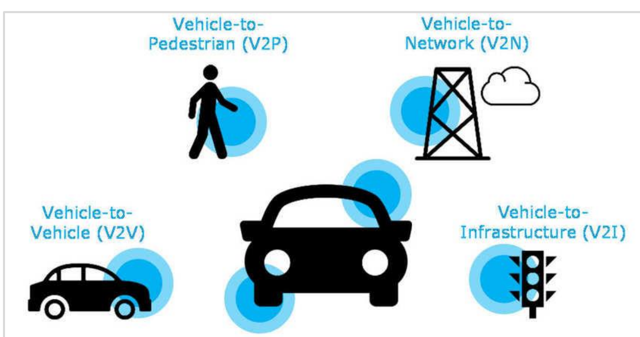


Figure 1-2 Communication technologies in connected [27]

The combination of automation and connectivity is expected to yield an unprecedented opportunity to improve the safety and mobility at construction workzones. Previous studies have investigated a number of these opportunities as crash elimination, reduced need for new infrastructure, travel time dependability, and improved energy efficiency. We briefly illustrate each of them in the bullets below [28] [29] [30].

- **Crash elimination:** Improved vehicle safety with monitoring the environment continuously by the high-level automated vehicle.
- **Reduced need for new infrastructure:** Self-driving vehicles are capable of reducing the need for building new infrastructure and decreasing maintenance costs by managing the traffic flow.
- **Travel time dependability:** V2V, V2N, and V2I can significantly decrease the uncertainty in travel times via real-time, predictive assessment of travel times on all routes.
- **Improved energy efficiency:** Reduced energy consumption will be resulted from the more time dependable and more efficient driving.

1.2 Problem Statement

In areas of construction work zones, particularly under conditions of full road closure, road agencies routinely provide route guidance to road users (through FM radio and electronic road signs) so that they can navigate the network with minimal delay and maximum possible safety. The agencies seek to provide such guidance in a manner that addresses the concerns of all the three key stakeholders (the agency, the road users, and community) in manner that is sustainable (addresses social, economic and environmental capital of the area). Therefore, issues of safety, mobility, accessibility, and emissions are critical considerations to road agencies as they develop such guidance. However, the literature lacks a sustainable routing methodology that addresses these concerns.

1.3 Study Objectives

Based on the problem statement presented in the previous section, this thesis seeks to develop and demonstrate a methodology for routing road users in a network with CWZ, in a manner that addresses the concerns of key stakeholders and therefore is consistent with the three pillars of sustainability. The methodology considers the information sharing capabilities that is made available through a cooperative network of connected and automated vehicles. Using the methodology, the road agency can suggest to the road users in the network, a sustainable detour route (itinerary) for the road users in case of full closure. In this routing problem, the thesis considers accessibility to businesses and local communities, rapid access of emergency services such as ambulances, police stations, and fire stations, avoidance of the increased travel time due to the closure of any network link, avoiding the violation of noise pollution regulations, and minimize the Greenhouse Gas (GHG) emissions. We also aim to minimize the road user cost that includes the fuel consumption and the delay costs.

1.4 Study Overview

This thesis considers a general road network with its link attributes including link capacities and link travel times, with full lane closure on some of its links for construction purposes. It also considers a fleet of CAV traveling from their origins to destinations. It is assumed that each vehicle reports its origin and destination (OD) to a central operator before its departure. Hence, vehicles' trip schedules are known a priori. The operator of the fleet exploits the connectivity in CAV technology to provide route guidance to the vehicles in the fleet. Due to the full road closure, the impact on the community is also considered. The main concern is to maintain the accessibility to businesses and the rapid access of emergency services such as ambulances, police stations, and fire stations. Sufficient access for the residents and school zones should also be considered. However, due to the lack of resources and time, it was not possible in this study and is considered as a suggestion for the future work. Next concern is to avoid the increased travel time due to the closure of some of the network links. Another issue that is considered is the environmental impacts including Greenhouse Gas (GHG) emissions and noise pollution. The thesis gives due cognizance to accessibility for business owners and emergency services and noise pollution as hard constraints, where the minimum requirements must be satisfied. The thesis also defines a monetarized cost as a weighted sum of the total fuel consumption cost, the total travel time cost, and the total GHG emissions damage cost. Different values of time are used to convert the travel time into a monetarized value. As a result, it is possible to prioritize the business trips that have a higher value of time. The operator of the fleet seeks to provide route guidance for each vehicle to minimize travel time costs within the given constraints. Additionally, the thesis utilizes the concept of Nash equilibrium to model the routing of a non-cooperative automated fleet of vehicles, where each individual aims to minimize their own trip cost. Then, with a solvable optimization problem, the routing of the vehicles that follow this greedy behavior is developed. This enables the investigation of the potential benefits of a cooperative fleet of automated vehicles in the presence and then in the absence of connectivity.

1.5 Study Organization

This study is organized in the following order. Chapter 2 is dedicated to the study framework. Afterwards, a comprehensive literature review is presented in Chapter 3. Chapter 4 presents the methodological contributions of this study and Chapter 5 presents the collected data and the data collection procedure. Then, in Chapter 6, the numerical experiment and results are discussed. Lastly, the concluding remarks (consisting of the research summary, conclusion, limitations, and future work) are presented in Chapter 7.

CHAPTER 2. LITERATURE REVIEW

The literature review focuses on the CWZ (with full road closure) detour planning challenges and the beneficial impacts of Connected and Automated Vehicles (CAV) in facilitating the detour planning procedure. To reach this goal, the beneficial effects of operating a full road closure, where detour implementation is required, is first presented. Then, the literature containing the challenges related to planning a sustainable detour are presented, followed by an introduction to the prospective benefits of CAV to CWZ detour planning. Lastly, a summary of the key stakeholders, CWZ detour performance indicators, and considered cost components based on the case studies of the state Departments of Transportation (DOTs) are presented.

2.1 Effects of Full Closure in a Construction Work Zone

Maintenance projects are vital and unavoidable for the smooth operation roads. In some cases, to implement these projects, contractors are required to close the road to provide more workspace [31]. Full closure is beneficial in terms of the safety of motorists as well as the maintenance workers because it eliminates potential spatial conflicts between the motorists and workers. The advantages of full road closure include reduction in project duration, enhanced traveler and worker safety, increased workspace, higher final product quality, positive public sentiment, and increased flexibility in project planning. Moreover, full closure enhances workers' efficiency because they are less distracted with the traffic movements [32]. At this point, this improvement on safety is vital because contractors in CWZ have reported several safety issues that has worsened over the years [1].

Despite the promising improvements leading to resolving the CWZ safety concern, full road closure approach might bring up challenges that hinder engineers from vastly prescribing it at this stage of technology [33]. It should be noted that fully closing a road due to a construction work urges using other nearby roads to carry the routed traffic. In this procedure, a careful consideration of the link capacity usage is necessary to avoid overloading the links that carry the traffic load [34].

2.2 Affected Stakeholders in a CWZ with Full Closure

To understand the affected stakeholders on the closed road and the road that carries traffic, a full road closure case studies in urban areas have been carried out by some state DOTs. The case study reported by the FHWA on the implementation of full road closure in a work zone in Portland, Oregon suggested that the following stakeholders may be considered in detour planning [35].

- Emergency services, i.e., ambulances and fire station trucks.
- Law enforcement services, e.g., police
- Hospitals
- School zones
- Residents
- Commuters
- Local businesses
- Trucking firms
- Travel agents/tourism bureaus
- Special event planners
- Contractors working on other nearby road projects
- Airports
- Metro-cab companies
- Public/citizen associations or groups

2.3 Project Performance Assessment in a CWZ with Full Closure

At least one previous study identified the main considerations of DOTs regarding full road closures [36] as shown in Table 2-1.

Table 2-1 Performance factors considered in the previous full closure projects

	Safety	Mobility	Cost	Quality	Public sentiment	duration	Future investment	Environmentally friendly construction
I-40 [37]	■	■	■	■	■	■		
I-64 [38]	■	■	■		■			
I-65	■	■			■			
I-70	■	■	■	■	■	■		
I-84 [35]	■	■	■	■	■	■		
I-95 [39]	■	■	■	■	■	■	■	
I-295 [40]	■	■	■		■			■

2.4 Impacts of Work Zones on the Transportation Network

The assessment of the potential environmental, economic, and social impacts of work zones is well-investigated in the literature [41] [42]. Traffic flow modeling in work zones is one of the considered aspects [43]. Specifically, capacity reduction factors, and free-flow speed reduction factors have been analyzed for various activities related to construction and maintenance in CWZ [43]. Moreover, several studies have considered the impact of having special plans for CWZ project operations. For example, benefits and safety impact of night-time work zone activities, which is capable of reducing the project duration, have been studied [44] and been compared with the day-time project operations [45].

Although work zone impacts on the network have been well-studied, one major issue is still planning sustainable route guidance or detour after closing the road (fully or partially). In the recent INDOT study, several surveys, interviews, and case study reviewing were carried out [12]. According to the results of surveys (which was filled by fifty engineers working on full road closure in the state DOTs, FHWA, and AASHTO) the main reason for their difficulty in prescribing often full road closure (which is economically feasible and safer) is the inability to find an appropriate routing plan. Due to the importance of this topic, a summary of the available literature on the detour planning is presented in the next section.

2.5 Detour Planning in a CWZ with Full Closure

A recently published thesis [28] investigated the short and longterm effects of pre-planned detours on congestion alleviation and traffic operations at a CWZ. In that study, the road users’ travel behavior, e.g., detour route choosing, was studied and the reported results included the traffic flow pattern before, during, and after road construction projects. Recently, new approaches in detour planning in work zones have been investigated. The consideration of connected networks in easing the deotur planning procedure, reducing emissions, and enhancing safety [46, 47]. These studies mentioned the potential of connected vehicles (CVs) in improving mobility, enhancing safety, and reducing greenhouse gas emissions (GHG) in a network level model.

2.6 Connected and Automated Vehicles and Prospective Impacts on CWZ

Connected and Automated Vehicles (CAVs) consists of two main aspects: (1) automation; (2) connection. There are 5 defined levels for automation as shown in (Figure 2-1).

- **Level 0 – No automation**

  also called as conventional vehicles with no driving assistance.

- **Level 1 – Driver assistance**

  Adaptive cruise control and lane-keeping assistance are provided to assist the driver. The former will keep a safe distance between the consecutive vehicles by using radars and/or cameras and the latter will help the vehicle stay within the lanes. Although this level of automation assists the drivers, it still requires the driver to take the control of the vehicle and be aware of the road condition at all times. This level of automation is currently available in a great percentage of vehicles, e.g., Toyota Corolla 2018 (Toyota Safety Sense 1) and Nissan Sentra (Intelligent Cruise Control).

- **Level 2 – Partial automation**

  Level 2 automation is helpful in controlling the speed and steering, while the driver must have hands on the wheel and be aware of the road condition to take over the control of the vehicle at any given moment. This technology assists the driver with the stop-and-go traffic by maintaining the distance between the consecutive vehicles, while also providing steering assistance by centering the vehicle within the lane. Examples of this level of automation are Tesla Autopilot, Volvo Pilot Assist, and Audi Traffic Jam Assist.

- **Level 3 – Conditional automation**

  Level 3 autonomous vehicles are capable of driving themselves. Although hands are off the wheel in this level of automation, drivers are still required to take over the control of vehicle in case of automation failure. The next generation 2019 Audi A8 is expected to be the first to market a level 3 autonomous driving system.

- **Level 4 – High automation**

  Level 4 autonomous vehicles are capable to drive without human interactions besides entering the destination. However, these vehicles will be restricted to some driving purposes because of the restrictive regulations and legal obstacles. These regulations mainly concern the safety issues and ethical concerns that might be resulted from the implementation of the automated systems [48, 49]. As the first company to examine the high automation level, Waymo has developed and is in the process of testing level 4 vehicles capable of driving themselves in most environments and road conditions [50].

- **Level 5 – Full automation**

  Level 5 autonomous vehicles are capable of monitoring and maneuvering through all road conditions without any human interactions, eliminating the need for a steering wheel and pedals. These vehicles can be called the "true driverless vehicles".

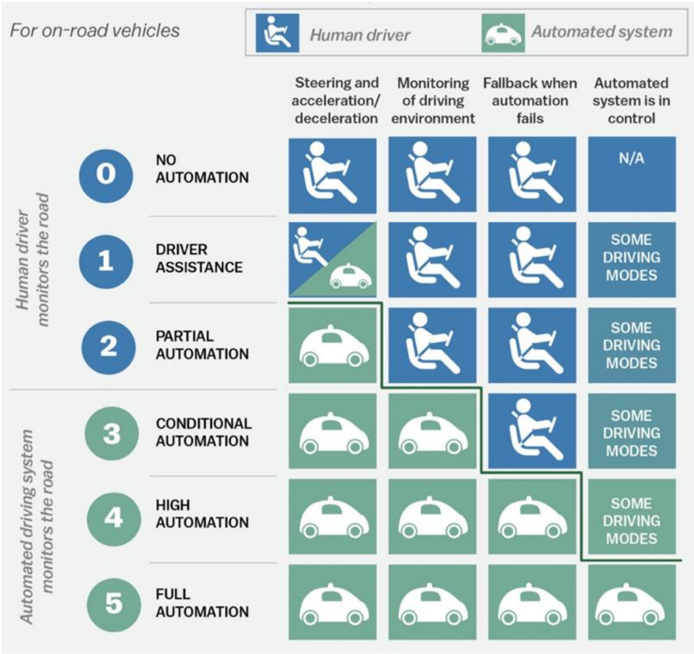


Figure 2-1 Levels of vehicle automation [51]

One of the advantages of the automation is that higher levels of automation have the potential to increase the capacity of the road by improving the traffic flow characteristics, which will be exploited in this study [24] [25]. Connected vehicle technology is also a rapidly emerging paradigm aimed at developing and deploying a fully connected transportation system that enables data exchange among vehicles and the infrastructure to improve mobility, enhance safety, and reduce the adverse environmental impacts of the transportation systems [52]. In this study, a level (1) automated vehicle is considered in all scenarios.

2.7 Sustainability Definition in CWZ [53]

The three components of sustainable development are: (1) economic, (2) social, and (3) environmental [54] (Figure 2-2). According to this figure, development is equitable when the planner considers the social and economic aspects, viable when both economic and environmental aspects are considered, and bearable when both social and environmental aspects are considered. In terms of mobility in work zones, sustainability components are defined for each of the stakeholders, i.e., construction agency, community, and road users in Table 2-2.

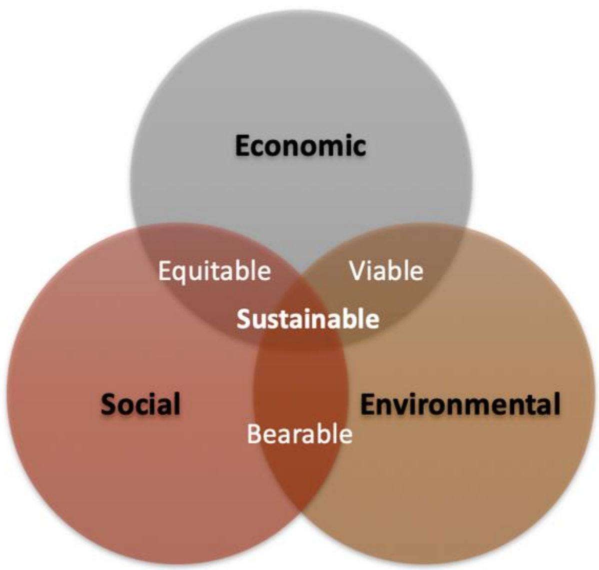


Figure 2-2 Sustainability components in planning

Table 2-2 Sustainability considerations for each stakeholder of work zones

Pillar Stakeholder	Economic	Environmental	Social
Highway agency	Construction cost Work zone cost Public outreach cost		Public relations
Community	Delay cost for the local business owners	Noise pollution Hospitals Residential areas Greenhouse Gas (GHG) emissions	Accessibility to local businesses and residence
Road users	Travel delay cost Extra fuel consumption cost		Accessibility Emergency service providers Law enforcement agencies Airport authorities Trucking firms

2.8 Chapter Summary and Discussion

Due to the great potential that both connected and automated vehicles bring to the network improvements considering the safety and mobility aspects [24], [25], [46, 47], it seems promising to consider these concepts in solving the issues with the sustainable routing in work zones. This field of research is emerging and there are a numbrt of gaps that should be investigated. First of all, there is no study available to propose a model for both connected and non-cooporative networks to mathematically prove the potential impacts of connected vehicles comparing to not-connected ones. Secondly, there is no scalable traffic assignment and solution algorithm to propose deotur routes in full road closure. Lastly, there is no mathematical model that considers all three aspects of sustainability. In this study, we strive to fill these gaps.

