AMERICAN UNIVERSITY OF BEIRUT

DEVELOPMENT AND EVALUATION OF DYNAMIC INTELLIGENT VEHICLE EVACUATION ALERT SYSTEM (IVEAS) IN CONGESTED URBAN SETTINGS: A CASE STUDY OF BEIRUT

by

JAD IMAD SARI EL DINE

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An Abstract of the Thesis of

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Major: Electrical and Computer Engineering

Title: Development and Evaluation of Dynamic Intelligent Vehicle Evacuation Alert System (IVEAS) in Congested Urban Settings: A Case Study of Beirut

Natural and man-made disasters shed light on the importance of advanced intelligent and emergency evacuation planning and protocols. In congested urban settings, evacuation under emerging scenarios becomes more challenging. This paper explores the uncertainties that surround the benefits associated with implementing infrastructure-less Vehicular ad-hoc networks (VANET) in a congested urban setting. The paper develops a high-level integrated VANET-based evacuation routing system with priority metrics for evacuation enhancement in highly congested areas. The system is tested under varying levels of VANET market penetration (MP), network disruption (ND), and traffic flow rates. The developed model can be used as a testing platform for emergency planning to help planners and decision-makers to identify the critical links in the traffic network. Results showed that the benefits of the proposed solution begin to materialize with regards to decreasing clearance times of vehicles within the network and thus allowing safe passage through crisis-affected areas at lower market penetration levels for increasing traffic volumes and communication ranges.

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Chapter 1

Introduction

1.1 Objective and Motivation

The evacuation process in highly populated and congested areas due to natural and man-made disasters is a challenge still being confronted. The efficiency of the evacuation plan is a crucial element towards the success of evacuation of large urban areas where the chance of survival depends on the individuals' access to the surrounding facilities [1]. In evacuations, the response time is dependent on the nature of hazards and an individual's perception of the imminent risk.

In emergency scenarios, the need for evacuating the affected places arises. The known evacuation routes are found to be congested which leads to an increase in panic due to the lack of guidance and information on how to reach safe areas [2] which is aggravated by the lack of real-time information required to perform efficient evacuation [3]. This is attributed to disrupted communication networks in the impacted areas, such as the case of the Great East Japan Earthquake [4] where the disruption in the mobile communication services resulted in the delay of critical information exchange.

In such events, time is a crucial factor in reducing the mortality rates in disasters where many lives can be saved if affected victims can be rescued within the first 72 hours after a disaster occurs [5]. Further, [6] states that evacuation of casualties in times of crisis where disruption of traffic networks negatively impacts the access to primary and tertiary health facilities, access to medications are among the factors that adversely affect emergency health services. Thus, it is obvious that the reliance on existing infrastructure amplifies the effect of the crises on the survivability of individuals [7]. While previous research on evacuation planning mainly focused on infrastructure-related issues such as traffic network capacity [8, 9], the increase in natural and man-made disasters sheds light on the importance of advanced emergency response systems as crucial components in future smart cities [10].

Technological advancements in vehicle communication holds promises to life-saving innovations [11]. Despite the ability of vehicles to communicate with each other through the vehicle to vehicle (V2V) communication in Ad hoc fashion creating a vehicular ad-hoc network (VANET) [12], less attention has been given to exploring their impact on the efficiency of the evacuation of traffic networks. This project aims to investigate the impact of vehicle communication technology on route choice behavior and evacuation time in case of natural or man-made hazards. Accordingly, there is a dire need to have an infrastructure-less system to provide disaster guidance information to reduce mortality and increase survival rates.

This thesis studies the uncertainties associated with the benefits of deploying V2V technologies in a transportation network, with unplanned network disruption, with competing goals of costs and benefits. The aforementioned challenges in mass evacuation are aggravated in high-density urban areas with potential, disaster-associated, traffic and communication networks disruption.

In this work, an agent-based modeling and simulation (ABMS) framework that simulates a short-lead emergency scenario represented in a sudden disruption in the transportation network with complete absence of the communication network is developed. The system addresses a transportation network with a varying levels of market penetration of connected vehicles, vehicles' communication range, and different percentages of disrupted road network links. Further, this research utilizes the vehicle dynamics, represented in the car-following model, dynamic traffic status, develops a modified Dijkstra routing algorithm, as well as

1.2 Problem Description

The main problem this work seeks to tackle is the creation of VANETs that could reliably aid vehicles within the network to evacuate the crisis affected area using the route ensures the shortest travel time using real time knowledge of the current state of the network. This work aims to facilitate the creation of VANETs in order to achieve maximum network coverage. With this increased network coverage, the hope would be to increase information permittivity throughout the network of roads in the crisis affected area completely removing the reliance on preexisting infrastructure. The vehicles receiving relevant information regarding the state of the network (congestion, blockages, average speed...) would then leverage this information to develop a better route to their respective destinations. Thus achieving the ultimate goal of this work which is to relax traffic in crisis affected areas in order to mitigate the damages caused by an unforeseen and unaccounted for obstruction of the traffic network.

1.3 Challenges and Contributions

Designing an efficient routing algorithm that leverages VANETs involves overcoming these challenges:

1. **Reduce Mean Travel Time of congested vehicles:** This includes disseminating information to as many vehicles as possible so that they may form an evacuation route that minimizes their mean travel time. Information may reach these vehicles once they become part of a cluster.

2. **Reroute oncoming traffic optimally:** Here the benefits of increased network coverage due to the VANETs created by the presence of Connected Vehicles in the network, would present key information for oncoming vehicles in order to create an optimal route avoiding any congested areas altogether.

3. **Maintain communication in congested areas under crisis:** To remove the point of failure presented by previous reliance on infrastructure, the connected vehicles would act as nodes in a communication network, creating a VANET, and thus providing key functionalities needed to propagate information where previously no communication could occur in these crisis stricken areas.

The main contributions of this work is to provide a strong evidence-based framework to create effective evacuation strategies thus achieving the following:

1. **Mitigate the effects of crises in urban areas:** Reducing the mean travel time of vehicles stuck in crisis affected areas means more emergency responders could reach the area and attend to the survivors, the vehicles would reach their destinations in a relatively acceptable time-frame, and would ultimately lead to less loss of life in case a truly damaging scenario occurred.

2. **Develop and evaluate a network-based simulator for crises in urban areas:** The developed simulation platform could be used as tool in the future to test the efficiency of a multitude of proposed traffic routing algorithms under different scenarios.

1.4 Thesis Organization

As this section introduced the background and motivation behind this research, the rest of the paper is organized as follows. The coming section presents the previous work related to vehicle emergency evacuation and the contribution of this research. Next, the methodological background and network modeling and simulation parameters is presented. Finally, the results acquired from the developed model, research conclusion, and potential future work are presented.

Chapter 2

Literature Review

The increase in natural and man-made disasters sheds light on the importance of advanced emergency response systems as crucial components of future smart cities [13]. Previous research on evacuation planning mainly focused on infrastructure-related issues such as traffic network capacity [8, 12]. Despite vehicles having the ability to communicate with each other through the V2V communication in an ad-hoc fashion creating a vehicle ad-hoc network [1], less attention has been given to exploring their use and impact on the efficiency of the evacuation of traffic networks.

A wireless ad hoc network is a decentralized, infrastructure-less wireless network that does not rely on a pre-existing infrastructure in its operation. In this system, each node can operate as a router that forwards data received from other nodes. These networks are self-organizing networks that, known as "spontaneous networks" [14], are formed on the go and are described as dynamic self-configuring and organizing infrastructure-less networks [15]. VANETs allow vehicles to form self-organized infrastructure-less networks, but unlike MANETs, VANETs are characterized by **i)**high dynamic topology [16]; **ii)** frequent communication path disruptions making it more challenging to maintain stable communication path [17]; **iii)** restricted movement by a predefined road network; and **iv)** no battery energy limitations. This, and their built-in wireless communication capabilities allow them to form a promising approach to use for information dissemination in emergencies [18, 19]. Evacuation route guidance using ad-hoc networks has been studied for different scenarios. For building an evacuation system, ad-hoc networks showed the potential to improve evacuation experience through improving route guidance in both static [19] and dynamic situations [18].