CHAPTER 3. METHODOLOGY

In this section, we present the assumptions, considerations, and formulations for each of the components in the optimization problem. The subsections in this chapter consist of (1) Key Assumptions; (2) study framework, where we represent the hierarchy of research in this study; (3) network representation; Afterwards, we will show the constraints and cost components as (4) business access; (5) Emergency access facilitating; (6) Noise pollution consideration; (7) GHG emissions consideration; (8) Link travel cost consideration, which consists of the travel time cost and the fuel cost; Lastly, we present the two different formulations in modeling the cooperative network; (9) System optimal formulation; and the non-cooperative network; (10) Nash Equilibrium formulation.

3.1 Key Assumptions

1. Full road closure in work zones is considered.
2. Two different types of vehicles (i.e., automated vehicles and connected and automated vehicles) are studied to demonstrate the potential impacts of connectivity in a road network with work zones.
3. Road closure impact on the businesses only on the closed route is considered.
4. A specific portion of the capacity of roads (i.e., 5%) with high emergency demand is considered for the emergency access.
5. In calculating the GHG emissions, the best-selling vehicle in the U.S. is considered.
6. Truck accessibility facilitating, school zones, airport accessibility, etc. are not considered in this study.

3.2 Study Framework

In this section, the roadmap of the thesis research is presented (Figure 3-1).

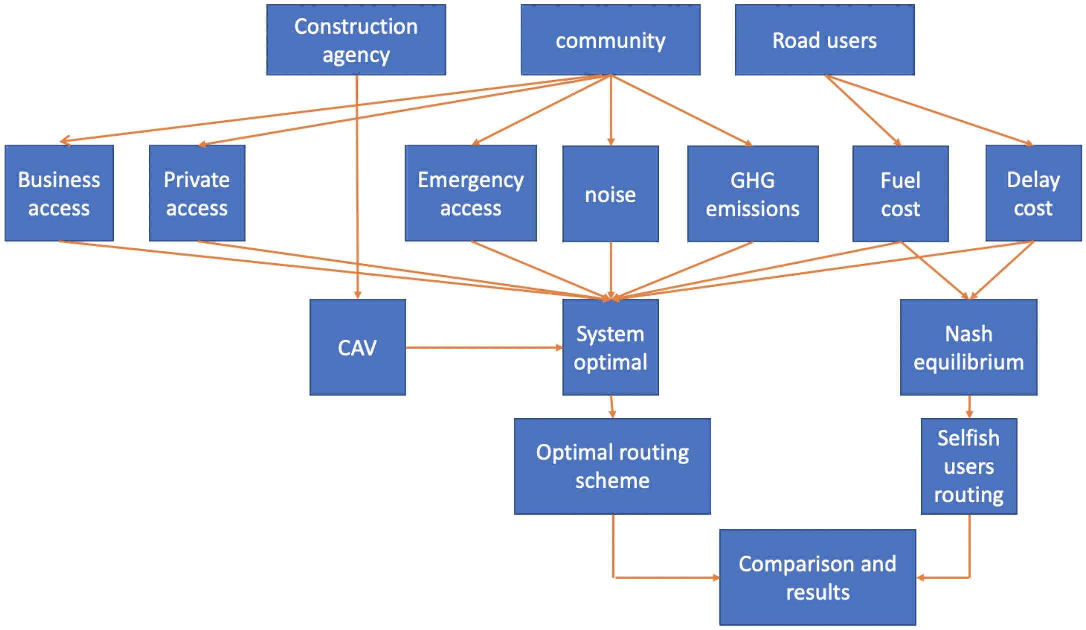


Figure 3-1 Study framework

3.3 Network Representation

We formulate the problem as a physical network $G = (V, E)$, where V represents the set of nodes in the network and E represents the set of links in the network. For each link $l \in E$ in the network we denote the link capacity by u_l and the travel time by t_l. As we mentioned in the introduction section, we model the congestion in the network utilizing the capacitated network modeling approach by defining the maximum link capacities [55]. We also assume there exist two stationary demands for personal and business trips between each origin destination pair (o, d) and denote them by $p_{(o,d)}$and $b_{(o,d)}$, respectively. We also model the flow of personal and business vehicles on link l from node o towards node d by defining variables $\boldsymbol{x}_{\boldsymbol{l}}^{\boldsymbol{p},(\boldsymbol{o},\boldsymbol{d})}$ and $\boldsymbol{x}_{\boldsymbol{l}}^{\boldsymbol{b},(\boldsymbol{o},\boldsymbol{d})}$, respectively.

3.4 Business Access

The main concern for the business owners is the excess delay their customers incur in order to take a trip to their business centers due to the closure of some of the links in the network during a construction project. To address this issue, for each origin destination pair (o, d) we set two prespecified values $e_{(o,d)}^{p}$and $e_{(o,d)}^{b}$ as the maximum extra delays for the personal and business trips from o to d, respectively. To ensure a trip does not violate the pre-specified maximum delay from its origin to its destination, it is sufficient to ensure that no link on the path connecting the origin to the destination violates this constraint [56].

We can obtain the set of feasible links a personal/business trip can utilize applying a pre-processing procedure proposed by [57] [58]. The core idea is to find the links traveling on which would make it impossible for the excess delays to remain under the prespecified values. We denote by $E^{p}_{(o,d)}$ and $E^{b}_{(o,d)}$ the set of feasible links in the network for the personal/business trips from *o* to d. Below, we present a pseudo code to obtain the set of feasible links, $l = (i,j)$, that are included in at least one trip from *o* to *d* with maximum delay $e_{(o,d)}$, where *o=origin and d=destination*.

Algorithm 1: Pre-processing procedure to find the set of feasible links for origin destination pair (o,d) with maximum delay $e_{(o,d)}$

for l=$(i,j) \in E$ **do**
  if $dist(o,i) + dist(i,j) + dist(j,d) > dist(o,d) + e_{(o,d)}$ **then**
    $E_{(o,d)} = E_{(o,d)} \cup l$
  end
end

3.5 Emergency Access

To satisfy emergency access concerns, we consider two main issues. First, the emergency service provider should be within the acceptable range of service. Second, emergency service providers should not experience more than the minimal delay inside the network. To address the range-related concerns, we utilize a pre-processing procedure to determine the potential emergency providers to any given node inside the network. Doing this for each node $i \in V$, we can determine the set $H(i)$ consisting of all service provider nodes that are within acceptable range of node i. To address the delay concern, we assume the emergency vehicles that provide service from node $h \in H(i)$ to node i utilize only the links that are on one of the shortest paths from h to i. We can use the pre-processing procedure (Algorithm 1) to obtain the set of links $E^{em}_{(h,i)}$ that are located on the shortest path from service the node h to the node i. Additionally, we assume a constant demand v_i for the emergency services exist at each node i. The reason for considering a constant demand is that we do not consider the stochasticity in demand at this phase of the project. However, we are mentioning this aspect as our future work in Chapter 6.

To mathematically model the emergency service access, we define variables $\boldsymbol{y_l^{(o,d)}}$ to represent the flow of emergency vehicles on the link l from node $o \in H(d)$ towards node d. We also define variables $\boldsymbol{s_{(o,d)}}$ to represent the part of demand at node d that is satisfied by emergency service providers at node o. We formulate the emergency access problem using the following feasibility problem:

$$\sum_{\substack{j:l=(i,j) \\ l \in E^{em}_{(o,d)}}} \boldsymbol{y_l^{(o,d)}} - \sum_{j:l=(j,i)} \boldsymbol{y_l^{(o,d)}} = \begin{cases} \boldsymbol{s_{(o,d)}: i = o} \\ \boldsymbol{-s_{(o,d)}: d = i} \\ \boldsymbol{0: otherwise} \end{cases} \quad \forall \boldsymbol{i, d} \in \boldsymbol{V}, \forall \boldsymbol{o} \in \boldsymbol{H(d)} \qquad \text{Equation 3-1}$$

$$\sum_{\boldsymbol{o}} \boldsymbol{s_{(o,d)}} = \boldsymbol{v_d} \quad \forall \boldsymbol{d} \in \boldsymbol{V}, \forall \boldsymbol{o} \in \boldsymbol{H(d)} \qquad \text{Equation 3-2}$$

Constraint set 1 (Equation 3-1) represents the flow conservation constraint for the portion of demand in node *d* that is satisfied with the emergency provider at node $o \in H(d)$ and constraint set 2 (Equation 3-2) ensures that the emergency demand in each station *d* is satisfied.

3.6 Noise Pollution Evaluation

In this study, we have utilized the Road Noise Mitigation Program formulation, which is based on the results of a three-phase project (MJPG) in Netherlands [59] [60]. The script computes the noise level in dB(A) at a given distance from a road. The most effective inputs consist of the number of vehicles, number of trucks, the mean speed, and the distance from the road. Each of the components in the formulation are presented in the following paragraphs.

In this method, vehicle categories consist of the motorcars, vans (i.e., delivery trucks, and all types of buses), heavy vehicles (i.e., all trucks that have more than two axles or 2 tires on any of the axles), and motorbikes. Also, in the road surface choices, smooth asphalt, concrete/asphalt mixtures, paved bricks, regular porous, sound absorbing asphalt that reduces noise by approximately 2 dB(A) at higher speeds, and special sound absorbing road surfaces are considered.

The default mean speed for each vehicle class is considered in both $\frac{Km}{hr}$ and miles per hour (mph) and we use the mph system in this thesis.

The shortest horizontal distance between the observer and the center of road is defined as the distance to the observer. Regarding the distance from an intersection, in is noteworthy that intersections generate more traffic noise compared to the free-flowing segments. However, in a distance over 490 ft from any intersection, the noise effect can be considered to be negligible. The observers' height in the calculation is based on the story of the building, and the default value is considered as 5 meters. Moreover, the default value for the height of the road is considered as 0 in this method.

The standard angle of sight is 127°. However, in case of road impediment by an obstacle, the remaining angle may be used. For example, if half of the view of the road is obstructed, the angle of sight will change into $\frac{127^{\circ}}{2}$. Absorption varies in different types of soils and the range for this value is (0-1). The lower bound is for very hard soil without absorption and the upper bound is for soft absorbing soil. Absorbing soils consist of grass, forest floor, and also snow. The default value for the formulation is 0 (city street) which has been used in this study. Figure 3-1 presents an image of the website platform for road traffic noise calculation.

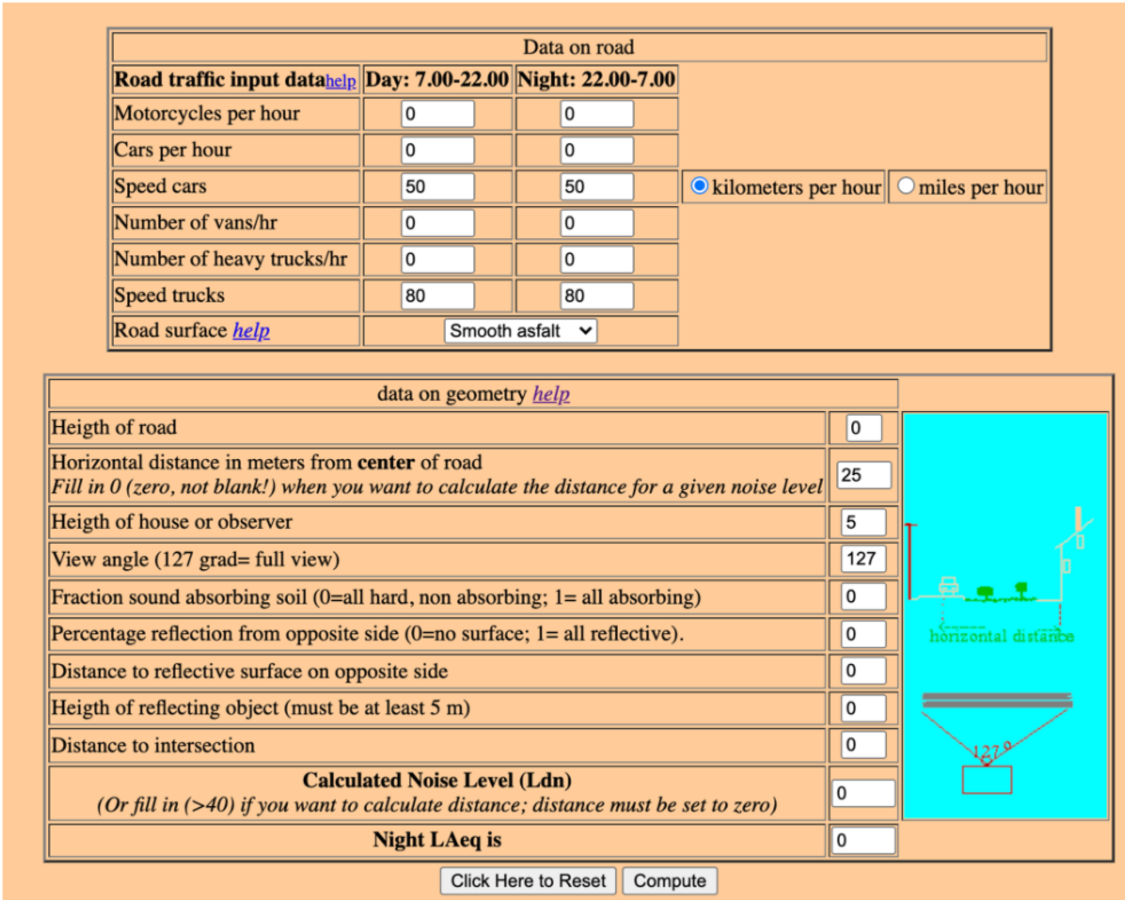


Figure 3-2 Traffic noise calculation platform [60]

Our approach to this problem is such that we consider the maximum acceptable dB(A) for hospital and residential areas. Afterwards, we enter the average speed on road based on the speed limit, the horizontal distance from the center of road, number of cars, and number of trucks. In order to calculate the number of trucks, we utilize the truck percentage on road. After computing the results, we receive the calculated noise level from this platform and find the number of cars and trucks, maximum noise capacity level u_l^n, that will result in having an acceptable noise level.

3.7 GHG Emissions Consideration

In this study, the Comprehensive Modal Emissions Model (CMEM) [61] was used to estimate the damage cost resulted from the GHG emissions. In this model, in general, the Engine-out Emissions Module can be calculated by utilizing a linear formulation as shown in Equation 3-3.

$$E_X = a_X . FR + r_X \qquad \text{Equation 3-3}$$

Where:

E_X is the engine-out emissions rate for the pollutant (x) (g/s), a_X and r_X are the emissions index coefficients, and FR is the fuel rate module. As such, the emission cost for a vehicle travelling on the link l can be computed as:

$$\boldsymbol{c}_l^{(\boldsymbol{o},\boldsymbol{d}),\boldsymbol{GHG}}(\$/_{veh}) = \sum_{X\in GHG}(E_X\ (^g/_s) \times dmg_X\ (^\$/_g)) \times t_l(hr) \times 60(^S/_{hr})$$

Where dmg_X is the unit damage cost of producing 1 g of pollutant X.

The basic fuel consumption module is calculated as shown in Equations 3-4 to 3-7.

$$FR \approx \left(K \times N \times V + \frac{P}{\eta}\right)\left(\frac{1}{43.2}\right)(1 + b_1(N - N_0)^2) \qquad \text{Equation 3-4}$$

$$K = K_0(1 + C(N - N_0)) \qquad \text{Equation 3-5}$$

$$N_0 = 30\sqrt{\frac{30}{V}} \qquad \text{Equation 3-6}$$

$$N \approx \frac{45.4}{60} \times S \qquad \text{Equation 3-7}$$

Where:

FR is the fuel usage rate (g/s), *P* is the engine power output (kW), *K* is the engine friction factor, *N* is the engine speed (revolutions per second), *V* is the engine displacement (lit) and $\eta \approx 0.45$ is a measure of the indicated efficiency for the engines. $b_1 \approx 10^{-4}$ and $C \approx 0.00125$ are two coefficients; the lower heating value of a typical diesel fuel is 43.2 kJ/g, and S is the vehicle speed.

In order to calculate the *FR*, one needs to find the specific vehicle model details from the manufacturer’s catalogues and substitute them in the aforementioned formulas. Moreover, the index coefficients in the engine-out emissions are calculated based on the vehicle model using the standard tables and are presented in the Data Collection chapter of this thesis.

3.8 Link Travel Cost Computations

Link travel cost consists of the travel delay and the fuel consumption costs. These are presented in 3.7.1 and 3.7.2, separately.

3.8.1 Travel Delay Cost Computations

After the construction agency introduces a full closure in the road network, the traffic has to use the other links to reach their destinations. This procedure might increase the total distance that drivers need to run. The extra distance is calculated using Equation 3-8, and then, by dividing this value with the average vehicle speed, the extra travel time as a result of detour will be calculated. This is referred to as the travel delay time and is presented in units of time. However, a cost representation of this delay is necessary for economic analysis purposes and planning, and the concept of Value of Time (VOT) facilitates the conversion of time to money.

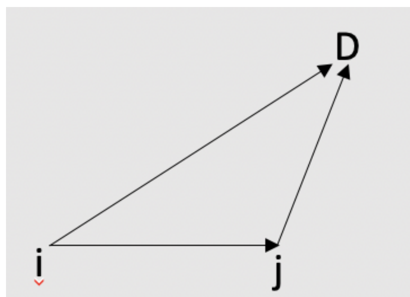


Figure 3-3 Extra distance representation

The excess distance that driver drives is presented in Equation (8).

$$Extra\ distance\ (l, O, D) = dis(l) + dis(j, D) - dis(i, D) \qquad \text{Equation 3-8}$$

Where $dis\big(l = (i, j)\big)$ is the distance traveled on link l between node i, node j;

$dis(j, D)$ is the distance traveled between node j and the new node D;

and $dis(i, D)$ is the distance traveled between node i, node D.

In transportation economics, the value of time is the opportunity cost of the time that a traveler spends on the journey. This value is the amount that a traveler would be willing to pay in order to save time, or the amount they would accept as compensation for lost time [62]. VOT has most often been determined by estimating the mode choice models and evaluating the marginal rate of substitution (MRS) between the cost and the travel time for the alternative modes [63]. This value can be represented based on different factors, e.g., personal monthly income or trip length and its value differs when travel purpose changes [64]. Generally, the total delay cost is calculated via Equation 3-9. In these formulas, travel delay time is calculated by dividing the extra distance to the vehicles' average speed. In this study, vehicles' average speed is equal to the speed limit in the region.

$$\begin{cases} \boldsymbol{c_l^{p,(o,d),delay}} = travel\ delay\ time\ (l, O, D) \times VOT_p \\ \boldsymbol{c_l^{b,(o,d),delay}} = travel\ delay\ time\ (l, O, D) \times VOT_b \end{cases} \qquad \text{Equation 3-9}$$

Where,

$\boldsymbol{c_l^{p,(o,d),delay}}$ is the travel delay cost for driving between node o (origin) and node d (destination)$in\ personal\ trips$;

VOT_p is the value of travel time for personal trips;

$\boldsymbol{c_l^{b,(o,d),delay}}$ is the travel delay cost for driving between node o (origin) and node d (destination)in business trips;

and VOT_b is the value of travel time for business trips.

In this study, we consider two different values of travel time for the business commuters and the other personal road users. The data for these two values are presented in the Data Collection chapter of this thesis.

3.8.2 Fuel Consumption Cost Computations

In order to calculate the fuel cost for a road user, we first need to define the Miles-per-Gallon (MPG) concept. MPG is utilized to indicate the fuel economy of a vehicle to represent the expense of running it. This concept is also helpful in comparing the fuel efficiency of different vehicles, i.e., a higher MPG represents a higher fuel efficiency. Practically, manufacturers test the vehicles' MPG both on road and in a laboratory under strict supervision and report this information to public. Afterwards, it will be possible to calculate the fuel consumption cost by having the unit fuel price, MPG, and vehicle speed. This procedure is shown in Equation 3-10.

$$\boldsymbol{c_l^{(o,d),fuel}} = P_f \times \frac{1}{MPG} \times V \times t_l \qquad \text{Equation 3-10}$$

Where

$\boldsymbol{c_l^{(o,d),fuel}}$is the Fuel consumption cost $\left(\$/_{\text{hr.veh}}\right)$;

P_f is the average fuel price $\left(\$/_{\text{gal}}\right)$; MPG is the fuel efficiency factor ($^{gal}/_{mi}$);

V is the vehicle speed$\left(^{mi}/_{hr}\right)$; $and\ t_l\ is\ the\ travel\ time\ on\ link\ l\ (hr)$.

3.9 System Optimal Formulation

Now, we integrate the components of the problem as a unified optimization problem that aims to minimize the total cost, while respecting the feasibility constraints. The total cost in the objective function, c_l consists of three weighted components, i.e., $c_l^{p,(o,d)} = w_1 c_l^{p,(o,d),delay} + w_2 c_l^{(o,d),fuel} + w_3 c_l^{(o,d),GHG}$. Where w_1 is the weight for personal travel delay cost, $c_l^{p,(o,d),delay}$ is the delay cost for personal trips on link *l* as stated in Section 3.7.1 of this thesis, w_2 is the weight for the fuel consumption cost on link *l*, $c_l^{(o,d),fuel}$ is the fuel consumption cost on link *l* as stated in Section 3.7.2 of this thesis, w_3 is the weight for GHG emissions cost, and $c_l^{(o,d),GHG}$ is the GHG emissions damage cost of travelers on link *l* as stated in Section 3.6 of this thesis.

The optimization problem is stated by Equation 3-11(a)-(e).

$$\boldsymbol{Min} \sum_{(o,d)} \sum_{l=(i,j)} \boldsymbol{c}_l^{p,(o,d)} \boldsymbol{x}_l^{p,(o,d)} + \sum_{(o,d)} \sum_{l=(i,j)} \boldsymbol{c}_l^{b,(o,d)} \boldsymbol{x}_l^{b,(o,d)} \qquad \text{Equation 3-11(a)}$$

$$\sum_{\substack{j:l=(i,j)\\ l\in E^b_{(o,d)}}} \boldsymbol{x}_l^{b,(o,d)} - \sum_{\substack{j:l=(j,i)\\ l\in E^b_{(o,d)}}} \boldsymbol{x}_l^{b,(o,d)} = \begin{cases} \boldsymbol{b}_{(o,d)}: \boldsymbol{i} = \boldsymbol{o} \\ -\boldsymbol{b}_{(o,d)}: \boldsymbol{d} = \boldsymbol{i} \\ \boldsymbol{0}: \boldsymbol{otherwise} \end{cases} \qquad \forall \boldsymbol{i}, \boldsymbol{o}, \boldsymbol{d} \in \boldsymbol{V} \qquad \text{Equation 11(b)}$$

$$\sum_{\substack{j:l=(i,j)\\ l\in E^p_{(o,d)}}} \boldsymbol{x}_l^{p,(o,d)} - \sum_{\substack{j:l=(j,i)\\ l\in E^p_{(o,d)}}} \boldsymbol{x}_l^{p,(o,d)} = \begin{cases} \boldsymbol{p}_{(o,d)}: \boldsymbol{i} = \boldsymbol{o} \\ -\boldsymbol{p}_{(o,d)}: \boldsymbol{d} = \boldsymbol{i} \\ \boldsymbol{0}: \boldsymbol{otherwise} \end{cases} \qquad \forall \boldsymbol{i}, \boldsymbol{o}, \boldsymbol{d} \in \boldsymbol{V} \qquad \text{Equation 11(c)}$$

$$\sum_{\substack{j:l=(i,j)\\ l\in E^{em}_{(o,d)}}} \boldsymbol{y}_l^{(o,d)} - \sum_{\substack{j:l=(j,i)\\ l\in E^{em}_{(o,d)}}} \boldsymbol{y}_l^{(o,d)} = \begin{cases} \boldsymbol{s}_{(o,d)}: \boldsymbol{i} = \boldsymbol{o} \\ -\boldsymbol{s}_{(o,d)}: \boldsymbol{d} = \boldsymbol{i} \\ \boldsymbol{0}: \boldsymbol{otherwise} \end{cases} \qquad \forall \boldsymbol{i}, \boldsymbol{d} \in \boldsymbol{V}, \forall \boldsymbol{o} \in \boldsymbol{H}(\boldsymbol{d}) \qquad \text{Equation 11(d)}$$

$$\sum_{\boldsymbol{o}} \boldsymbol{s}_{(o,d)} = \boldsymbol{v}_{\boldsymbol{d}} \qquad \forall \boldsymbol{d} \in \boldsymbol{V}, \forall \boldsymbol{o} \in \boldsymbol{H}(\boldsymbol{d})$$

$$\sum_{\substack{(o,d):\\ l\in E^b_{(o,d)}}} \boldsymbol{x}_l^{b,(o,d)} + \sum_{\substack{(o,d):\\ l\in E^p_{(o,d)}}} \boldsymbol{x}_l^{p,(o,d)} + \sum_{\substack{(o,d):\\ l\in E^{em}_{(o,d)}}} \boldsymbol{y}_l^{(o,d)} \le \boldsymbol{u}_l^t \qquad \forall \boldsymbol{l} \in \boldsymbol{E} \qquad \text{Equation 11(e)}$$

Constraint set 11(b) ensures the flow conservation for the business trips. Constraint set 11(c) ensures the flow conservation for the personal trips. Constraint sets 11(d) ensure the emergency access for the emergency service providers, as mentioned in Section 3.4. Constraint set 11(e) ensures that the total flow on each link does not exceed the upper-bound, $u_l^t = \min(u_l, u_l^n)$, which is the minimum of the link capacity, u_l, introduced in Section 3.2 and the noise pollution capacity, u_l^n, introduced in Section 3.5.

3.10 Nash Equilibrium Formulation

In Nash Equilibrium (NE), no user can reduce their travel time by unilaterally changing their path. The Wardrop's first principle for User Equilibrium (UE) states that the chosen paths' travel time between an O-D pair is less than or equal to the travel time for the other paths in a system with selfish users [65]. These two equilibria are shown to be equivalent under special conditions for the uncapacitated UE that volume-delay functions are continuous, separable, non-negative and non-decreasing. Here, we apply the paper published by Zokaei Ashtiani et al. (2020) [66] to find the Nash Equilibrium solution for capacitated networks in the optimization problem defined by Equation 3-12(a)-(d).

$$\boldsymbol{Min} \sum_{l=(i,j)} \int_{0}^{\sum_{(o,d)} x_l^{b,(o,d)} + x_l^{p,(o,d)}} t_l(w)dw \qquad \text{Equation 3-12(a)}$$

$$\sum_{\substack{j:l=(i,j)\\ l\in E^b_{(o,d)}}} x_l^{b,(o,d)} - \sum_{\substack{j:l=(j,i)\\ l\in E^b_{(o,d)}}} x_l^{b,(o,d)} = \begin{cases} b_{(o,d)}: i = o \\ -b_{(o,d)}: d = i \\ 0: otherwise \end{cases} \qquad \forall i,o,d \in V \qquad \text{Equation 12(b)}$$

$$\sum_{\substack{j:l=(i,j)\\ l\in E^p_{(o,d)}}} x_l^{p,(o,d)} - \sum_{\substack{j:l=(j,i)\\ l\in E^p_{(o,d)}}} x_l^{p,(o,d)} = \begin{cases} p_{(o,d)}: i = o \\ -p_{(o,d)}: d = i \\ 0: otherwise \end{cases} \qquad \forall i,o,d \in V \qquad \text{Equation 12(c)}$$

$$\sum_{\substack{(o,d):\\ l\in E^b_{(o,d)}}} x_l^{b,(o,d)} + \sum_{\substack{(o,d):\\ l\in E^p_{(o,d)}}} x_l^{p,(o,d)} \le u_l \qquad \forall l \in E. \qquad \text{Equation 12 (d)}$$

In this optimization problem, the objective function is the well-known BMW objective function, where the function $t_l(w)$ is the link travel time for link l if there is a flow w on link l. Note that in finding the equilibrium solution the business and personal trips for the same origin destination pair have the same effect on the objective function. Constraint set 12(b) ensures the flow conservation for the business trips; Constraint set 12(c) ensures the flow conservation for the personal trips; and constraint set 12(d) ensures that the total flow on each link *l* does not exceed the maximum capacity u_l.

CHAPTER 4. DATA COLLECTION AND COLLATION

This chapter presents the data collected from the Sioux Falls, South Dakota network, for which we have conducted the numerical study. The chapter is organized as follows: (1) Sioux Falls network general data including the nodes, links, link attributes, and origin-destination travel demand; (2) Business access data including the land use information, value of time (VOT), and the acceptable excess delay; (3) Emergency access data including the hospital location and emergency demand on each node (4) Noise pollution consideration data including the hospital areas, residential areas, speed limits, truck percentage, and the standards for the maximum acceptable noise level; (5) GHG emissions consideration data including the specific vehicle characteristics and energy consumption parameters in producing emissions; (6) Link travel cost consideration data including the acceptable travel delay and fuel consumption costs.

4.1 Sioux Falls Network Data

The data includes the nodes, links, link attributes, and origin-destination travel demand for Sioux Falls network in South Dakota (SD) [67], as shown in Figure 4-1, Table 4-1, and Table 4-2.