2.1 V2V in Emergency Evacuation

Vehicular ad-hoc networks are used to collect and disseminate data for ITS application [20]. Researchers in [21, 22] proposed a VANET-based smart vehicular crowd management system utilizing optimum stochastic routing. In the developed systems, the vehicles assume communication with the traffic management center in real-time. Besides, [23] proposed V2RSU and V2RSU+V2V schemes for emergency evacuation. Moreover, a VANET-assisted planned highway evacuation was studied while considering a limited vehicle to infrastructure communication [24]. Further, [25] proposed a disaster management system based on VANETs and mobile cloud computing. The utilization of communication technology, in the presented studies, showed significant enhancement in the evacuation time in comparison to no communication scenarios.

However, some studies focused on VANET-based emergency warning system for emergency vehicles [26, 27]. In [26], a VANET-based emergency warning system where vehicles receive a warning of an approaching emergency vehicle was developed. Besides, [27] developed and tested a similar system where detailed route information was also provided with limited communication to traffic signals. On the other hand, congestion avoidance emergency message dissemination schemes in the VANET scenario were studied using vehicular fog computing [28].

In crisis management, route selection is a key element to avoid aggregating the negative effects of the possibly hazardous situation. The work in [29], proposed a model to optimize a generic procedure for pedestrian route selection in crowded areas. The model is a black box implementation of Bayesian Optimization. Results showed the efficiency of the proposed model in enhancing the evacuation and safety rates of the evacuees. Moreover, [30] proposed VANET crowd-sourcing models for disaster management with partial V2I connectivity. These algorithms showed a proper reaction allowing an efficient evacuation in short-lead events. On the other hand, [31] utilized dynamic programming for critical signalized intersection during urban evacuation. Research results highlighted the importance of signal timing plans for emergency evacuation.

2.2 Empirical Data in Emergency Evacuation

Several studies aimed to utilize real-time data for evacuation and risk management purposes. Real-time operational traffic demand and supply needs data was utilized to address evacuation response problem through dynamic vehicle routing [32]. Moreover, [33] developed a web-based, spatially-enabled decision support system that provides evacuation instruction that relies on the temporal-spatial road network information. Besides, [34] developed a machine learning model to estimate the information relevance to vehicles to mitigate false alarms, increase efficiency, and increase the accuracy of the message recipients. Other study focused on irrelevant information can negatively impact the driver's compliance with the relevant information provided [34]. Thus, [35] developed a K-Medoids clustering model for data filtration relying on real-time and historical data.

Traffic congestion has an adverse impact on safety, especially during emergencies. To maintain a smooth traffic flow, [36] proposed a cloud-based real-time

Big Data analysis and prediction system that predicts traffic congestion and accidents using Naive Bayes (NB) and Distributed Random Forest (DRF) approaches. The system aims to ease the traffic around the accidents area to help the arrival of emergency respondents. Further [37] leveraged real-time dynamic traffic assignment to minimize evacuation time during crises using Pontryagin minimum principle. However, the system assumes the availability of traffic information during the evacuation process and no real-time operational data are considered. On the other hand, a new transportation evacuation strategy called Speed Strategy (SS) is presented [38]. The SS evacuation system manipulates speed limits on road segments during crises for some critical links to facilitate the escape from the affected zones.

In summary, the performed literature survey has revealed an absence of a fully infrastructure-less approach to VANET based crisis management. Besides, disaster evacuation guidance is unable to collect and utilize the real-time information required to perform efficient evacuation [3]. Thus, previous work relied on full infrastructure communication [25, 23, 21, 22], partial infrastructure communication [24], mobile cloud computing [25]. Other research focused on traffic congestion ease to enhance evacuation time [37, 36, 38]. Due to the severe nature of emergencies, as well as having that emergency's severity only heightened by the density of population in urban areas, damage to pre-existing infrastructure or overloading their capacities becomes even more probable. Thus, to maintain the safety of citizens and mitigate the effects of the crises in urban areas, the motivation of further investigating the capabilities of V2V communications that do not rely on pre-built infrastructure in VANETs becomes well validated. Figure 2.1 presents the a summary of the most relevant literature in emergency evacuation.

Unlike previous research [24, 25, 23, 21, 22], this study integrates the utilization of intelligent transportation systems (ITS) technologies in an infrastructure-less manner to solve a contemporary issue of an increasing need, emergency evacuation in a short-lead emergency evacuation. The developed framework, like previous studies [21, 22], focuses on traffic network relaxation, but also aims that every vehicle reaches its designated destination.

This research developed and tested a high-level integrated VANET-based evacuation routing system with a right-of-way (ROW) priority metric for evacuation enhancement in a congested urban network. This research **i)** bridges the gap in the infrastructure-less emergency evacuation by integrating the microscopic car-following behavior, represented in the utilized Intelligent Driver Model (IDM) in urban network evacuation in unplanned network disruption; **ii)** developed an advanced agent-based modeling and simulation (ABMS) platform that is able to mimic individual vehicles behavior and decision-making process based on the assessed surrounding environment with competing goals of costs and benefits; **iii)** considers an exponentially decaying function and ROW priority metric that takes into consideration the link's traffic congestion status and the vehicle's location with respect to the blocked section. Therefore, the developed platform can

Approach	Studies	Focus & Application
Simulation	Chen & Zhan [39]	Dynamic traffic Assignment in emergencies
	Alazawi et al.[25]	VANET-based emergency vehicle warning system
	Szczurek et al.[34]	Passive ITS warning message dissemination
	Bhosale et al.[26]	VANET-based emergency vehicle warning system
	Pu[40]	V2V+V2R emergency evacuation scheme
	Kostovasili et al.[41]	Drivers' behavior impact on evacuation efficiency
	Mostafizi et al.[42]	Unplanned network disruption in emergency
	Yuan et al.[43]	Driving-decision process modeling in evacuation
	Pu[23]	V2V+V2R emergency evacuation scheme
	Ramkumar et al.[44]	Real-time path planning
Empirical	Buchenscheit et al.[27]	VANET-based emergency vehicle warning and routing
	Khaliq et al.[45]	VANET-based emergency response system
Analytical	Peeta & Hsu[32]	Integration of traffic data in mass evacuation
	Najada & Mahgoub[36]	Traffic congestion and accident prediction
	Zoppi et al.[35]	Data collection and emergency message dissemination
	Tu et al.[46]	Driving behavior and evacuation studies
	Elbery et al.[20]	VANET and transportation system modeling
	Elbery et al.[47]	Vehicular crowd management system
	Elbery et al.[21]	Vehicular crowd management system
	Lebre et al.[30]	VANETs for disaster management
	Parr & Kaisar[31]	Signal optimization in urban evacuation

Figure 2.1: A Summary of Existing Related Studies

serve as a planning tool for emergency planners and decision-makers to analyze and evaluate the impact of VANETs on future emergency evacuation plans and cope with unplanned transportation network disruption during short-lead natural or man-made hazards.