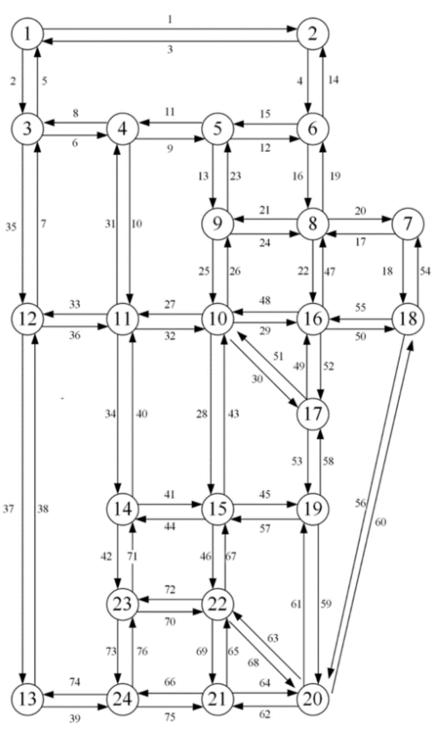


Figure 4-1 Nodes and links for the Sioux Falls road network

Table 4-1 Link capacity and travel time data for the Sioux Falls Network

Link	t_a^0 **(minute)**	u_a **(10^3 veh/hr)**
1	3.6	4.5
2	2.4	8.5
3	3.2	11.5
4	3.0	15.4
5	2.4	46.3
6	2.4	33.7
7	2.4	39.5
8	2.4	25.3
9	1.2	27.8
10	3.3	8.5
11	1.2	46.4
12	2.4	13.4
13	3.0	10.0
14	3.0	9.4
15	2.4	9.4
16	1.0	21.1
17	1.8	15.2
18	1.2	46.3
19	1.2	9.3
20	1.8	15.2
21	1.8	9.6
22	3.0	9.6
23	3.0	19.5
24	2.0	9.6
25	1.8	27.3
26	1.8	27.3
27	3.0	19.5
28	3.6	26.5
29	3.0	9.8
30	4.2	9.5
31	3.6	9.3
32	3.0	19.5
33	3.6	9.3
34	2.4	9.3
35	2.4	46.3
36	3.6	9.3
37	1.8	51.3
38	1.8	51.3
39	2.4	9.7
40	2.4	9.3
41	3.0	9.8
42	2.4	9.4
43	3.2	26.5
44	3.0	9.8
45	2.4	9.1
46	2.4	20.1
47	3.0	9.6
48	3.0	9.8
49	1.2	10.0

Table 4-1 continued

50	**1.8**	**38.9**
51	4.2	9.5
52	1.2	10.0
53	1.2	9.2
54	1.2	46.3
55	1.8	38.9
56	2.4	7.6
57	2.4	3.9
58	1.2	9.2
59	2.4	9.5
60	2.6	7.6
61	2.4	5.6
62	3.6	9.6
63	3.0	9.7
64	3.6	9.6
65	1.4	10.0
66	1.8	9.3
67	2.4	20.1
68	2.8	9.7
69	1.2	10.0
70	2.4	9.5
71	2.4	9.4
72	2.4	9.5
73	1.2	9.7
74	2.4	10.9
75	1.8	9.3
76	1.2	9.7

Table 4-2 O-D matrix for the network O-D trip matrix ($\times$ 1000 veh/hr)

	1	2	4	5	10	11	13	14	15	19	20	21	22	24
1		1.32	1.32	1.32	1.08	1.1	1.25	0.99	0.95	0.9	0.59	0.59	0.77	0.74
2	1.32		1.25	1.3	1.1	1.12	0.9	0.95	0.94	1.3	0.59	0.68	0.67	0.59
4	1.32	1.25		1.32	1.08	1.07	0.95	0.9	0.84	0.8	1.62	0.64	0.59	0.8
5	1.5	1.3	1.32		1.13	0.97	0.91	0.88	0.81	0.73	0.8	0.81	0.94	0.59
10	1.08	1.1	1.08	1.13		1.5	1.9	0.99	1.32	1.17	0.95	0.9	1.97	0.59
11	1.1	1.12	1.07	0.97	1.5		0.94	1.32	1.11	0.95	0.74	0.61	1.1	1.05
13	1.25	0.9	0.95	0.91	0.9	0.94		0.87	0.86	0.68	0.59	0.62	0.67	1.32
14	0.99	0.95	0.9	0.88	0.99	1.32	0.87		1.32	2.13	0.95	0.87	0.9	1.13
15	0.95	0.94	0.84	0.81	1.32	1.11	0.86	1.32		1.32	1.27	1.14	1.32	0.91
19	0.9	1.3	0.8	0.73	1.17	0.95	0.68	1.13	1.32		1.32	1.11	1.1	0.8
20	0.59	0.59	1.62	0.8	0.95	0.74	0.59	0.98	1.27	1.32		1.32	1.32	0.61
21	0.59	0.68	0.64	0.81	0.9	0.61	0.62	0.87	1.14	1.11	1.32		1.32	1.32
22	0.77	0.67	0.59	0.94	0.97	1.1	0.67	0.9	1.32	1.1	1.32	1.32		1.13
24	0.74	0.59	0.8	0.59	0.59	1.05	1.32	1.13	0.91	0.8	0.61	1.32	1.13	

4.2 Business Access Data

An important aspect of business access is the maximum tolerable detour by drivers. From the results of surveys and interviews [12], the maximum acceptable delay for the urban areas might increase the travel time (10-20) % which is a hard constraint in the optimization problem. Moreover, we reach the maximum of 8% increase in the travel time by using the Value of Time (VOT) for business and personal trips [68] as shown in Equation 4-1.

$$\text{Maximum delay for business trips (\%)} = \frac{(10+20)\%}{2} \times \frac{\text{VOT}_{\text{Personal}}}{\text{VOT}_{\text{Business}}} = 15\% \times \frac{\$12.00}{\$22.90} \approx 8\% \qquad \text{Equation 4-1}$$

We can obtain the values $e^{p}_{(o,d)}$ and $e^{b}_{(o,d)}$ as the percentages of the shortest paths from o to d, where $e^{p}_{(o,d)}$ and $e^{b}_{(o,d)}$ represent the maximum delay time for personal and business trips from o to d, respectively.

4.3 Emergency Access Data

In this study we focus on the ambulances as emergency service providers. Doing so, we have three hospitals in Sioux Falls network that are shown in Figure 8.

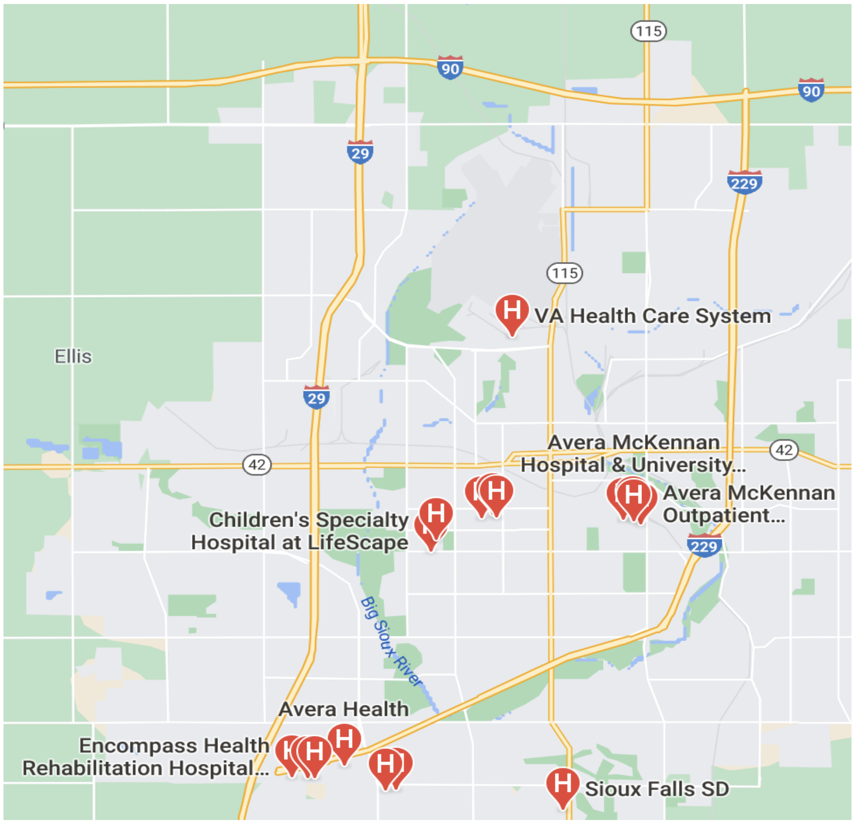


Figure 4-2 Sioux Falls hospital locations

According to the real-time data [69], the average time it takes for an ambulance to reach the demand node in emergency needs in 8 minutes. Therefore, we develop the set $H(i)$ for each node $i \in V$as the set of service providers nodes that are in a distance of at most 8 minutes from the demand node i. Moreover, due to the lack of access to emergency demand data, we assume that the stationary demand is distributed in the network in a manner that is proportional to the net demand at those points. As such, we set the demands v_i to be $0.05\sum_d(p_{(i,d)} + b_{(i,d)})$ as 5 percent of the total demand at node i.

4.4 Noise Pollution Data

4.4.1 Sioux Falls' hospital locations

According to the Google Maps, Figure 8, there are three main hospitals in Sioux Falls, i.e., Avera McKennan Hospital, Sanford USD medical center and hospital, and children's Specialty Hospital at LifeSpace.

4.4.2 Sioux Falls' residential area locations

The land use data for the Sioux Falls city is presented in Figure 4-3 [70].

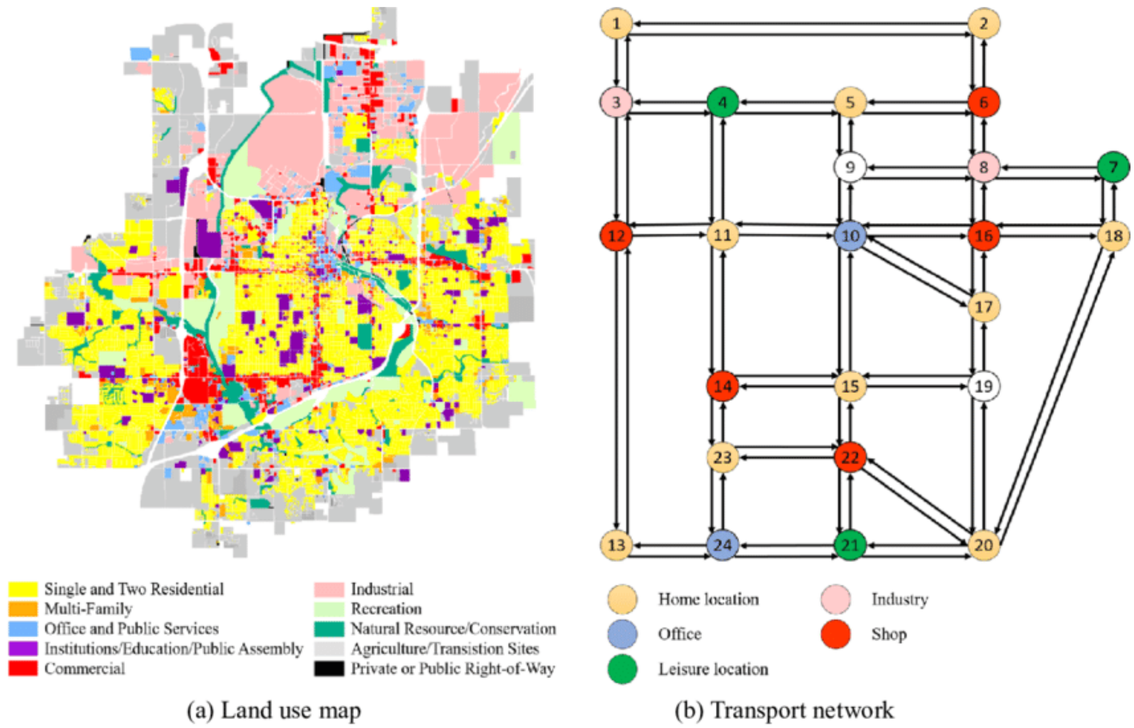


Figure 4-3 Sioux Falls city land use distribution

The residential areas in the network are represented by this figure by the following nodes: 1, 2, 5, 11, 13, 15, 17, 18, 20, and 23.

4.4.3 Speed limits

According to the South Dakota Department of Public Safety [71], the speed limit is 65 mph at all the secondary highways (unless otherwise stated), 25 mph at the city streets (unless otherwise stated, and 15 mph at school zones and obstructed intersections.

4.4.4 Truck Percentage

In general, trucks represent 4%-7% of the highway vehicles in the US. More specifically, large trucks make up 4.3% percent of all highway vehicles and 10% of the total highway miles traveled [72]. Due to the fact that the specific data for the Sioux Falls network was not available for the public, we assumed the average truck percentage for the US on different roads (e.g., highways, streets) for the Sioux Falls Network.

4.4.5 Standards for the maximum acceptable noise level

According to the World Health Organization guidelines, the maximum acceptable noise level near hospitals should not exceed 35 dB(A) with a maximum of 40 dB(A) over night [73]. Moreover, based on the US Environmental Protection Agency, the maximum of 55 dB(A) is considered for the residential areas [74].

4.4.6 Calculated noise levels

Google maps were used for finding the distance from hospitals and the selected residential areas to the center of nearby roads. Then, the maximum allowable traffic without violating the noise pollution guidelines was determined. Table 4-3 presents the results of this calculation. After comparing these binding number of vehicles with the actual demand on links, we realize that two links, i.e., link number 59 and 61, near the McKennan hospital bind the traffic and their capacity cannot be fully utilized. The values in this table are calculated using the Dutch method as state in Section 3.5 of this thesis.

Table 4-3 Maximum allowable traffic without violating the noise pollution guidelines

Link number	Maximum number of vehicles (noise criteria not violated)
Link 59	2400
Link 61	2400

4.5 GHG emissions consideration

In order to calculate the GHG emissions' damage cost, one first needs to find the vehicle type because produced emissions in each vehicle is unique and different from the other vehicles. In this study, we find and utilize the most popular vehicle in the US for each vehicle class to calculate the damage cost for them. Then, we assume all the vehicles in the Sioux Falls network are the same as the most popular type and calculate the GHG emissions' damage cost for the network.

As shown in Figure 10, Ford F-Series [75] are the most popular personal vehicle in the US as well as the South Dakota.

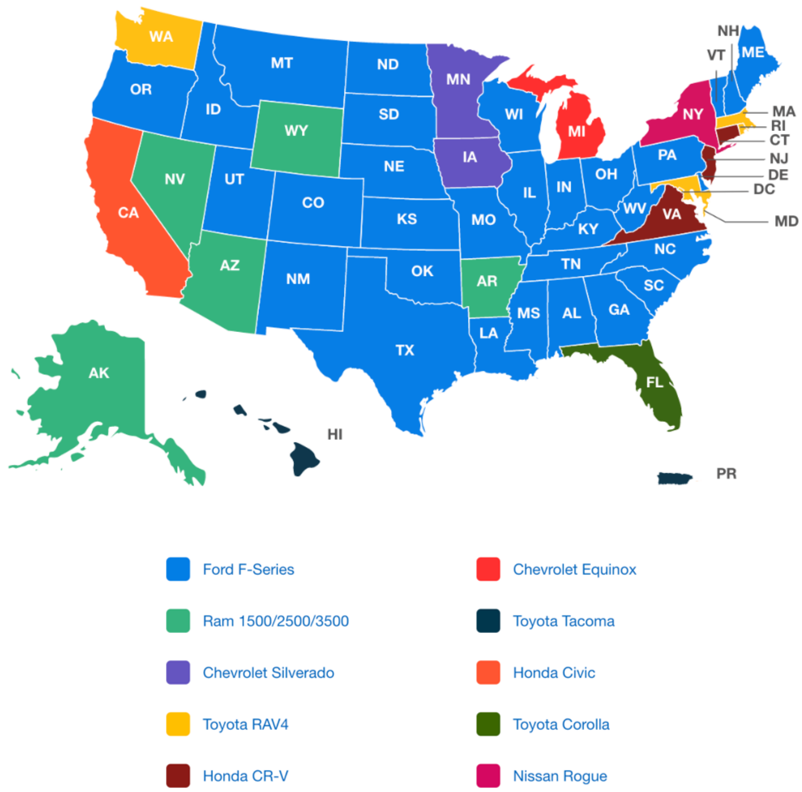


Figure 4-4 The most popular personal vehicle in the US in 2019

In the formulas presented in Section 3.6 of this thesis, data on the engine displacement (*V*), engine speed (*N*), engine power output (*P*), and the engine friction factor (*K*) are need for calculating the fuel consumption rate (*FR*). These values were determined for Ford Platinum F-150, the best-selling truck (and vehicle) in the US for more than 40 years [76]. Table 4-4 represents the engine coefficients for Ford Platinum F-150.

Table 4-4 Engine coefficients for Ford Platinum F-150

Parameter	Value
K_0	0.19
N_0	87.83
V	3.5
P	260
η	0.45
b_1	10^{-4}
C	0.00125

Substituting these parameter values in Equations 3-4 to 3-7 in the Section 3.6 yields the fuel consumption rate (Equation 4-2).

$$FR = \left(K \times N \times V + \frac{P}{\eta}\right)\left(\frac{1}{43.2}\right)(1 + b_1(N - N_0)^2) = (0.19\left(1 + 0.00125\,\frac{45.4S-87.83}{60}\right)\left(\frac{45.4}{60}\right)(3.5S) + \frac{260}{0.45})(\frac{1}{43.2})(1 + 10^{-4}(\frac{45.4\,S-87.83}{60})^2) \quad \text{Equation 4-2}$$

Where S is the speed limit (mi/hr).

Based on the information provided in Section 4.4 of this thesis, two different speed limits, i.e., 65 mph and 25 mph, are considered and utilized for the damage caused by GHG emissions. In order to calculate the GHG emissions' damage cost, the index coefficients in Equation 3-3, Table 4-5 presents the index coefficients and costs for the different greenhouse gas types.