Chapter 3

Methodology

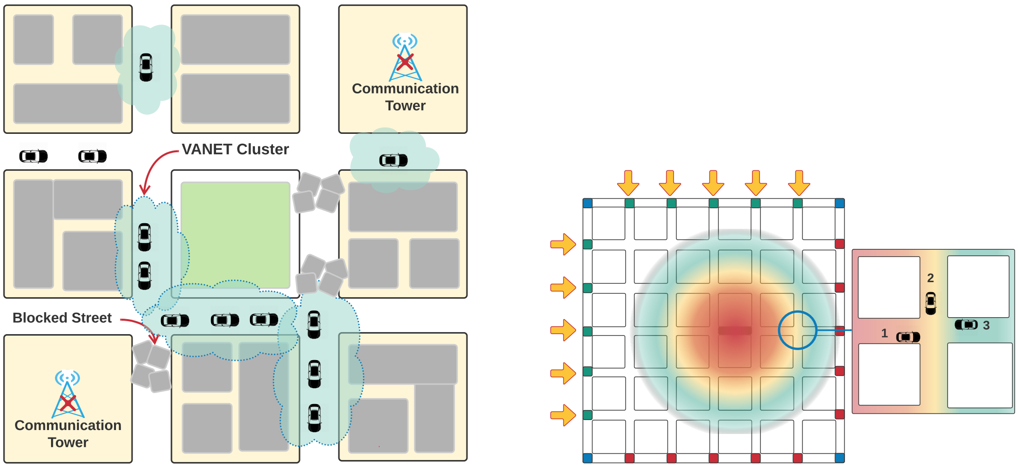
This section focuses on the development of the simulation platform including defining the network setting, infrastructure-less vehicle communication, and routing algorithms to capture the system dynamics in an ABMS platform.

The developed simulation platform consists of two main intertwined networks, a transportation network that consists of links and nodes, and a dynamic topology communication network resembled by the ad-hoc network formed by the VANETs.

3.1 Traffic Network Setting

This research considers a Manhattan grid network with a fixed distance between the links. The grid network can be considered as a subnetwork of a larger urban transportation network which will be similar in structure to a mesh or lattice grid. Therefore, this choice ensures that traffic would exhibit characteristics shared by real-life scenarios with a high degree of accuracy. In addition, the system considers dynamic speed limits of the traffic network to mimic a real urban network setting. Besides, the study evaluates the impact of infrastructure-less vehicle communication technology in disrupted transportation networks at varying connected vehicle market penetration levels, and varying levels of road network disruption. Figure 3.1(a) presents a schematic diagram for the proposed network. The figure shows the cluster formation for VANETs under disrupted communication and transportation networks.

The traffic network is represented as a direct graph composed of set of links $L = \{1, 2, ..., L\}$ and nodes $n = \{o' : d' = 1, 2, ..., N\}$ where link l is a segment between node o' and $'d \; \epsilon N$. Each link is characterized with link capacity (q_l), number of vehicles on the link (ρ_l), and average travel speed on the link (t_l^v). In this work, NetworkX is used to create the transportation network. NetworkX is a python package that facilitates the creation and modeling of complex networks with all their associated behaviors and functionalities. The nodes of the network represent the intersection, entry and exit points while the edges between the links are the roads that the vehicles traverse throughout their trip.



(a) (b)

Figure 3.1: A schematic diagram for the proposed network where it shows a disruption in the communication network and transportation network represented in the blocked streets. where in **(a)** the vehicles with turquoise clouds represents vehicles equipped with communication equipment (VANET). While **(b)** shows the proposed grid network and intersection priority metric. The network on the left shows the origin and destination and direction of Traffic.

To test the efficacy of the developed evacuation algorithm, the network is tested under congested traffic conditions with spatio-temporal Poisson distributed vehicle arrival rates (λ) of $\lambda_1 = 14400veh/hr$, $\lambda_2 = 7200veh/hr$, and $\lambda_3 = 3600veh/hr$. This allows the simulation of the arrival of vehicles onto the road and spacing out their inter-arrival times through the following equation:

$$\tau = \mu \times (-Ln(X(0,1))) \tag{3.1}$$

where τ is the mean inter-arrival time; μ is the traffic flow rate, and $X(0,1)$ is a random variable between 0 and 1. In the developed network, the origins and destination mimic the entrance and egress locations of the vehicles in the simulated network. Further, the vehicles enter the network from the north or west side and exit from the east and south based on their predefined origin and destination as shown in Figure 3.1(b). As this study considers routing optimization in a complex connected vehicle environment associated with transportation network disruptions, makes the developed platform computationally intensive. Besides, all the vehicles in the network are relying on a realistic car-following model and takes into consideration the vehicle dynamics and its behavior in the intersections is dramatically reflected in the developed platform complexity. Accordingly, to reduce the required computational intensiveness in the developed platform, a $2 \times 2km$ network with $250m$ block size was studied.

3.2 Communication Network Settings

The communication between the vehicles allows vehicles within the communication range to exchange information including the vehicle's physical location, speed, and acceleration behavior of the preceding vehicle [48]. The vehicles assume Dedicated Short Range Communication (DSRC) to establish V2V communication using the IEEE 802.11p protocols that are developed specifically for VANETs for communications. The DSRC provides a communication range of around $900m$ $(3000ft)$ with extension ability through multiple transmitters [49]. This research takes into consideration three different effective communication ranges of $300m(1000ft)$, $200m(650ft)$, and $100m(330ft)$ to account for a potential reduction in the communication range in urban areas. Therefore, VANETs within the communication range will be able to form clusters and exchange location, speed, link congestion status, and link accessibility with each other.

3.3 Vehicles Car Following Behavior in Traffic Network

This section describes the underlying modeling assumptions and parameters used for vehicle dynamics behavior in the traffic network.

To simulate the vehicle behavior in the traffic network, the developed model utilizes the Intelligent Driver Model (IDM) [50] to simulate the car following behavior. The IDM car-following model has been widely used to simulate the car-following behavior in different traffic network settings [51, 52, 53, 48]. The IDM assumes the behavior to be a continuous function of the speed v_i, spatial gap s_i, and speed differential Δv_i with the preceding vehicle [50]. The generic form of the IDM model is presented in Eq.3.2.

$$\dot{v}_i(t) = a_{max,i}\left[1 - \left(\frac{v_i(t)}{V}\right)^{\delta} - \left(\frac{S(v_i(t), \Delta v_i(t))}{S_i}\right)^{2}\right] \tag{3.2}$$

where $a_{max,i}$ is the maximum comfortable acceleration; $v_i(t)$ is the speed of the vehicle i, V is the desired velocity; δ is the acceleration exponent; S_i is the actual gap between the leading vehicle $i-1$ and the following vehicle i (i.e., $S_i = x_{i-1} - x_i$) and $\Delta v_i(t) = v_i(t) - v_{i-1}(t)$ is the removal rate of the vehicle i to its preceding vehicle $i-1$; $S(v_i(t), \Delta v_i(t))$ is the minimum desired gap defined by the following equation:

$$S(v_i(t), \Delta v_i(t)) = s_o + max\left[Tv_i(t) + \frac{v_i(t).\Delta v_i(t)}{2\sqrt{a_{max,i}b_{max,i}}}, 0\right] \tag{3.3}$$

where s_o is the inter-vehicular distance at standstill; T is the safe following time-headway; and $b_{max,i}$ is the desired deceleration of the vehicle i. The parameter values used by the IDM are the same presented in [50].

The stated car-following model is used to control the longitudinal behavior of the vehicle with regard to the preceding vehicle. In addition, since the simulation considers a network with disrupted infrastructure, it assumes that all the intersections are stop-controlled intersections. The behavior of the IDM model was tested for a fleet of vehicles transitioning through an intersection as shown in Figure 3.2. The plot presents two consecutive vehicles approaching an intersection where the vehicles decelerate, stop and wait, then proceed to the next roadway segment based on the calculated route.

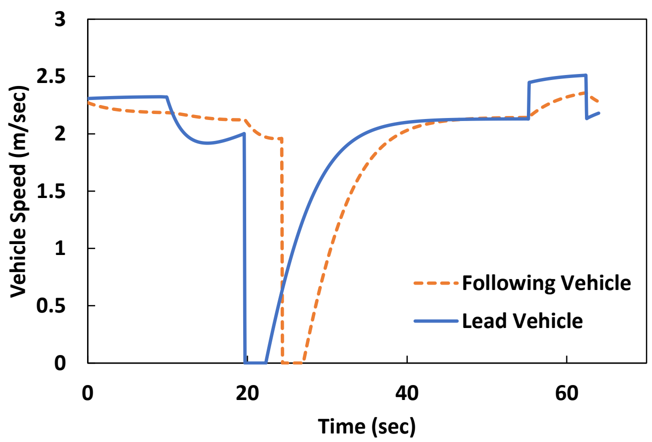


Figure 3.2: IDM-based Vehicle Behavior at Intersection. The blue line presents the lead vehicle behavior, prior, at and after an intersection, the orange dashed line represent the response of the following vehicle to the behavior of the lead vehicle.

Vehicles will follow the first come first serve rule when crossing the intersection. This means the vehicle that first arrives at the intersection will be given the priority to clear the intersection. In contrary, VANETs within a cluster will prioritize intersection clearance based on prioritization metrics that give the right-of-way (ROW) to the vehicles on critical links according to their level of congestion. Further details will follow in Section 3.4.

3.4 Problem Formulation

Defining the network, both at the transportation and communication network layers facilitates simulating scenarios in which an infrastructure-less approach to vehicular crowd management is implemented. This work allows vehicles to change their routes depending on the state of the roads in the direction of flow evading potential emergency situations and clearing up blockages caused by crises in an expedited manner. Achieving this lofty goal also ensures that blockages, damages, and other possible side effects that an unexpected emergency situation may incur on the network are dealt with promptly. The notation of parameters and variables are presented in Table 3.1 for the convenience of the reader.

The considered traffic flow dynamics, through the implemented IDM car-following model, provide realistic traffic behavior in the roadway network. Thus, the number of vehicles and the average speed in the traffic network reflect the needed metrics to be used in the evacuation and routing algorithms. The system solves the vehicle dynamic routing problem as a sequential, dynamic, and time-dependent stochastic problem. In this problem the CVs resolves the local optimization problem as the vehicle reaches an intersection.

Table 3.1: Notation of Parameters and Variables

Network and Vehicle Parameters	
v	Vehicle $v \epsilon V = 1, 2, ...\|V\|$
n	Nodes of network $n \epsilon N = 1, 2, ...\|N\|$
λ	The inter-arrival rate of vehicles $v \epsilon V$
l	Links of network $l \epsilon L = 1, 2, ...\|L\|$
o	Origin of vehicle $o \epsilon O = 1, 2, ...\|O\| \notin N$
d	Destination of vehicles $d \epsilon D = 1, 2, ...\|D\| \notin N$
t_l^v	Average speed of link $l \epsilon L$
t_n^v	Average speed of node $n \epsilon N$
d	Destination of vehicles $d \epsilon D = 1, 2, ...\|D\| \notin N$
q_l	Capacity of link $l \epsilon L$; maximum number of vehicles a link can handle
ρ_l	Number of vehicles on link $l \epsilon L$; number of vehicles currently traversing a link
β_l^v	Distance vehicle $v \epsilon V$ has traversed on link $l \epsilon L$
Cost function parameters	
$c_{o'd'}$	Travel cost of vehicle $v \epsilon V$ between the nodes o', d' of link $l \epsilon L$; $c_{o'd'} = f(t^t_{o'd'}, q_l)$
c_{w_n}	Cost of waiting time of a vehicle $v \epsilon V$ in intersection $n \epsilon N$
σ_n	fixed stopping time of any vehicle $v \epsilon V$ at intersection $n \epsilon N$
θ	Priority metric of vehicle v at the intersection $n \epsilon N$
Decision variables	
x_l	Binary variable: $x_j = 1$ if vehicle $v \epsilon V$ is not on link $l \epsilon L$; 0 otherwise
y_l	Binary variable: $y_j = 1$ if vehicle $v \epsilon V$ has not traversed link $l \epsilon L$; 0 otherwise
k_l	Binary variable: $k_j = 1$ if link $l \epsilon L$ is accessible by $v \epsilon V$; 0 otherwise
s_v	Binary variable: $s_v = 1$ if vehicle $v \epsilon V$ has priority in intersection $n \epsilon N$; 0 otherwise

3.5 Evacuation Behavior

This section describes the utilization of VANET under unplanned network disruption. As mentioned earlier, the vehicles, within a cluster, will communicate their physical location, speed, acceleration, as well as road network status to other vehicles located within the same cluster. Thus, when a vehicle within a cluster detects a disrupted link, information will be communicated to the other vehicles within the same cluster.

Within the context of the simulation, route choice behavior is governed by the travel cost of the selected routes. Thus, disrupted links are associated with a higher travel cost, resulting in these links being automatically discarded by the implemented EW-Dijkstra route choice algorithm depicted earlier. Since the disruption in the traffic network is unplanned, it is triggered after running the simulation for 60 minutes, to ensure full saturation of the traffic network. Therefore, if a conventional vehicle reaches a disrupted link that was within the predefined path upon departing the origin, the vehicle will update its path once reaches the intersection of the disrupted link.

For connected vehicles that are part of a cluster, the EW-Dijkstra algorithm, dynamically calculates the new routes based on the information received from the cluster as discussed in section 3.6.4. Thus, the connected vehicles update their paths regularly in a manner to achieve minimal residence times within the network.

3.6 Exploration-weighted Dijkstra (EW-Dijkstra) Routing Algorithm

Vehicle route choice plays a crucial role to achieve efficient evacuation. This study models the route choice of vehicles according to the information acquired by the vehicles depending on the type of vehicle. Vehicles with communication ability acquire information of the explored routes through information exchange with vehicles within their cluster. However, conventional vehicles will utilize a predefined route from their origin to destination. To model vehicle routing, this study utilizes a modified optimal routing algorithm that utilizes the information received from vehicles within a communication cluster for optimal routing. This study modifies the classical Dijkstra algorithm to account for vehicle communication through an infrastructure-less VANET-based technology.

The classical Dijkstra algorithm bases its shortest path exploration according to the lowest route of the lowest cost, usually the shortest path [54] with $O(n^2)$ computational complexity [55]. The new Dijkstra algorithm is an improved Dijkstra that considers the influence of traffic congestion and real-time information using infrastructure-less VANET-based communication technology to find the optimal route under evacuation scenarios.

Dynamic vehicle routing problem can accommodate the uncertainty of vehicle arrival in the traffic network [56], dynamic change in the events that might lead to route modification, such as updates in the travel time [57]. This algorithm selects the route that has the lowest travel cost and reduces the congestion near the blocked area. The updated algorithm has a cost function that considers the actual traffic flow, and traffic congestion, and waiting time at intersections that prioritizes the passage of the vehicles in critical network links rather than considering the distance between the origin and destination. The travel cost from the origin (o) to destination (d) consists of two main parts as depicted in equations 3.6 -3.10 . The first part consists of the travel time of the link. The second part is associated with the waiting time that each vehicle will spend at an intersection as a result of the prioritization metric based on the location of the vehicle from the blocked link. The modified algorithm is explained in Algorithm 1

3.6.1 *Intersection priority metric*

To facilitate the clearance of traffic in the vicinity of the affected area, a priority metric is used to define the right-of-way priority in the intersection. The priority metric is calculated using an exponentially decaying function that takes into consideration the difference between the current location of the vehicle and the location of the blockage in the network at the time of incident. The implementation of priority metric will ensure the dissipation of vehicles that are closer to the blocked area resulting in traffic relaxation in the surrounding area.This priority metric is calculated as described in Eq.3.4.

$$\theta_v = e^{\eta_v - \eta'} \tag{3.4}$$

where θ_v is the priority metric of any other vehicle at the intersection as calculated by 3.4; and θ_{v^*} is the priority metric of the vehicle currently attempting to exit the intersection; η' is the location of the blockage and η_v is the current location of the vehicle. The priority metric evaluates the priority of vehicle passage upon the occurrence of the incident to ensure traffic relaxation around the incident area.