Table 4-5 Coefficients and costs in GHG emissions [77] [78]

	a_{hq}			r_{hq}			cost
GHG type	H	M	L	H	M	L	Damage per ton in 2018 US $
CO_2	3.20	3.20	3.20	0.00	0.00	0.00	33.57
CO	7.56e-3	0.70e-3	8.10e-3	0.00	0.00	0.00	509.78
HC	7.03e-4	0.30e-3	0.90e-3	0.00	0.20e-2	0.30e-2	3.36e3
NO_x	1.95e-2	0.32e-2	0.26e-2	0.00	0.00	0.00	8.33e4

With the aforementioned data, the environmental damage that one vehicle makes on the considering each of these gas types will be calculated as follows:

$E_{CO_2} = 3.20 \times FR + 0.00$ Equation 4-3(a)

$E_{CO} = (8.10)10^{-3} \times FR + 0.00$ Equation 4-3(b)

$E_{HC} = (9)10^{-4} \times FR + 0.00$ Equation 4-3(c)

$E_{NO_x} = (2.60)10^{-3} \times FR + (1.65)10^{-2}$ Equation 4-3(d)

Where FR is calculated using Equation 4-2 for the highway and the city streets. Results are presented in Table 4-6.

Table 4-6 Amounts of the produced emissions (g/Veh. s)

Road class	E_{CO_2}	E_{CO}	E_{HC}	E_{NO_x}
Highway(S=65mph)	4.37×10^{1}	1.11×10^{-1}	1.23×10^{-2}	5.20×10^{-2}
City_Road(S=25mph)	4.55×10^{1}	1.15×10^{-1}	1.28×10^{-2}	5.35×10^{-2}

The results presented in Table 4-6 are calculated for one specific vehicle. To calculate the cost per vehicle per second, each of the values should be multiplied in the cost that is presented in Table 4-7.

Table 4-7 Cost of the produced emissions (g/Veh.s)

Road class	C_{CO_2}	C_{CO}	C_{HC}	C_{NO_x}
Highway(S=65mph)	1.47×10^{-3}	5.64×10^{-5}	4.13×10^{-5}	4.34×10^{-3}
City_Road(S=25mph)	1.53×10^{-3}	5.88×10^{-5}	4.30×10^{-5}	4.46×10^{-3}

4.6 Link Travel Cost Data

Link travel cost data consist of the travel delay cost and fuel consumption cost that are presented in the following sections.

4.6.1 Travel delay cost

Value of time for personal and business trips are shown in Table 4-8.

Table 4-8 Value of Time for personal and business trips [68]

Road user type	Value of Time (VOT)
Personal use	$12.00
Business use	$ 22.90

4.6.2 Fuel consumption cost

In order to calculate the fuel consumption cost for a vehicle, the MPG (miles per gallon) and the fuel unit price ($/gallon) need to be determined. According to Section 4.5 the best-selling vehicle in South Dakota is the Ford Platinum F-150. As such, the MPG for the fuel consumption calculation will be 25 mpg on highways, 20 mpg on city roads, and 22 mpg in a combined condition [79].

We have considered the average fuel cost per gallon in South Dakota (2019) and the value is 2.59 ($ / gallon) [80] this is because of the fact that the fuel cost has had an unusual trend in 2020 as a result of COVID-19 pandemic.

As such, by substituting these values in Equation 3-10, the fuel consumption cost for each vehicle will be calculated and is presented in Table 4-9.

Table 4-9 Fuel consumption cost

Road type	MPG (mi/gallon)	Average speed (mi/hr)	Fuel Consumption Cost ($/veh.hr)
Highway	25	65	6.73
City road	20	25	3.23

CHAPTER 5. RESULTS & DISCUSSION

In this section, we conduct a number of numerical experiments to quantify the impacts of a cooperative routing for CAVs in CWZ. The experiments are conducted on the data of the Sioux Fall network as stated in the previous chapter. We define four base scenarios to assess the performance of a cooperative routing for CAVs in both presence and absence of the full closure and the cooperation. These four scenarios are listed below:

- Scenario 1: None of the links in the network are under closure and vehicles are following a centralized controller that optimizes and assigns the routes to vehicles.
- Scenario 2: None of the links in the network are under closure and vehicles are following their greedy behavior to minimize their cost on their routes toward their destination.
- Scenario 3: The lane 65 is under full closure and vehicles are following a centralized controller that optimizes and assigns the routes to vehicles
- Scenario 4: The lane 65 is under full closure and vehicles are following their greedy behavior to minimize their cost on their routes toward their destination.

In the last two scenarios, the reason for considering link 65 for closure is that it has been subject to closure in the previous construction work zones. Also, it is possible to show the difference between the detour routes in the cooperative and non-cooperative cases easier. Moreover, this link is near the two links near the Mc Kennan hospital and the noise pollution violation in the non-cooperative scenario can also be demonstrated.

We use MATLAB software for solving the linear programming problems stated by Equations 11 (a)–(e) and 12 (a)–(d). The computational tests are conducted on a 3.4GHz Dell Optiplex 990 Pentium i7-2600 computer with 448 8GB RAM on the 64-bit version of the Windows 10 operating system. the solution time for both problems 11 and 12 is a fraction of a second in all scenarios.

5.1 Traffic flow results in different scenarios

In this section, the flow is calculated for all the links on the Sioux Falls road network in the four scenarios. Values shown on the links in Figures 5-1 to 5-4 represent the traffic flow on the links.

5.1.1 Scenario 1 flow results

Figure 5-1 displays the resulting link flows in an optimal system. We obtain these results by solving the optimization problem 3-11(a)-(e). This Figure demonstrates that the link flows on links 59 and 60 are equal to the upper-bound imposed by the noise constraint, $u_l^t = 2400$. Furthermore, this Figure suggests that under an optimal routing scheme there is a significant flow, 11120 (veh/hr), travelling through the critical link 65.

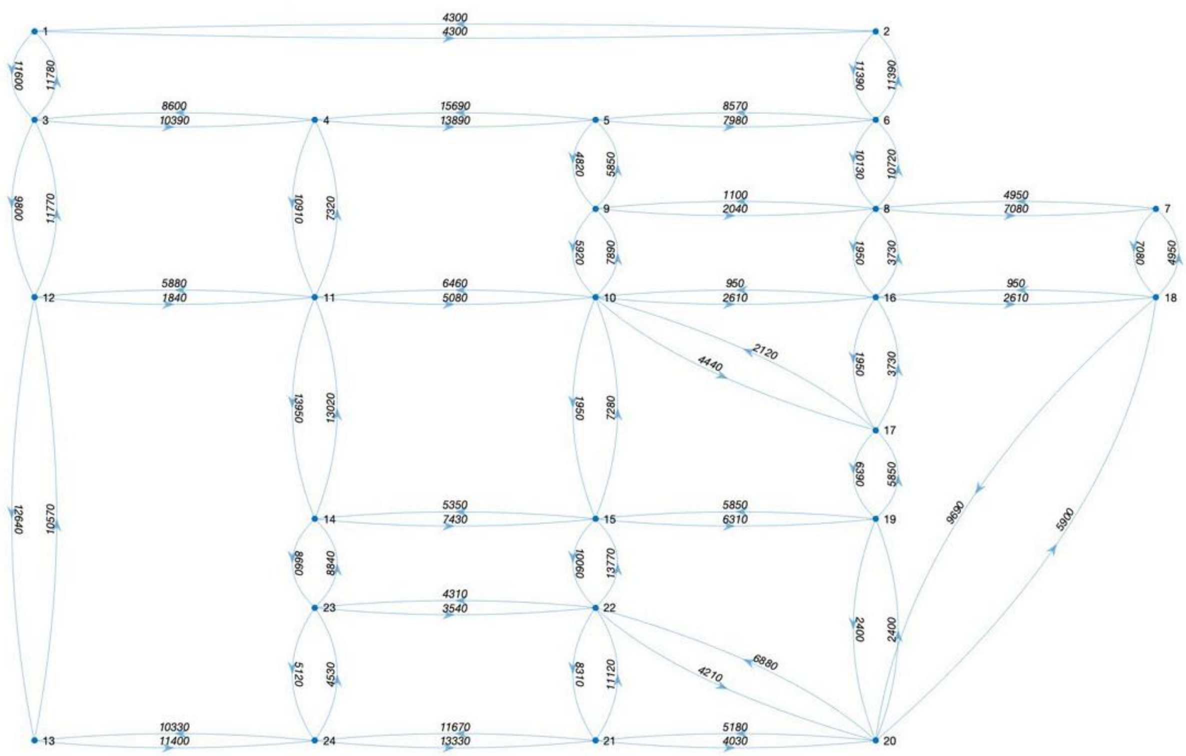


Figure 5-1 Actual flow in the links in the cooperative network before road closure

Moreover, the two links (59,61) connecting nodes 20 and 19 are controlled by the noise pollution constraint and the others are controlled by the link capacity and the accessibility constraints.

5.1.2 Scenario 2 flow results

Figure 5-2 demonstrates the resulting link flows under Nash Equilibrium. We obtain these results by solving the optimization problem 3-12(a)-(d). In this scenario, the users' greedy behavior in minimizing their own travel time has been considered. As a result of this assumption, the noise criteria has been violated in the links 59 and 61 (connecting node 20 and 19). Moreover, in this case, one link has remained unused, while in the first scenario the flow on the same link is 2120. Therefore, the total network facilities will not be operated in this case.

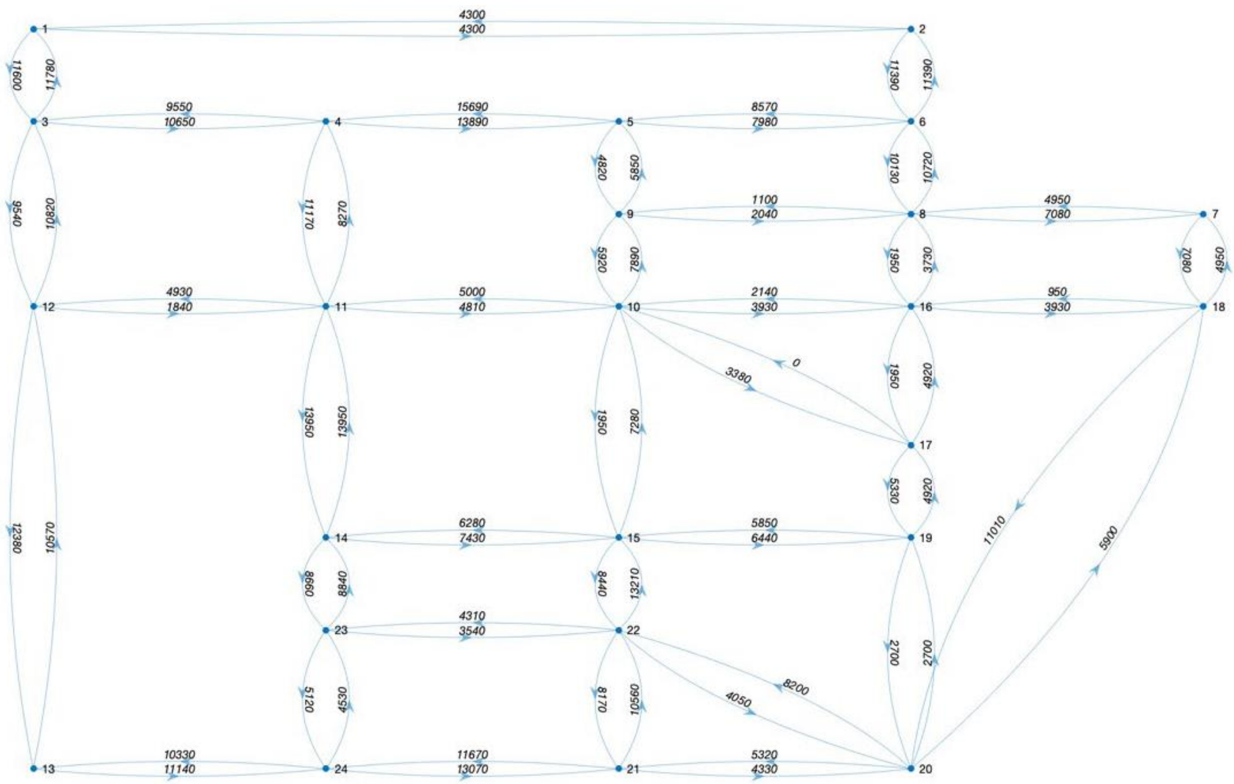


Figure 5-2 Actual flow in the links in the non-cooperative network before road closure

This Figure shows that the link flows on links 59 and 60 exceed the upper-bound imposed by the noise constraint, $u_l^t = 2400$. Another fact is that the links 43, 63, 68 that are near hospitals are more congested comparing to the first scenario, which is because of not considering the emergency service access. Moreover, unlike the system optimal case the same link 51 is unutilized. This results in an inefficient usage of the capacity of the network.

5.1.3 Scenario 3 flow results

Figure 5-3 demonstrates the resulting link flows in an optimal system with a full closure on link 65. We obtain these results by solving the optimization problem 3-11(a)-(e) in the Sioux Falls network with link 65 that connected nodes 21 and 22 is closed because of the CWZ. This Figure suggests under this scenario some of the less utilized links are more congested comparing to Figure 5-1. However, due to the consideration of business higher value of time, this excess flow has been distributed between the links with less connection with the downtown areas. Moreover, this Figure demonstrates that the link flows on links 59 and 60 are equal to the upper-bound imposed by the noise constraint, $u_l^t = 2400$. This means in both system optimal scenarios the noise constraint is binding.

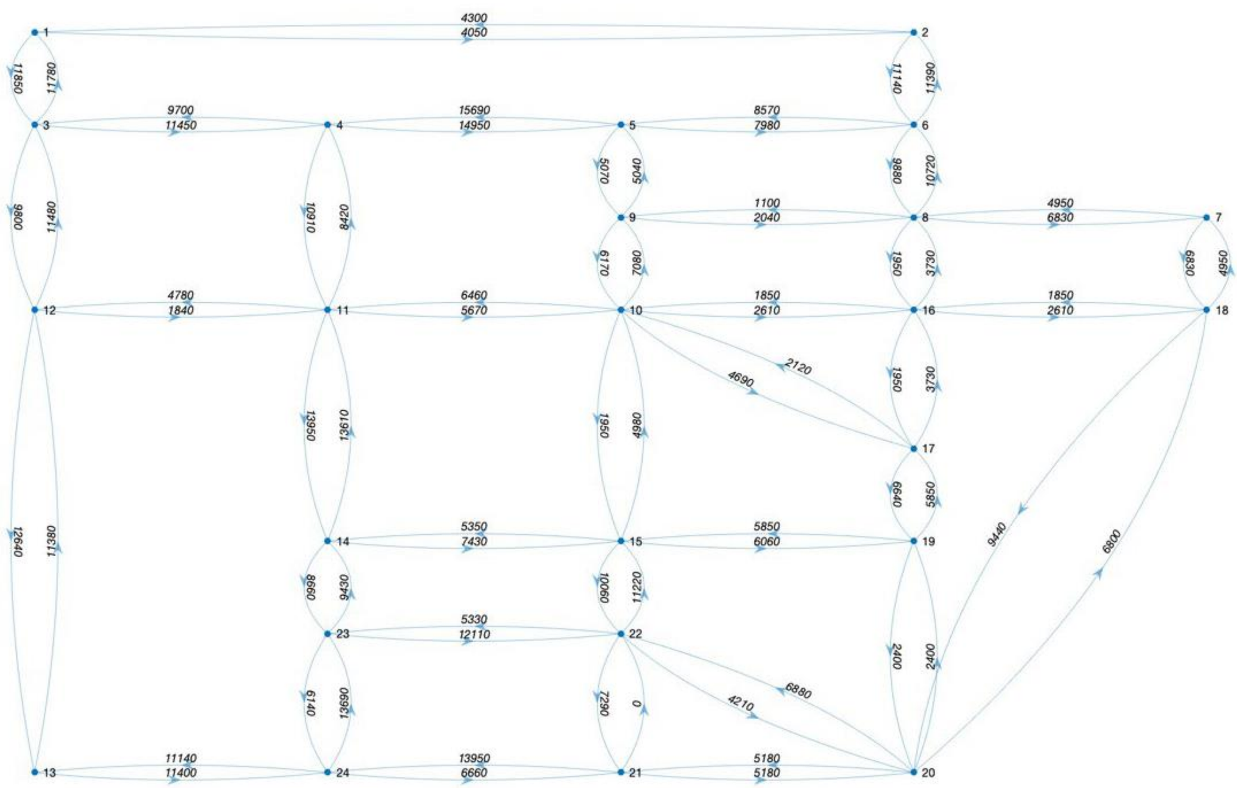


Figure 5-3 Actual flow in the links in the cooperative network after road closure

5.1.4 Scenario 4 flow results

Figure 5-4 demonstrates the resulting link flows under Nash Equilibrium with a full closure on link 65. We obtain these results by solving the optimization problem 3-12(a)-(d) in the Sioux Falls network with link 65 that connected nodes 21 and 22 is closed because of the CWZ. In this scenario, the users' greedy behavior in minimizing their own travel time has been considered. As a result of this assumption, the noise criteria has been violated in the links 59 and 61 (connecting node 20 and 19). Moreover, in this case, one link has remained unused, while in the first scenario, the flow on the same link is 2120. Therefore, the total network facilities will not be operated in this case.