According to the value of θ_v, priority of passing the intersection will be given as follows:

$$Pr = \max \theta_v | \forall v \epsilon V \subseteq n_i \tag{3.5}$$

3.6.2 *Optimization Problem*

The travel cost over a link $l \epsilon L$ is a function of link travel time between the two ends of the link, o' and d', and the current number of vehicles ρ_{l_v}, and the waiting time cost at the intersection. Equation 3.6 presents the cost function of the travel path of vehicle v traveling from origin o to destination d.

$$\min_{c_{od}}(\sum_{l} c_{o'd'}x_l y_l k_l + \sum_{n} c_{w_n}) \tag{3.6}$$

s.t

$$\rho_l \leq q_l \quad \forall l \epsilon L \tag{3.7}$$

$$t_l^v > 0 \quad \forall l \epsilon L \tag{3.8}$$

At each intersection, the vehicles will calculate the travel path from their current location to their destination using Equation 3.9. The equation calculates the minimum travel cost based on the real-time traffic data of the link $l \epsilon L$, such as traffic density and travel time and the waiting time at each intersection. The problem defined in Equation 3.9 is subject to two conditions presented in Equations 3.7 and 3.8 where in 3.7, the capacity of the link shall not exceed the maximum capacity and in Equation 3.8, the travel time of the link should be greater than 0 to be considered in the routing algorithm.
The travel cost of link $l \epsilon L$ is calculated according to Equations 3.9 and 3.10.

$$c_{o'd'} = (1/\rho_l)(\sum_{v}^{\rho_l} \beta_l^v / t_l^v) \tag{3.9}$$

$$c_{w_n} = \sigma_n + \sum_{v} s_v t_n^v \theta \tag{3.10}$$

The problem defined in Equations 3.9 -3.10 will be used to define the shortest path from origin to destination by both non-CV and CV vehicles. However, the CVs will dynamically update the route from their position to their destination based on the real-time data acquired through their clusters. Detailed explanation of the routing behavior and driver's compliance is explained in the following sections.

3.6.3 *Non-CV routing behavior*

The conventional vehicles have no information regarding the travel time, congestion state, or link accessibility status in the network. Accordingly, the vehicles will use Dijkstra algorithm to determine the path with the least cost between their origin and destination based on the defined link's travel speed instead of the defined cost function 3.6. The vehicle will update the route once it reaches the intersection and select the next segment based on the traffic status of the surrounding links if the next road to pass through is blocked.

3.6.4 *CV routing behavior*

Travel time information exchange through inter-vehicle communication (IVC) facilitates the utilization of available road network capacity [58]. IVC also results in congestion reduction and increased throughput of cleared vehicles from the affected network . When vehicles fall within the communication range of each other, they form a group of vehicles called a cluster. These clusters are integral in forming an interconnected communications network along the road and increase the coverage area while remaining fully infrastructure-less. The formation of a cluster is highly dependent on the MP level of VANET, the traffic demand, and communication range [42].

The clusters allow intercommunication between vehicles on different segments of roads where previously dissemination of crucial information was not available. These vehicular clusters form a large network where the VANETs form nodes and increase the coverage area and therefore the knowledge that the network and subsequently the algorithm is exposed to. As a vehicle connects to a cluster, real-time information of the roadway links covered by the cluster is acquired. The information includes the average speeds, number of vehicles within the cluster, location of the vehicles, and congestion status of links covered by the cluster. Figure 3.1 shows the cluster formation of the vehicles within a simple network. It can be noticed that vehicles within the large cluster will have knowledge of the traffic.

Upon entering the network, the CV will have a predefined preliminary route between the origin and destination based on the links' free-flow speed. Once the vehicle is connected to a cluster, the traffic status of the roadways covered by the CVs in the cluster will be communicated. This information includes the roadway speed and accessibility, and delay at intersection. According to the real-time information received from the cluster, the vehicle will dynamically recalculate the new route upon the arrival at each intersection.

Clusters formation: The formation of clusters is a two step process. The first includes exploring the current vehicle's one hop neighbors. This is done by extracting the vehicles currently occupying the links surrounding the vehicle and that are reachable, meaning they lie within the communication range. Once all the vehicles collect their one hop neighbors list, the second step of forming the clusters is initiated. In this step, any vehicle that has any number of neighbors will form a cluster containing those neighbors. If any two vehicles share at least one neighbor, this will lead to the joining of the two clusters and forming one larger cluster of vehicles that allows for communication between a larger set of vehicles and the exploration of a larger number of links.

However, depending on the cluster size, communication range, and network coverage, travel information of some roadway links might be unavailable. Therefore, under infrastructure-less communication, there is no reliable way to anticipate the travel information or traffic status of the network. That will result in inaccurate fastest path optimal solution due to partial information of the unexplored links.

To take that into consideration, this research implemented a route selection equation, for CV that is a function of the size of the cluster that the vehicle is in. The implemented formula will assure that vehicles within a larger VANET will have a larger compliance ratio with the communication information. The compliance ratio is a function of vehicle's cluster size and the minimum compliance rate calculated as follows:

To account for that, a compliance metric (ζ) of explored route selection is developed based on an ongoing study of selecting infrastructure-less evacuation information dissemination systems [59].

$$\zeta = 1 - \zeta_{base}(1 + GC_t)^e \tag{3.11}$$

where ζ is the compliance rate as a function of VANETs cluster size; ζ_{base} is the compliance rate with the real-time information communicated through the VANETs; GC is the the giant component size in the network at time t. The routing behavior of the vehicles, both VANETs and conventional vehicles can be summarized in Algorithm 1

Algorithm 1: EW-Dijkstra

N : Set of nodes in the network Q : set of nodes $\subseteq N$ to destination d
d' : is node ϵN with min distance
n^v : set of nodes $\subseteq N$ covered by cluster c^v
$C_{d'}$: cost to the nearest intersection $C_{d"}$: cost to the edge of the cluster
C_{r_i} : cost of route r_i where i is route alternatives
while *Q is not empty:* **do**
$v \epsilon CV$ **if** *v at o' and $v \subset c^v$* **then**
$C_{r_1} = C_{d'} + \zeta C_{d',d"} + C_{d",d}$ $C_{r_2} = C_{d'} + C_{d',d}$ *route* $\leftarrow \min(C_{r_1}, C_{r_2})$
$C_r = C_{d'} + C_{d',d}$
return *solution*

3.7 Relevant Simulation Events

Throughout the duration of the simulation key events are monitored since they affect the state of the vehicles, the VANET created by these vehicles, and subsequently the permeability of the proposed system in the network of vehicles.

- **Arrival Event:** The first event is the vehicle arrival onto the network. This event drives the entirety of the scenario. Where the arrival of a vehicle on a certain section of road is described. Once a vehicle has entered the road, its speed is set using the variation of the IDM mentioned in section 3. In order to achieve correct flow of traffic, the arrival of the next vehicle is calculated using this vehicle's arrival instant as reference. In this work, the proposed algorithm, as described in figure 4, should be triggered as soon as the vehicle arrives onto a road segment. Thus, an arriving vehicle queries the platoons of vehicles present on the road ahead. Based on the head-of-line speeds collected the vehicle decides of either continuing on the current path or choosing another route until this criterion is met.

- **Departure Event:** The second type of event is the departure event. This event marks the end of the trajectory of the vehicle on the road segment. The vehicle is accordingly removed from the road segment, has its clearance time calculated, and incurs an update of the road conditions. The updating of road conditions entails maintaining the structure of the caravans (their length, the head and tail of the caravans, the head-of-line speeds, number of caravans on the road...).

- **Connection Event:** The third type of event is a connection. This event occurs when a vehicle comes in the communication range of another vehicle. These vehicles then become part of a caravan either themselves or the joining vehicle becomes part of a larger caravan of vehicles. This event will incur an update of road conditions. In order to keep an updated view of the road ahead the vehicle that is connecting to the cluster also triggers the algorithm set in place.

- **Disconnection Event:** The fourth type of event is the disconnection event. This event occurs when a vehicle exits the communication range of the OBUs fitted into the vehicles; this will in turn incur another update of the road condition.

- **Disruption Event:** Finally, the last type of event is the disruption or emergency event. This event represents the unforeseen emergency crisis that shall take place. It is set to occur at a random time throughout the simulation run. The crisis is represented by a blockage on a section of the studied roads. The blockage negatively affects the speeds of the vehicles that are present before this blockage point.

3.8 Simulation

After describing the different components of a discrete event simulator, we move on to discuss how these components behave and interact. A data structure is an entity that organizes, stores, and allows the management of data in a certain manner. The choice of the data structure was a minimum heap to allow for dynamic insertion and acquisition of events from the event list with minimal cost

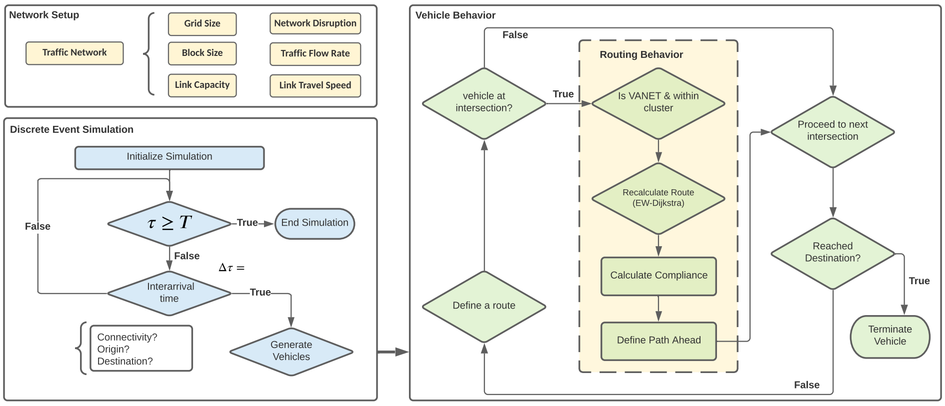


Figure 3.3: A flowchart describing the simulation platform

(best case O(1), worst case O(log(n))). The previously mentioned cost is referring to the time needed to retrieve and insert events into the event list. Minimizing this time allows for more extensive testing. The main feature of the min heap and the driving factor of this choice was the ability of the min heap to maintain at its root the item with the smallest value while needing to perform the least number of calculations and comparison between its other entries; thus, the efficiency and cost reduction should be evident. In this case, the items are events and the comparison is between their times of occurrence. Thus, the event at the root and the first one the be popped will be the event with the earliest time which will maintain the coherence of the simulation.

The simulation begins with an initial arrival event that is created and added to the event list when the event scheduler is initialized. The event scheduler's main tasks are to retrieve events from the event list at the correct times within the simulation run and to add newly created events into the list at the correct indexes. The initial arrival will be retrieved first this will create another arrival event and so on. The retrieval and addition of events are done using the heap's built in pop and push functions respectively. The list will then be reorganized such that the event with the earliest time will be at the root and to be the next event to be popped out from the list.

This model replicates the impact of CV communication and MP rate on the the Giant Component Size (GCS) as depicted in [42].

Chapter 4

Results & Analysis

This section presents the impacts of infrastructure-less VANET communication at different MP levels, traffic flow, communication ranges, and network disruption on emergency evacuation. The developed simulation tests the proposed evacuation algorithm in a Manhattan-grid network as defined in section 3.1. This study utilizes the following metrics to evaluate the efficacy of the developed system under the present conditions:

- Mean Travel Time (MTT): is the travel time for vehicle $v\epsilon V$ to clear the network from the vehicle point of origin (o) to destination (d).
- Vehicle Throughput: is the number of vehicles that cleared the network during the analysis period.
- Connection Duration (CD): reflects the duration of which a vehicle $v\epsilon V$ remains connected to other vehicles during its journey in the network.
- Average Cluster Size: is the average size of cluster (component) of vehicles measured over different MP levels.
- Number of Clusters: is the number of clusters are formed by the vehicles present in the network.
- Network Coverage (NC): is the percentage of the road network covered with the infrastructure-less VANET network.

To test the efficacy of the system, the system was tested using different levels of VANETs MP ranging from 0% to 100% of vehicles, varying levels of network disruption, between 0% -30%, communication ranges of 100m, 200m, and 300m as well as different levels of traffic flow rates to represent low, medium, and high levels of traffic congestion.

4.1 Mean Travel Time & Throughput Analysis

The improvement in network evacuation efficiency, in terms of MTT, associated with the deployment of VANETs as an infrastructure-less vehicle communication network is an essential element to assess the impact of VANETs on the evacuation performance. Traffic congestion associated with uneven distribution of vehicles over the traffic network results in highly congested traffic segments while others remain unused [2]. This may result in inaccurate and unreliable travel time predictions that is aggravated by unpredictable events [60]. Besides, real-time incident information has the potential to improve travel time information and predictability [61].

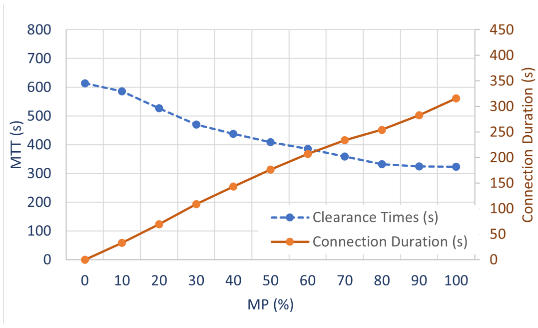
As stated earlier, this research evaluated the MTT for different vehicle flow rates and different MP levels. The network disruption level reflects the percentage of the network links that are inaccessible due to unpredicted traffic network disruption. Figures 4.1-4.6 present the impact of VANET communication on MTT and CD and NC under different levels of network disruption.

The average travel time of the vehicles between their origin and destination in the network, represented in MTT, as well as the time that the vehicles are within a connected cluster, is represented in Figure 4.1, for the λ_1 traffic rate scenario, representing the high level of congestion in the traffic network. The general trend shows that the benefits of VANET are highly correlated with the MP level where the MTT decreases with the increase in the MP level. At low MP levels, the benefits associated with VANETs are minimal in comparison to higher levels for the same level of traffic flow and network disruption. For instance, Figure 4.1 (a) shows no significant improvement in the MTT between 0% and 20% MP level, while benefits start to surface beyond 30% of MP. The aforementioned behavior is independent of the traffic flow rate and network disruption level.

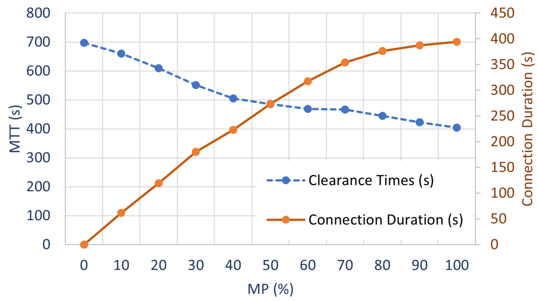
Figure 4.2 presents the three traffic intensity scenarios as well as different network disruption percentages on the MTT at different MP levels. The presented graphs show that at a high MP level, the variation in MTT for different network disruption levels becomes negligible. Besides, the plots also show that the MTT curve is steeper, which reflects a higher impact at low traffic intensity. This behavior is attributed to the variety of route options that a vehicle has to traverse between its origin and destination due to the low traffic congestion in the network.

The improvement in the MTT is subject to the traffic flow in the network and the communication range of the vehicles. At higher communication ranges, the trend of the MTT shows a steeper decrease with the increase in MP. This is most evident in the λ_1 scenario where the maximal improvement rate of 50% for the MTT is achieved at 60% MP for the 300m communication range, 70% MP for the 200m communication range and 80% MP for the 100m communication range.