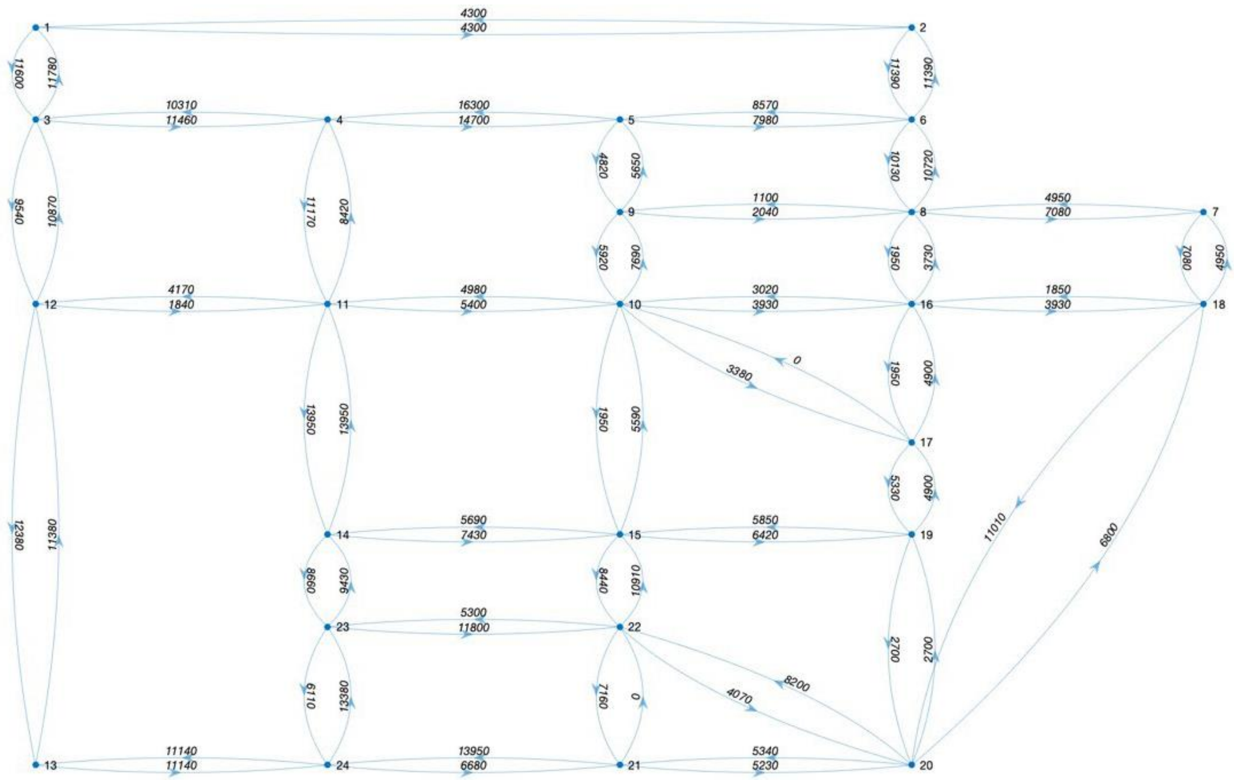


Figure 5-4 Actual flow in the links in the non-cooperative network after road closure

In this scenario, the same link (65) has been closed and the noise pollution standard on links 59 and 61 are violated. Moreover, link 51 is remained unutilized even after closure. Next, the suggested and the chosen routes for the cooperative and the non-cooperative scenarios both before and after the road closure (link 65), are presented. In these Figures, the utilized percentage of the link capacity, has been represented.

5.2 Routing results in different scenarios

In this section, the percentage of capacity utilized is calculated for all the links on the Sioux Falls road network in the four scenarios. Values shown on the links in Figures 5-1 to 5-4 represent the traffic flow on the links. Furthermore, a random origin destination pair (21,19) is chosen and the obtained/optimal routes for them has been demonstrated by green color.

5.2.1 Scenario 1 routing results

Figure 5-5 on each link shows the percentage of that links' capacity utilized by the flow in the network. This Figure also highlights an optimal routing for the vehicles with origin node *21* and destination node *19* by green color. This means in an optimal system the suggested route for the entire demand from origin *21* to destination *19* is routed through the critical link 65. Furthermore, the noise critical links, 59 and 61, are highlighted by brown color.

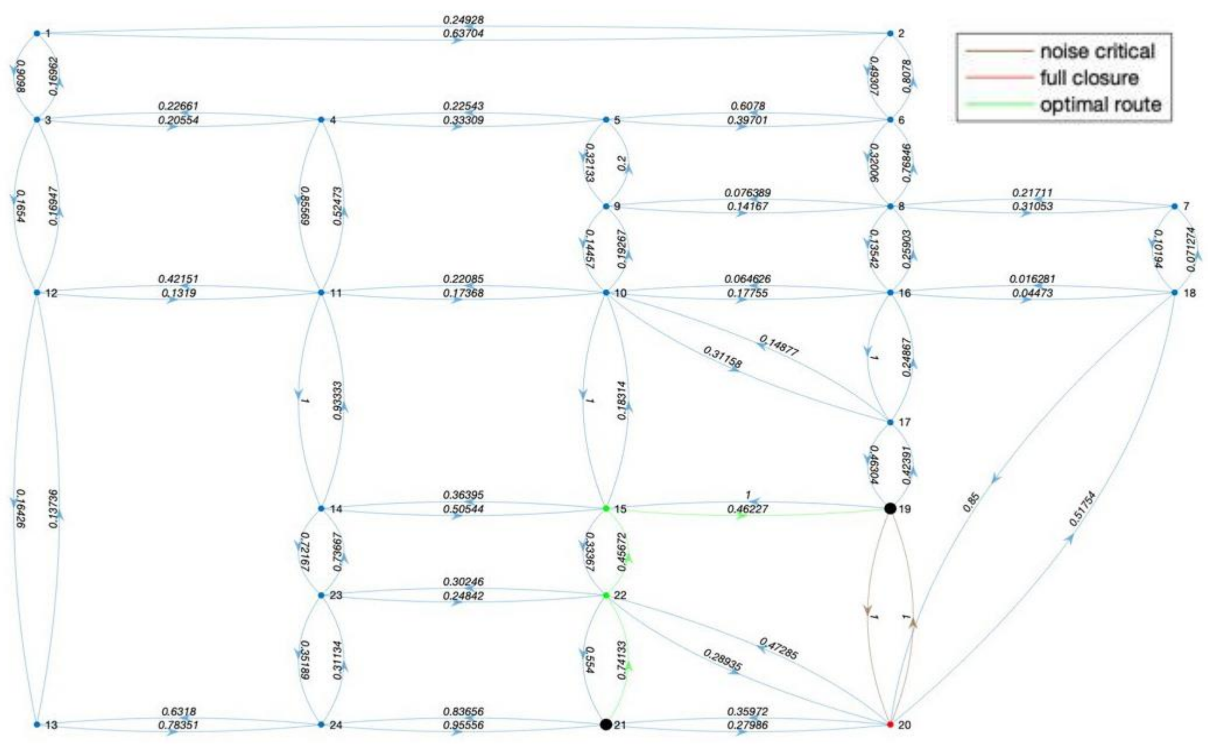


Figure 5-5 Suggested route in the cooperative network before closure

In this scenario, the suggested route between nodes 21 and 19 has been represented. As can be seen in this scenario, the noise binding links are not considered in the suggested detour.

5.2.2 Scenario 2 routing results

Figure 5-6 demonstrates the percentage of link capacity utilized under Nash Equilibrium. This Figure also shows the set of obtained routes for the vehicles with origin node *21* and destination node *19* by green color. Furthermore, the noise critical links, 59 and 61, are highlighted by brown color. As this Figure suggests, under Nash Equilibrium road users prefer to violate the maximum noise level to minimize their own travel times.

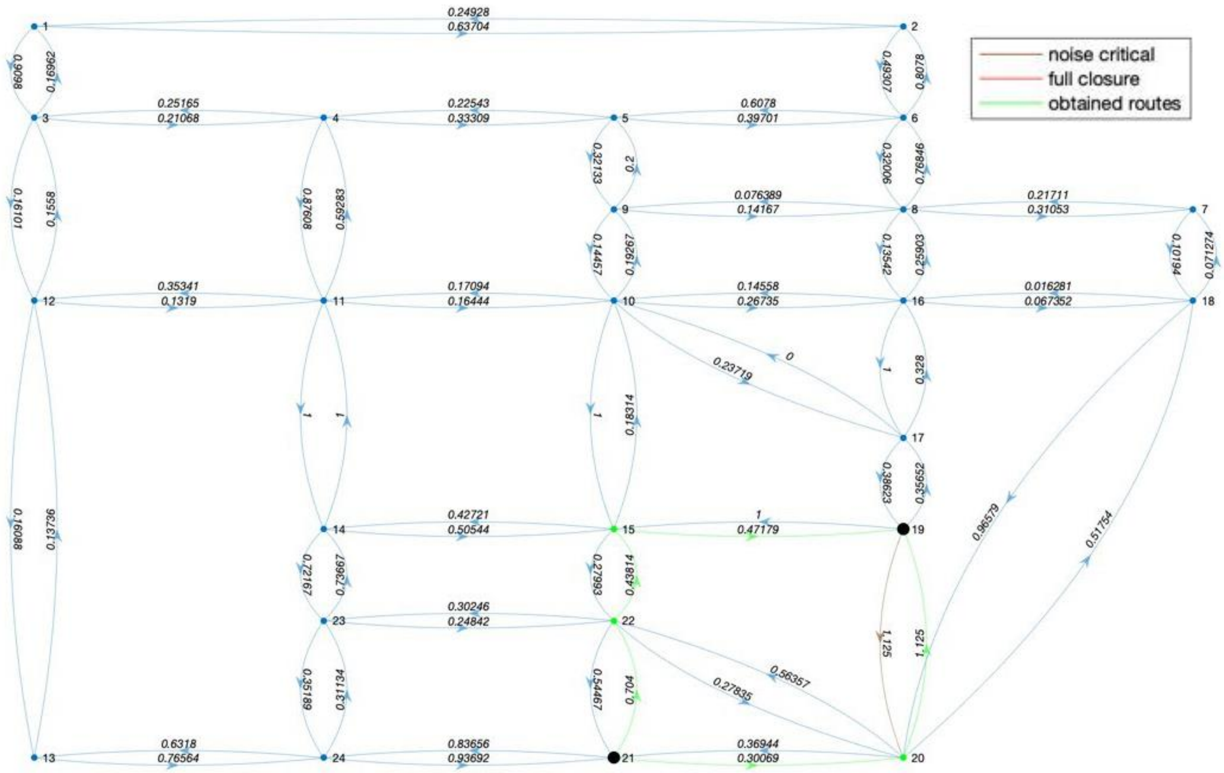


Figure 5-6 Chosen routes in the non-cooperative network before closure

In this scenario, two different routes are used by the selfish road users for going from node 21 to node 19. Moreover, the links that connect downtown to the more residential areas are more congested in the non-cooperative case.

5.2.3 Scenario 3 routing results

Figure 5-7 on each link demonstrates the percentage of that links' capacity utilized by the flow the Sioux Falls network with link 65 that connected nodes 21 and 22 is closed because of the CWZ. This Figure also highlights an optimal routing for the vehicles with origin node *21* and destination node *19* by green color. As we mentioned earlier in an optimal system without full closure on link 65 the suggested route for the entire demand from origin *21* to destination *19* is through the critical link 65. As such, the entire demand for the mentioned origin destination pair has to be rerouted in this scenario.

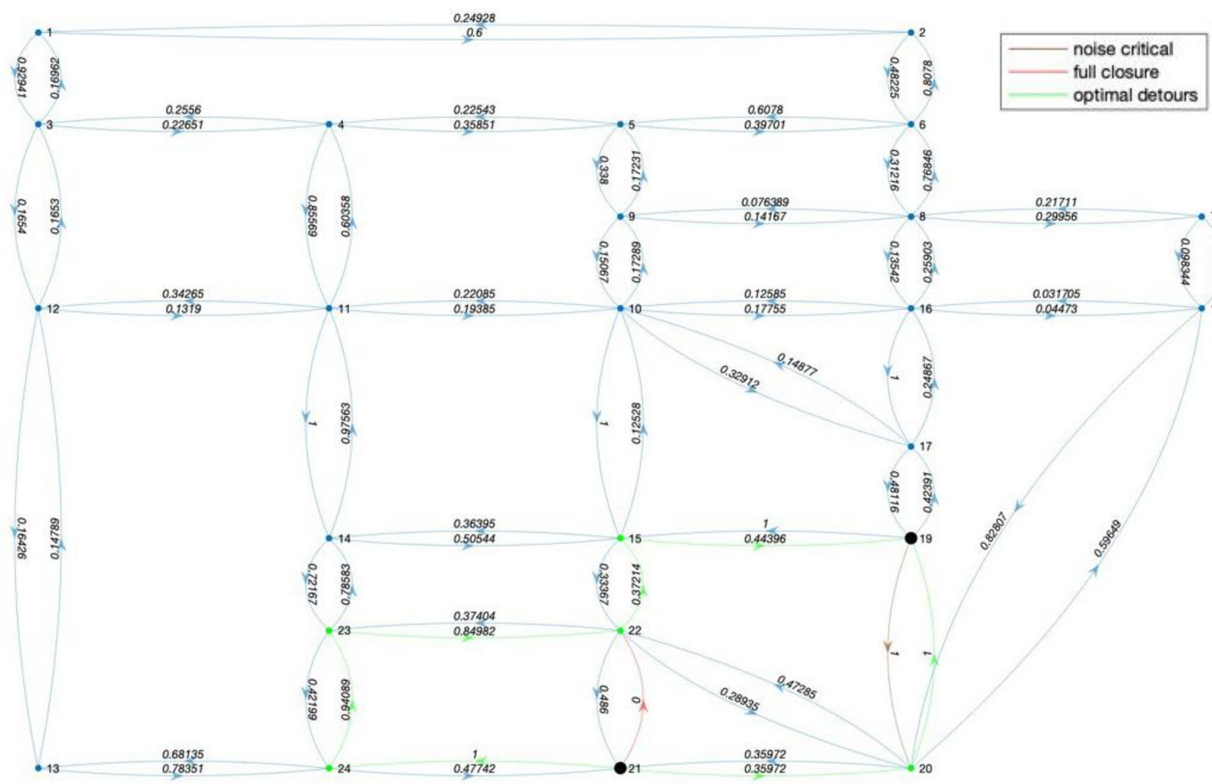


Figure 5-7 Suggested route in the cooperative netowrk after closure

In this scenario, after closing link 65, some of the users will be routed through the link with binding noise constraint. However, after meeting the noise constraint condition, other users are routed from the other route, which is between the following nodes: 21-24, 24-23, 23-22, 22-15, 15-19. In this scenario, the downtown area is still less congested comparing to the non-cooperative condition.