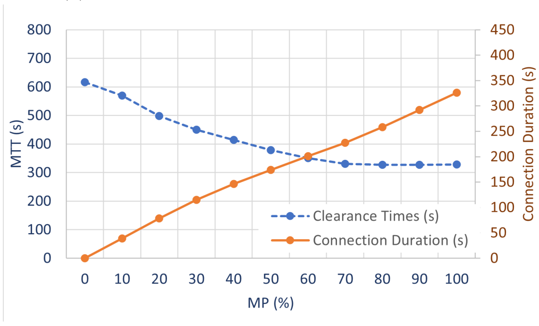
Furthermore, Figure 4.1 illustrates the relationship between the CD and the MP levels. The CD-MP non-linear relationship is reflected in the MTT earlier



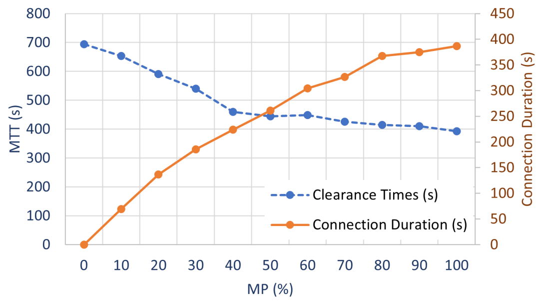
(a) 0% Network Disruption - 100m Comm Range



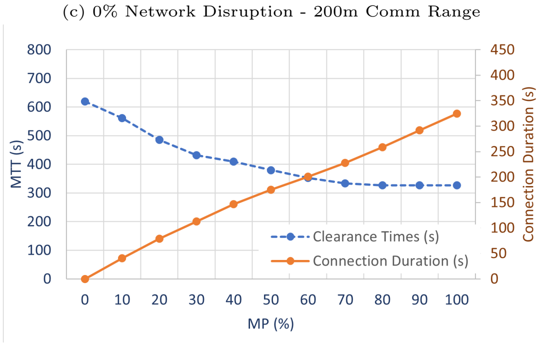
(b) 30% Network Disruption - 100m Comm Range



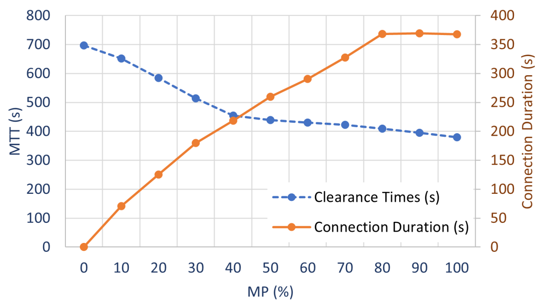
(c) 0% Network Disruption - 200m Comm Range



(d) 30% Network Disruption - 200m Comm Range



(e) 0% Network Disruption - 300m Comm Range

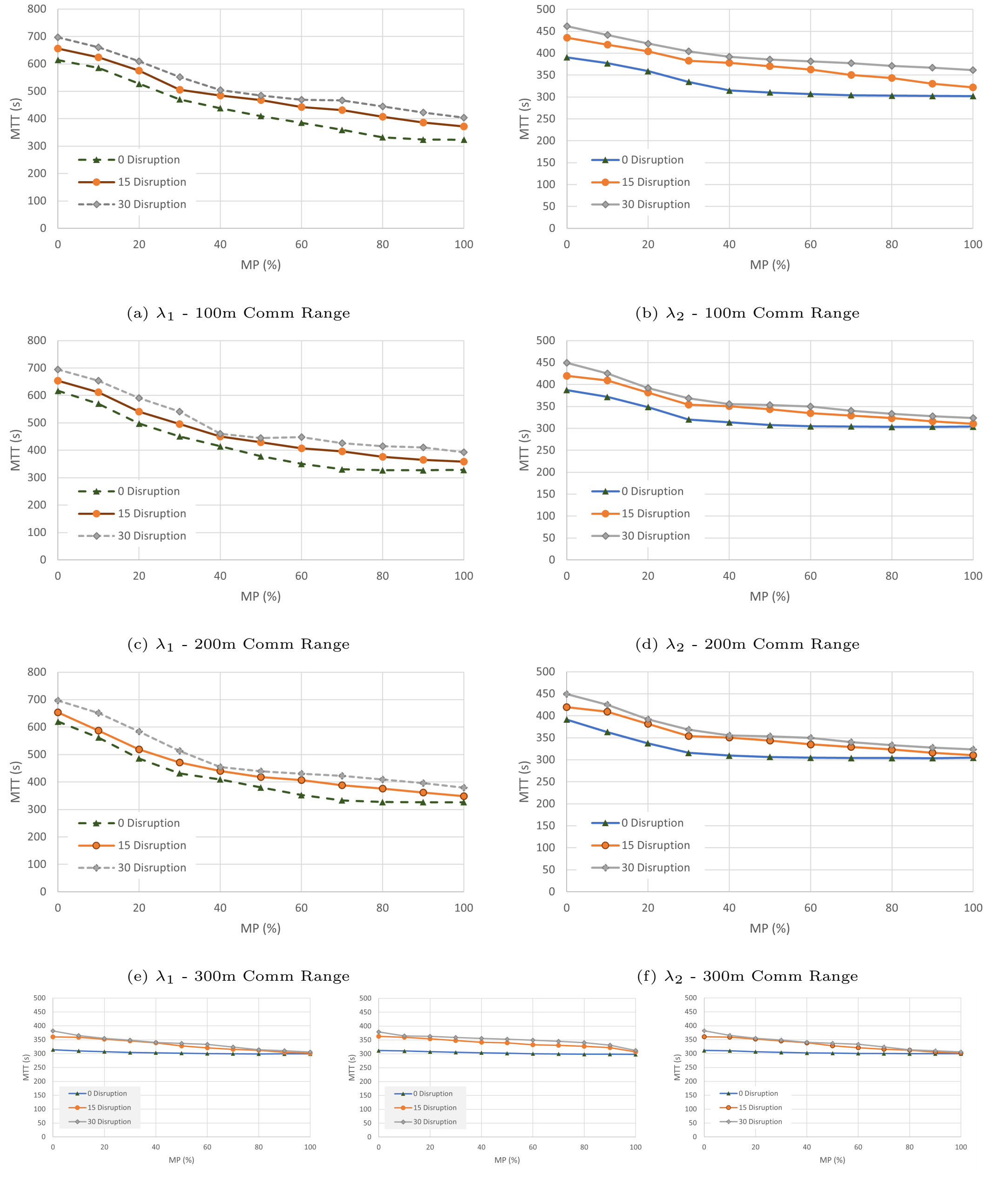


(f) 30% Network Disruption - 300m Comm Range

Figure 4.1: Mean Travel Time and Communication Duration with varying VANET MP level and network disruption levels for λ_1 arrival rate. The dashed blue curve depicts the average of the iterations. Similarly, the orange curve represents the communication duration over the trip over multiple runs.

where it can be noticed that at 40% MP level the vehicle will be connected to a cluster for around 30% of the trip time as presented in Figure 4.4. While this is relatively low, the CD to MTT ratio starts to increase at higher MP levels where it reaches 75% at 80% MP level. This reflects that vehicles at the full level of MP will be within a cluster, receiving real-time information for almost all the trip duration.