5.2.4 Scenario 4 routing results

Figure 5-8 shows the percentage of link capacity utilized under Nash Equilibrium with link 65 that connected nodes 21 and 22 is closed because of the CWZ. This Figure also shows the set of obtained routes for the vehicles with origin node *21* and destination node *19* by green color. Comparing to the results for Nash Equilibrium without full closure on link 65 the portion of demand that used to utilize the link 65 along their route towards node 19 changed their route to utilize the noise critical link 61.

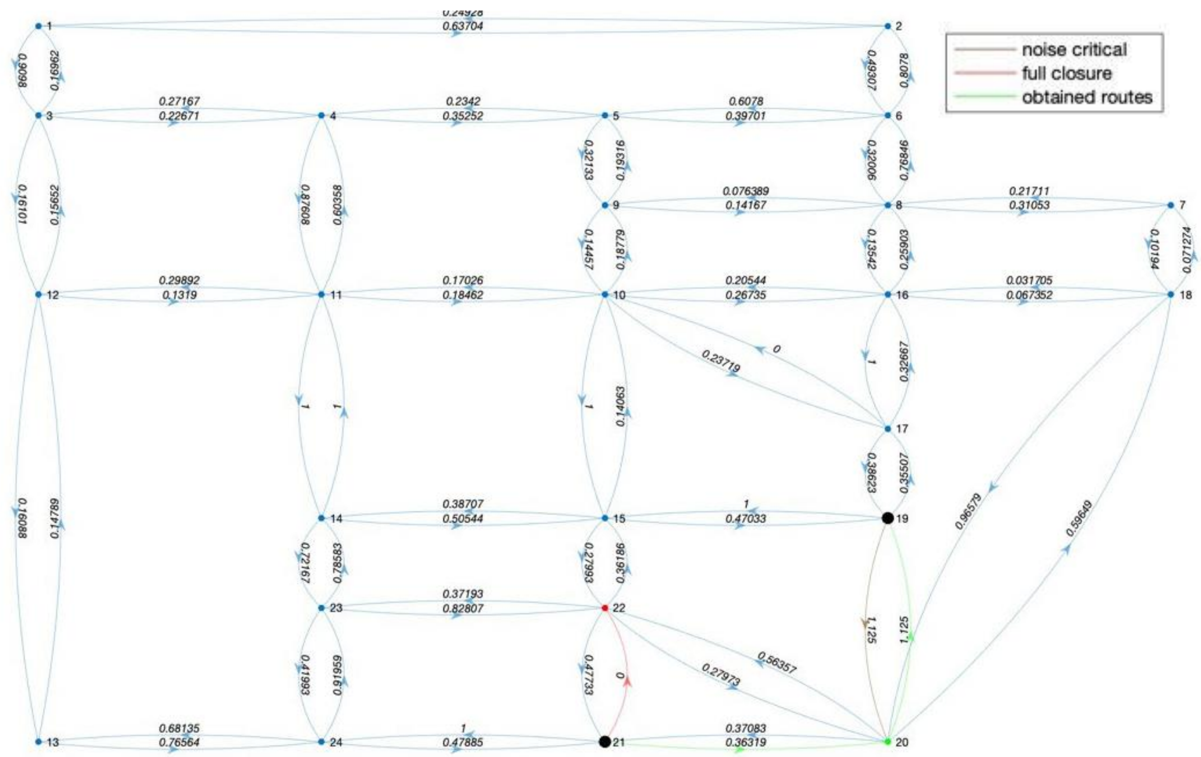


Figure 5-8 Chosen route in the non-cooperative network after closure

Furthermore, the noise critical links, 59 and 61, are highlighted by brown color. As this Figure suggests, under Nash Equilibrium and road closure road users maintain their preference to violate the maximum noise level to minimize their own travel times.

5.3 Objective function values with different weights for the cost components

The objective function in scenario 3 consists of the delay cost, fuel consumption cost, and the GHG emissions' damage cost. Table 12 shows the values for each of them in the optimal solution by considering the weight of the other two equal to zero. This procedure shows us the value of each of these components to assist us in finding the appropriate weights for them in the objective function.

Table 5-1 Values for the cost components in the objective function

	Pure delay cost	**Pure fuel consumption cost**	**Pure environmental damage cost**
cost ($/hr)	4.32×10^3	8.54×10^4	2.82×10^6

As shown in the table, the value for the environmental damage cost is significantly higher than the other two components. As such, this cost should be considered with a lower weight in our optimization problem. To be consistent with the real-world projects, where the green construction is less considered as shown in the Literature review chapter, the weight for the environmental damage cost is considered as 0.1% for the rest of the results. Next, we emphasize the sensitivity of cost to the relative weights of the delay and fuel consumption costs. Results are presented in Table 13.

Table 5-2 Cost sensitivity to the relative weight of delay and fuel consumption costs

	$\frac{w_1}{w_2} = \frac{1}{3}$	$\frac{w_1}{w_2} = 1$
Delay and fuel consumption cost ($/hr)	9.9233×10^4	9.9185×10^4
Delay cost ($/hr)	9.6360×10^3	9.5468×10^3

As shown in the Table 13, the total fuel consumption and delay cost is not sensitive to the relative weight of these two costs. This is because of two facts. First, as shown in Table 13, delay cost is significantly lower than the fuel consumption cost. As such, a small variation in the relative weight is not capable of changing the optimal solution for the cost. Secondly, the trend for the cost variation in both delay and fuel consumption costs is approximately the same. The main takeaway from this sensitivity analysis is that there might exist solutions that have almost the same value for the total cost. However, the cost components may defer significantly. This gives the opportunity to policy makers to consider different stakeholders without investing any significant further budget by changing the weights in the objective function.

5.4 Cost comparison

Another important aspect that should be taken into the account in a routing scheme are the cost components. Although in a system optimal we can ensure to consider the different stakeholders concerns represented by the hard constraints, we have to make sure the total cost as well as the separate cost components such as delay cost for business and personal trips, GHG and fuel costs are also improved.

5.4.1 Comparison between the total cost in the cooperative/non-cooperative networks

In this section we compare the total cost for the four base scenarios. Figure 5-9 shows the total objective values Considering the same weights for the delay and the fuel consumption.

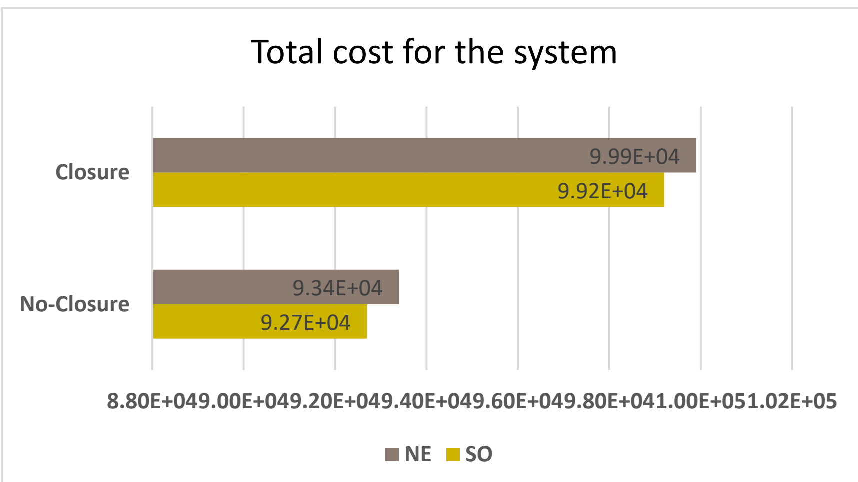


Figure 5-9 Total system cost in 4 scenarios

Results confirm that the total system cost is higher in the Nash Equilibrium case both in presence and absence of the full closure. This result is not surprising, as in the Nash Equilibrium case users try to minimize their own delay and fuel consumption cost and do not consider the routes that minimize the total system cost.

5.4.2 Comparison between the delay cost for business destinations in the cooperative/non-cooperative networks

In this section we compare the delay cost for the four base scenarios. The delay cost for business users is an important factor that assess the efficiency of a routing scheme.

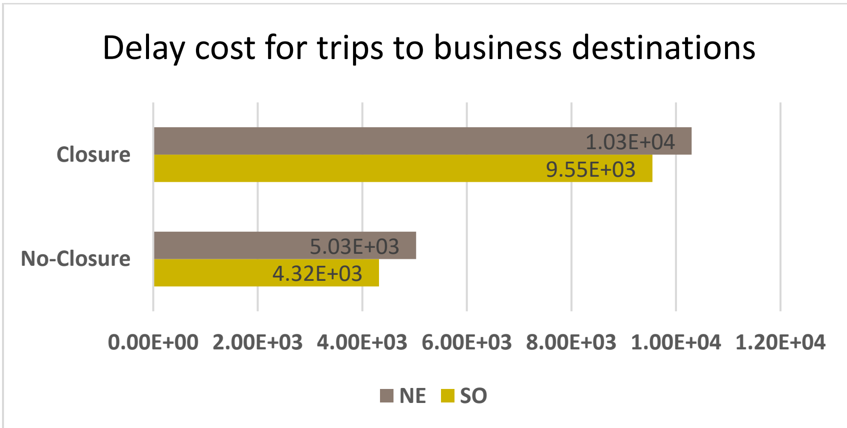


Figure 5-10 Delay cost for business destinations in 4 scenarios

Figure 20 demonstrates the delay cost for the road users with business destinations in all four scenarios. According to the results, the total delay cost both before and after the road closure is higher in the Nash Equilibrium case, where the greedy behavior of drivers exists. As such, by using a connective network, the delay cost for those who have business destinations will be reduced. This reduction is helpful in incentivizing the users to head into those businesses (e.g., shopping centers). Moreover, it decreases the delay cost for the business owners.

CHAPTER 6. CONCLUDING REMARKS

6.1 Summary

The core problem that this study addresses is the detour routing issues in full closure condition in a construction work zone. In this regard, safety and mobility are two important factors that become affected in the presence of work zones. In this study, we find a methodology to consider the issues in the detour routing in work zones and suggest appropriate detours, accordingly. In this procedure, we consider the advancements of advent technologies in Transportation Engineering [81] [82], i.e., cooperative network and automated vehicles.

Due to the full road closure, we consider concerns that affect the community. The main concern is to maintain the accessibility to businesses and the rapid access to emergency services such as ambulances, police stations, and fire stations. Next concern is to avoid the increased travel time due to the closure of some of the network links. Another issue we consider is the environmental impacts including Greenhouse Gas (GHG) emissions and noise pollution. We respect the accessibility for business owners and emergency services and noise pollution as hard constraints, where the minimum requirements must be satisfied.

We also define a monetarized cost as a weighted sum of the total fuel consumption cost, the total travel time cost, and the total GHG emissions damage cost and use different values of time to convert the travel time into a monetarized value. As a result, we can prioritize the business trips that have a higher value of time.

Additionally, we utilize the concept of Nash equilibrium to model the routing of a non-cooperative automated fleet of vehicles, where each individual aims to minimize their own trip cost. Then, with a solvable and scalable optimization problem, we obtain the routing for the vehicles that follow this greedy behavior. This enables us to investigate the potential benefits of a cooperative fleet of automated vehicles in the presence and then in the absence of connectivity.

6.2 Key Findings

In this study, we are able to demonstrate the beneficial impacts of the CAV technology on resolving some of the issues in CWZ full road closure planning. A comparison between the connected and non-cooperative networks proved that we are capable of reducing the delay cost for business trips in the cooperative network. However, this is not possible for non-cooperative systems because of the greedy behavior of the personal road users in decreasing their own travel time. Another key finding is that we are able to assign appropriate itinerary (detour routes) to road users in CWZ in all the scenarios. In our routing scheme, we also consider the sufficient access to businesses and rapid access to emergency services such as ambulances, police stations, and fire stations. Results demonstrate that this condition is performable only in the connected network of CAVs. The model and solution algorithm we present also calculates the environmental aspects, i.e., noise pollution and greenhouse gas emissions. Results prove that GHG emissions have an extremely high damage cost comparing to the delay and fuel costs. Mathematically, the model we proposed is scalable and able to solve large transportation networks. This is due to the fact that the model is simply designed and that it solved the optimization problem for the Sioux Falls network, a medium size network, in seconds.

6.3 Limitations

The most important limitation in this study is the lack of access to a large-scale network data to showcase the performance of our scalable solution algorithm. Moreover, as a result of the lack of sufficient resources and time, only one vehicle class and brand is considered in calculations.

Another overlooked aspect is the partial road closure case, which can be superior to the full road closure in specific cases [83]. The reason for not considering partial road closure in this study is that this aspect makes the model more complicated and difficult to solve. Moreover, data stochasticity for demand and vehicles' speed is not considered in this study because of the increased complexity in the model that makes it difficult to solve. One method to decrease the complexity in modeling the partial road closure in work zones and considering the demand stochasticity is to exploit Microsimulation (Vissim), which is considered for the future study.

In the consideration of business access, only businesses on the closed road are considered. However, although we acknowledge that businesses on the detour routes might benefit from the road closure, we are not able to model this aspect because of the lack of detailed data on the business types and trips with business destinations. Additionally, in the estimation of environmental pollution, linear models for the human driven vehicles are utilized for estimating the GHG emissions. However, we acknowledge that the Next Generation of Transportation, e.g., AV and CAV, will decrease the environmental emissions and this study's technique overestimates the GHG emissions.

6.4 Future Work

We aim to consider the stochasticity of the problem (e.g., demand variations during the day and year both for emergency services and other road users) and evaluate the performance of our model by exploiting microsimulation tools like Vissim. Additionally, we want to model and investigate the potential impacts of partial road closure in solving work zone issues using microsimulation tools.

Due to the fact that the presented model in this study is simple as a result of utilizing linear constraints and pre-processing, the scalability is one of the key features in it. However, it was not possible in this study to demonstrate the scalability by using a large network data as the resources are usually confidential for these network instances. Our goal is to reach out to the DOTs to ask for a large network data and run the analysis for such a network.

Moreover, we plan to search for additional data for different vehicle classes and brands to improve the GHG emissions estimation. In this regard, our goal is to substitute the current formula with a model more suitable for Av and CAV. Moreover, we aim to incorporate several other components into our model. Namely, calculating the detour route rehabilitation cost for truck usage, considering sufficient access to the airports, etc. Lastly, it will be useful for future researchers to consider the inclusion of new and emerging transportation technologies in the study framework. For example, the locations of existing or prospective future electric charging stations (Radvand et al, 2019a; Radvand et al., 2020) can influence the methodology and outcomes of the framework.

Also, it can be shown in future research how a mixed fleet of human-driven and autonomous vehicles can influence the study outcomes and optimal solutions.

BIBLIOGRAPHY

[1] A. G. C. o. America, "2019 Associated General Contractors of America (AGC) Highway Workzone Safety Study," 23 May 2019. [Online]. Available: https://www.agc.org/news/2019/05/23/2019-highway-work-zone-safety-survey.

[2] A. G. C. o. America, " 2018 Associated General Contractors of America (AGC) Highway Workzone Safety Study.," 23 May 2018. [Online]. Available: https://www.agc.org/news/2018/05/23/2018-highway-work-zone-safety-survey.

[3] A. G. C. o. America, " 2017 Associated General Contractors of America (AGC) Highway Workzone Safety Study.," 25 May 2017. [Online]. Available: https://www.agc.org/news/2017/05/25/2017-highway-work-zone-safety-survey.

[4] A. G. C. o. America, " 2016 Associated General Contractors of America (AGC) Highway Workzone Safety Study.," 24 May 2016. [Online]. Available: https://www.agc.org/news/2016/05/24/2016-work-zone-safety-survey.

[5] A. G. C. o. America, "2015 Work Zone Awareness Survey Results," Associated General Contractors of America, 2015.

[6] A. G. C. o. America, " 2014 Associated General Contractors of America (AGC) Highway Workzone Safety Study.," Associated General Contractors of America, 2014.

[7] A. G. C. o. America, " 2013 Associated General Contractors of America (AGC) Highway Workzone Safety Study.," Associated General Contractors of America, 2013.

[8] W. Z. B. TM, "Work Zone Crashes, Injuries, & Fatalities," Work Zone Barriers TM, 2020. [Online]. Available: https://www.workzonebarriers.com/work-zone-crash-facts.html#:~:text=In%20a%202019%20survey%2C%20a,improve%20safety%20on%20their%20projects.&text=The%20rising%20number%20of%20accidents,the%20need%20for%20positive%20protection..

[9] F. H. Administration, "Road Closure and Lane Closure," FHWA, 11 April 2019. [Online]. Available: https://ops.fhwa.dot.gov/wz/construction/full_rd_closures.htm#fc.

[10] K. C. M. B. G. B. D. M. K. S. F. J. D. &. L. S. Sinha, "An Evaluation of the Hyperfix Project for the Reconstruction of I-65/I-70 in Downtown Indianapolis," Final Report No. FHWA/IN/JTRP-2004/2, School of Civil Engineering, Purdue University, West Lafayette, IN, 2003.

[11] K. C. &. L. S. Sinha, Transportation decision making: Principles of project evaluation and programming, Hoboken, NJ: John Wiley & Sons, 2011.

[12] *Safety, Mobility, and Cost Benefits of Closing One Direction of Interstate in Rural Areas During Construction Work*, Indianapolis: INDOT, 2020.

[13] M. W. W. A. D. M. C. S. L. S. &. C. Z. Miralinaghi, "Network-level scheduling of road construction projects considering user and business impacts.," *Computer-Aided Civil and Infrastructure Engineering*, 2020.

[14] K. K. Fiawoyife, *An Empirical Study of Work-zone Safety and Mobility Using Surveys and Anonymous User Generated Trip Information*, Oregon State University, 2019.

[15] Y. &. C. S. Tang, "Optimization of work zone schedule considering time-varying traffic diversion," *Transportation Research Record: Journal of the Transportation Research Board,* pp. 21-30, 2005.

[16] A. M. W. J. S. H. S. M. R. S. M. F. G. D. &. B. D. M. Hainen, "Estimating route choice and travel time reliability with field observations of Bluetooth probe vehicles," *Transportation research record,* pp. 43-50, 2011.

[17] A. R. J. M. M. S. P. W. J. C. &. H. H. Memarian, "An optimization-based traffic diversion model during construction closures," *Computer-Aided Civil and Infrastructure Engineering,* vol. 34, no. 12, pp. 1087-1099, 2019.

[18] W. A. A. M. M. A. D. M. &. S. K. Woldemariam, "Network-Level Scheduling of Road Projects During the Construction Season Considering Network Connectivity.," FHWA/IN/JTRP, 2019.

[19] Y. Zou, *The Role That Connected and Automated Vehicles Can Play In Re-Organizing Traffic Flow: Work Zones and Emergency Services,* Doctoral dissertation, 2020.

[20] D. W. G. B. K. &. B. M. J. Tian, "Performance Measurement Evaluation Framework and Co-Benefit\/Tradeoff Analysis for Connected and Automated Vehicles (CAV) Applications: A Survey," *EEE Intelligent Transportation Systems Magazine,* vol. 10, no. 3, pp. 110-122, 2018.

[21] F. B. Sanusi, *Modeling Connected and Autonomous Vehicles Impacts on Mobility and Safety in Work Zones,* Tallahassee: Florida State University , 2018.

[22] P. &. K. K. M. Bansal, "Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies," *Transportation Research Part A: Policy and Practice,* vol. 95, pp. 49-63, 2017.

[23] T. U. A. B. N. &. L. S. Saeed, "Preparing Road Infrastructure to Accommodate Connected and Automated Vehicles: System-Level Perspective," *Journal of Infrastructure Systems,* vol. 27, no. 1, 2020.

[24] F. S. R. Z. A. &. T. A. Fakhrmoosavi, "Impacts of connected and autonomous vehicles on traffic flow with heterogeneous drivers spatially distributed over large-scale networks," *Transportation research record,* vol. 2674, no. 10, pp. 817-830, 2020.

[25] K. G. N. K. B. &. A. M. A. Heaslip, "Assessment of Capacity Changes Due to Automated Vehicles on Interstate Corridors," FHWA/VTRC , 2020.

[26] A. A. H. A. B. &. R. S. N. Olia, "Assessing the potential impacts of connected vehicles: mobility, environmental, and safety perspectives," *Journal of Intelligent Transportation Systems,* vol. 20, no. 3, pp. 229-243, 2016.

[27] M. C. B. M. M. &. T. C. Aloso Raposo, "The r-evolution of driving: from connected vehicles to coordinated automated road transport (C-ART): part I, framework for a safe & efficient coordinated automated road transport (C-ART) system: study," in *Transportation Research Board,* 2018.

[28] C. f. A. A. T. CAAT, "Connected and Automated Vehicles," Center for Advanced Automative Technology CAAT, [Online]. Available: http://autocaat.org/Technologies/Automated_and_Connected_Vehicles/.

[29] S. C. R. D. J. D. Y. L. S. L. Paul Young Joun Ha, " Vehicle connectivity and automation: a sibling relationship," Frontiers in Built Environment, 2020.

[30] T. U. A. B. N. &. L. S. Saeed, "Preparing Road Infrastructure to Accommodate Connected and Automated Vehicles: System-Level Perspective.," *Journal of Infrastructure Systems*, no. 27, p. 1, 2020.

[31] H. P. M. Y. P. Y. Q. K. &. Z. Q. A. Wei, "Synthesis of unconventional dynamic merge metering traffic control for work zones.," *The Open Transportation Journal,*, vol. 4, no. 1, 2010.

[32] T. F. H. A. (FHWA), "Full Road Closure for Work Zone Operations," The Federal Highway Administration (FHWA), 2003. [Online]. Available: https://ops.fhwa.dot.gov/wz/index.asp.

[33] K. K. Fiawoyife, *An Empirical Study of Work-zone Safety and Mobility Using Surveys and Anonymous User Generated Trip Information*, Oregan State University, 2019.

[34] M. S. A. Khan, *Planning of Detours for Major Construction Projects and Assessing Their Impacts on Traffic Operations,* Doctoral dissertation, The University of Alabama at Birmingham, 2020.

[35] F. H. Administration, "Full Road Closure for Work Zone Operations: A Case Study. Using weekend closures to expedite road rehabilitation and minimize the impacts on motorists and road builders: I-84 Banfield Freeway in Portland, Oregon.," in *Federal Highway Administration. Work Zone Program*, United States, Administration, Federal Highway, 2004.

[36] S. &. L. D. M. Zhu, "Disruptions to transportation networks: a review," New York, Network reliability in practice, Springer, 2012, pp. 5-20.

[37] T. S. Government, "TDOT’s SmartFIX40 Project Wins America’s Transportation Award," Tennessee State Government, 2010. [Online]. Available: https://www.tn.gov/news/2010/8/31/tdots-smartfix40-project-wins-americas-transportation-award.html.

[38] F. H. A. (FHWA), "Missouri DOT I-64 Rehabilitation Case Study," Federal Highway Administration (FHWA), 05 Feb 2017. [Online]. Available: https://ops.fhwa.dot.gov/wz/resources/final_rule/modotcasestudy.htm.

[39] F. H. A. (FHWA), "FULL ROAD CLOSURE FOR WORK ZONE OPERATIONS: A Case Study Reducing the Impact of Construction During the Rehabilitation of a Major Interstate Highway," Federal Highway Administration (FHWA), 2004. [Online]. Available: https://ops.fhwa.dot.gov/wz/docs/Delaware_v3/index.htm.

[40] F. H. A. (FHWA), "Rehabbing Maine's I-295 Southbound," Federal Highway Administration (FHWA), 2009. [Online]. Available: https://www.fhwa.dot.gov/publications/publicroads/09novdec/02.cfm.

[41] H. Y. Lee, "Optimizing schedule for improving the traffic impact of work zone on roads," *Automation in Construction*, vol. 18, no. 8, pp. 1034-1044, 2009.

[42] O. P. S. G. S. &. A.-R. A. Salem, "Reducing environmental, economic, and social impacts of work-zones by implementing Lean Construction techniques," in *Annual Conference of the International Group for Lean Construction*, 2014.

[43] N. E. P. S. C. B. H. &. C. Y. Bharadwaj, "Traffic flow modeling of diverse work zone activities," in *Transportation research record*, 2018.

[44] F. D. &. C. J. B. H. Shepard, "Benefits and safety impact of night work-zone activities," Virginia Transportation Research Council, 1984.

[45] J. S. K. A. A. &. S. C. J. Shane, A guidebook for nighttime construction: Impacts on safety, quality, and productivity, Transportation Research Board, 2012.

[46] F. B. Sanusi, "Modeling Connected and Autonomous Vehicles Impacts on Mobility and Safety in Work Zones," Florida State University, 2018.

[47] A. A. H. A. B. &. R. S. N. Olia, "Assessing the potential impacts of connected vehicles: mobility, environmental, and safety perspectives," *Journal of Intelligent Transportation Systems,* vol. 20, no. 3, pp. 229-243, 2016.

[48] W. J. L. S. J. O. M. D. &. B. R. A. Kumfer, "A human factors perspective on ethical concerns of vehicle automation," in *In Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Los Angeles, 2016, September.

[49] A. H. M. N. C. O. M. &. L. F. C. Jamson, "Behavioural changes in drivers experiencing highly-automated vehicle control in varying traffic conditions," *Transportation research part C: emerging technologies*, vol. 30, pp. 116-125, 2013.

[50] WAYMO, "We're building the World's Most Experienced DriverTM," Waymo, 2019-2020. [Online]. Available: https://waymo.com/.

[51] S. I. Lawyers, "The Rise of Autonomous Vehicles," SteinLaw Injury Lawyers, [Online]. Available: https://www.steinlaw.com/resources/studies/the-rise-of-autonomous-vehicles/.

[52] H. W. M. A. Y. Y. B. Z. Xiaotong Sun, "Investigating the Potential of Truck Platooning on Energy Savings: an Empirical Study on the US National Highway Freight Network," in *Transportation Research Board*, 2021.

[53] S. Labi, Introduction to civil engineering systems: A systems perspective to the development of civil engineering facilities, John Wiley & Sons, 2014.

[54] F. Learn, "The three pillars of sustainability," The University of Nottingham, UK, [Online]. Available: https://www.futurelearn.com/info/courses/sustainability-society-and-you/0/steps/4618.

[55] C. F. Daganzo, "Queue spillovers in transportation networks with a route choice," *Transportation Science,* vol. 32, no. 1, pp. 3-11, 1998.

[56] M. S. Y. Y. N. M. Mojtaba Abdolmaleki, "Itinerary planning for cooperative truck platooning," *SSRN 3481598,* 2019.

[57] N. &. J. R. Masoud, "A decomposition algorithm to solve the multi-hop peer-to-peer ride-matching problem," *Transportation Research Part B: Methodological,* vol. 99, pp. 1-29, 2017.

[58] N. M. Y. Y. Mojtaba Abdolmaleki, "Vehicle-to-vehicle wireless power transfer: Paving the way toward an electrified transportation system," *Transportation Research Part C: Emerging Technologies,* vol. 103, pp. 261-280, 2019.

[59] A. A. B. A. &. N. E. Boroiu, "Identifying ways to reduce urban noise pollution by road noise prediction," in *IOP Conference Series: Materials Science and Engineering*, 2018.

[60] "Calculation of ROAD traffic noise.," [Online]. Available: https://rigolett.home.xs4all.nl/ENGELS/vlgcalc.htm#explain.

[61] G. &. B. M. Scora, "Comprehensive modal emissions model (cmem), version 3.01. User guide.," Centre for environmental research and technology., University of California, Riverside, 2006.

[62] T. C. &. S. K. A. Lam, "The value of time and reliability: measurement from a value pricing experiment," *Transportation Research Part E: Logistics and Transportation Review,,* vol. 37, pp. 231-251, 2001.

[63] I. C. M. C. P. K. K. &. A. M. V. L. R. Athira, "Estimation of value of travel time for work trips," *Transportation Research Procedia,* vol. 17, pp. 116-123, 2016.

[64] C. &. L. D. Carrion, "Value of travel time reliability: A review of current evidence," *Transportation research part A: policy and practice,* vol. 46, no. 4, pp. 720-741, 2012.

[65] J. G. Wardrop, "Road paper. some theoretical aspects of road traffic research," *Proceedings of the institution of civil engineers,* vol. 1, no. 3, pp. 325-362, 1952.

[66] H. P. H. &. N. M. Zokaei Aashtiani, "Wardrop's First Principle: Extension for Capacitated Networks," Scientia Iranica, Tehran, 2020.

[67] T. N. f. R. C. Team, "Transportation Networks for Research," [Online]. Available: https://github.com/bstabler/TransportationNetworks. [Accessed 2020].

[68] V. T. P. Institute, "Transportation Cost and Benefit Analysis II – Travel Time Costs," Victoria Transport Policy Institute, 2020.

[69] REUTERS, "Be prepared for ambulance wait times," REUTERS, 19 July 2017. [Online]. Available: https://www.reuters.com/article/us-health-emergency-response-times/be-prepared-for-ambulance-wait-times-idUSKBN1A42KQ.

[70] D. L. F. G. Z. R. S. &. H. H. J. Wang, "Tolerance-based column generation for boundedly rational dynamic activity-travel assignment in large-scale networks," *Transportation Research Part E: Logistics and Transportation Review,* vol. 141, p. 102034, 2020.

[71] S. D. D. o. P. Safety, "Safety, South Dakota Department of Public," South Dakota Department of Public Safety, 2017. [Online]. Available: https://dps.sd.gov/safety-enforcement/highway-patrol/faqs#:~:text=What%20are%20the%20speed%20limits,65%20mph%2C%20unless%20otherwise%20posted..

[72] F. t. F. USA, "Get the numbers of that truck," George Washington University, 10 Jan 2013. [Online]. Available: https://facethefactsusa.org/facts/get-numbers-truck/#:~:text=Trucks%20represent%204.3%25%20of%20highway,10%25%20of%20total%20miles%20traveled.

[73] J. L. &. Y. J. D. Darbyshire, "An investigation of sound levels on intensive care units with reference to the WHO guidelines," *Critical Care,* vol. 17, no. 5, p. R187, 2013.

[74] M. S. S. T. K. &. N. R. L. Hammer, "Environmental noise pollution in the United States: developing an effective public health response," *Environmental health perspectives,* vol. 122, no. 2, pp. 115-119, 2014.

[75] edmunds, "Most popular cars in America," edmunds, 2019. [Online]. Available: https://www.edmunds.com/most-popular-cars/.

[76] B. Insider, "The glorious history of the Ford F-Series truck, America's best selling vehicle for 36 years," Business Insider, 2020. [Online]. Available: https://www.businessinsider.com/ford-f-series-f150-truck-sales-record-history-2017-1.

[77] X. &. Y. Y. Sun, "Behaviorally stable vehicle platooning for energy savings," *Transportation Research Part C: Emerging Technologies,* vol. 99, pp. 37-52, 2019.

[78] C. L. N. K. M. K. T. &. K. M. Tomagian, Passive and Low Energy Architecture, Elsevier, 1983.

[79] S. (. a. A. Agency), "2020 Ford F-150 XL MPG and Fuel Economy," SOKAL (an automotive Advertising Agency), 2020.

[80] A. company, "National Average Gas Prices," AAA company, 2020. [Online]. Available: https://gasprices.aaa.com/.

[81] T. M. M. L. S. A. M. (. Radvand, "Electric Charging Infrastructure Deployment: The Past, The Present, The Future," in *INFORMS Annual Meeting*, Seattle, Washington, 2019.

[82] T. C. Z. L. S. Radvand, "Deploying Power Bank Stations: The Bright Future of Electric Vehicle Adoption," in *INFORMS Annual Meeting*, Online, 2020.

[83] C. E. Guide, "INDOT Completes $175M Super 70 Reconstruction," Construction Equipment Guide, 12 February 2008. [Online]. Available: https://www.constructionequipmentguide.com/indot-completes-175m-super-70-reconstruction/10016.

[84] A. G. C. o. America, " 2018 Associated General Contractors of America (AGC) Highway Workzone Safety Study," 23 May 2018. [Online]. Available: https://www.agc.org/news/2018/05/23/2018-highway-work-zone-safety-survey.

[85] "Safety, mobility, and cost benefits of closing one direction of interstate rural areas during construction work," Indiana Depatemt of Transportation, Indianapolis, 2021.