Since the main goal is to evaluate the impact of an infrastructure-less VANET-based system on the travel time of the vehicles throughout the network, the study also analyzed the outcome of the developed algorithm on the vehicle throughput. This is conducted to evaluate the number of vehicles that able to successfully and safely depart the network under varying levels of traffic intensity and network



(a) λ_1 - 100m Comm Range

(b) λ_2 - 100m Comm Range

(c) λ_1 - 200m Comm Range

(d) λ_2 - 200m Comm Range

(e) λ_1 - 300m Comm Range

(f) λ_2 - 300m Comm Range

(g) λ_3 - 200m Comm Range

(h) λ_3 - 100m Comm Range

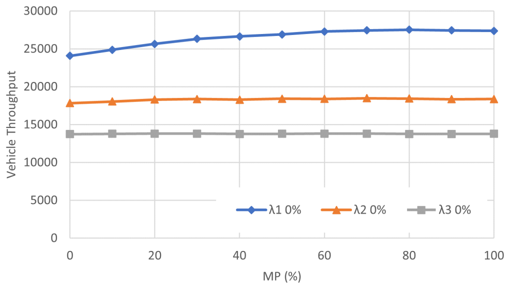
(i) λ_3 - 300m Comm Range

Figure 4.2: Mean Travel Time **(MTT)** with varying levels of MP and Network Disruption rates for 0.25, 0.375 and 0.5 sec vehicle inter-arrival rates.

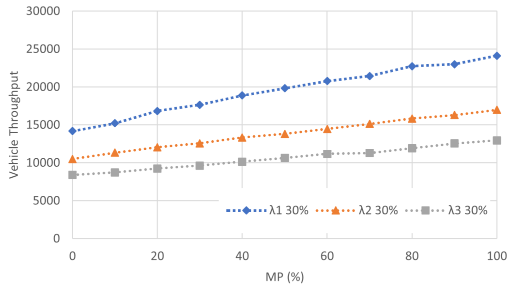
disruption rates. Figure 4.3 presents the vehicle throughput under varying levels of VANET MP, traffic intensity, and network disruption. The figure presents the base condition, 0% network disruption, against the extreme condition, 30% network disruption, for different inter-arrival rates. The plotted results follow a similar trend to the MTT results where the benefits of VANETs start showing steadily and then increase sharply near the higher MP levels

especially for high traffic intensity, λ_1. The developed system results in a 11% improvement in vehicle throughput at full MP level for 0% network disruption level, while it showed an increase in the vehicle throughput by 42% at 30% network disruption level. On the other hand, at medium and low traffic intensity, λ_2 and λ_3, it showed an increase in the vehicle throughput by around 5% and 53% for 0% and 30% network disruption respectively.

The presented results promise that the developed algorithm's capability of substantially enhancing the evacuation efficiency by increasing the MTT and the vehicle throughput through the network. While the MTT improvement is subject to the roads speed limit and intersection control type, the drastic increase in the vehicle throughput is promising.



(a) 0 % Disruption Rate



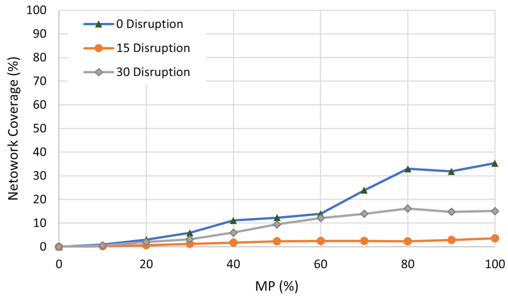
(b) 30% Disruption Rate

Figure 4.3: Vehicle throughput during two hours of simulation. A combination of different traffic intensity levels with 0% and 30% network disruption is plotted

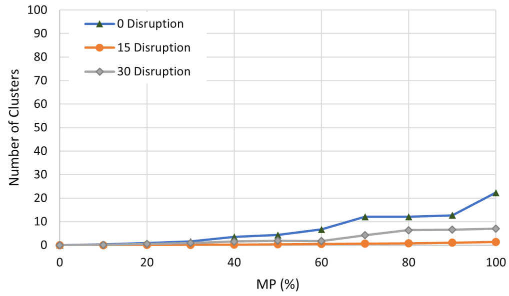
4.2 Network Coverage and Clusters Analysis

This study used other metrics to analyze the system dynamics including, but not limited to, NC which is presented in Figure 4.4. The plots show that NC is dependent on the traffic flow intensity and the communication range. The presented plots prove that the higher improvement needed to provide the vehicles in the highly congested networks (with λ_1 scenarios) with better MTTs, are the scenarios where higher NC is achieved. The higher NC achieved is also facilitated with larger communication ranges. As the plots show the maximal improvement rate of the MTTs is linked to when the NC surpasses the threshold of 40%. That threshold is reached sooner in the cases with larger communication ranges and thus the maximal improvement rate of the MTTs is also achieved sooner.

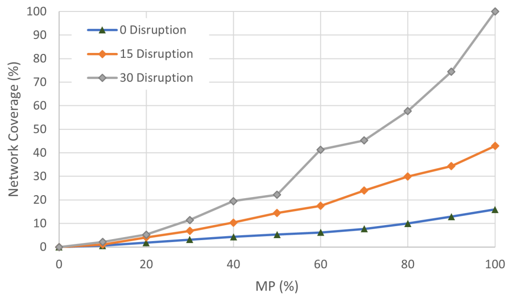
Further, results showed that the CD to MTT ratio and the NC are independent of the network disruption percentages. The CD-MP non-linear relationship is reflected in the MTT, Figure 4.1, where it can be noticed that at 40% MP level the vehicle will be connected to a cluster for around 20% of the trip time as presented in Figure 4.4. While this is relatively low, the CD to MTT ratio starts to increase at higher MP levels where it reaches 75% at 80% MP level. This reflects that vehicles at the full level of MP will be within a cluster, receiving real-time information for almost all the trip duration.



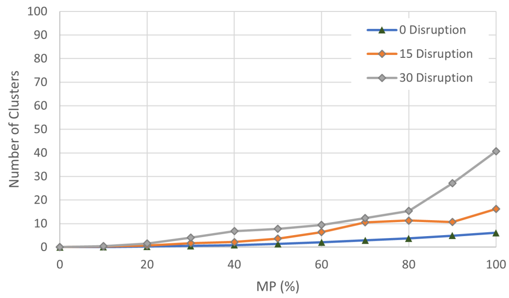
(a) λ_1 - 100m Comm Range



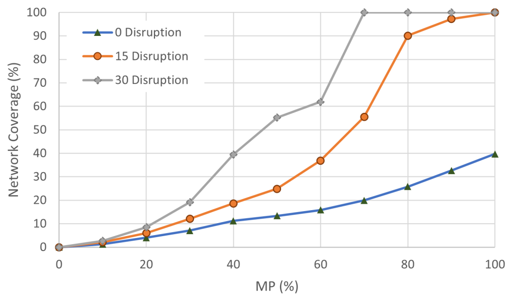
(b) λ_2 - 100m Comm Range



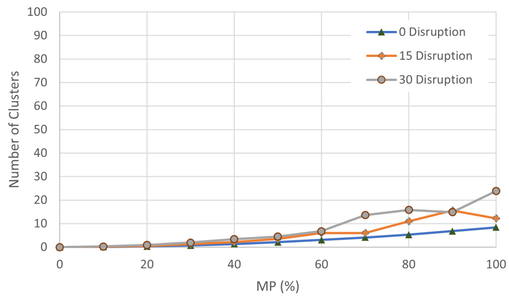
(c) λ_1 - 200m Comm Range



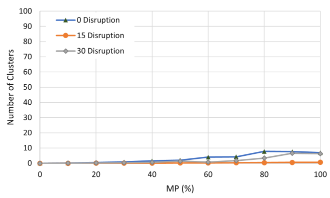
(d) λ_2 - 200m Comm Range



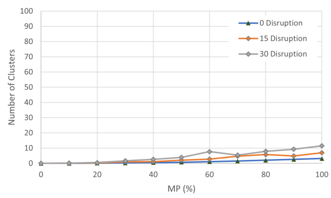
(e) λ_1 - 300m Comm Range



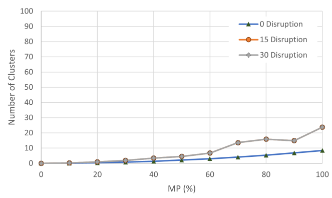
(f) λ_2 - 300m Comm Range



(g) λ_3 - 100m Comm Range



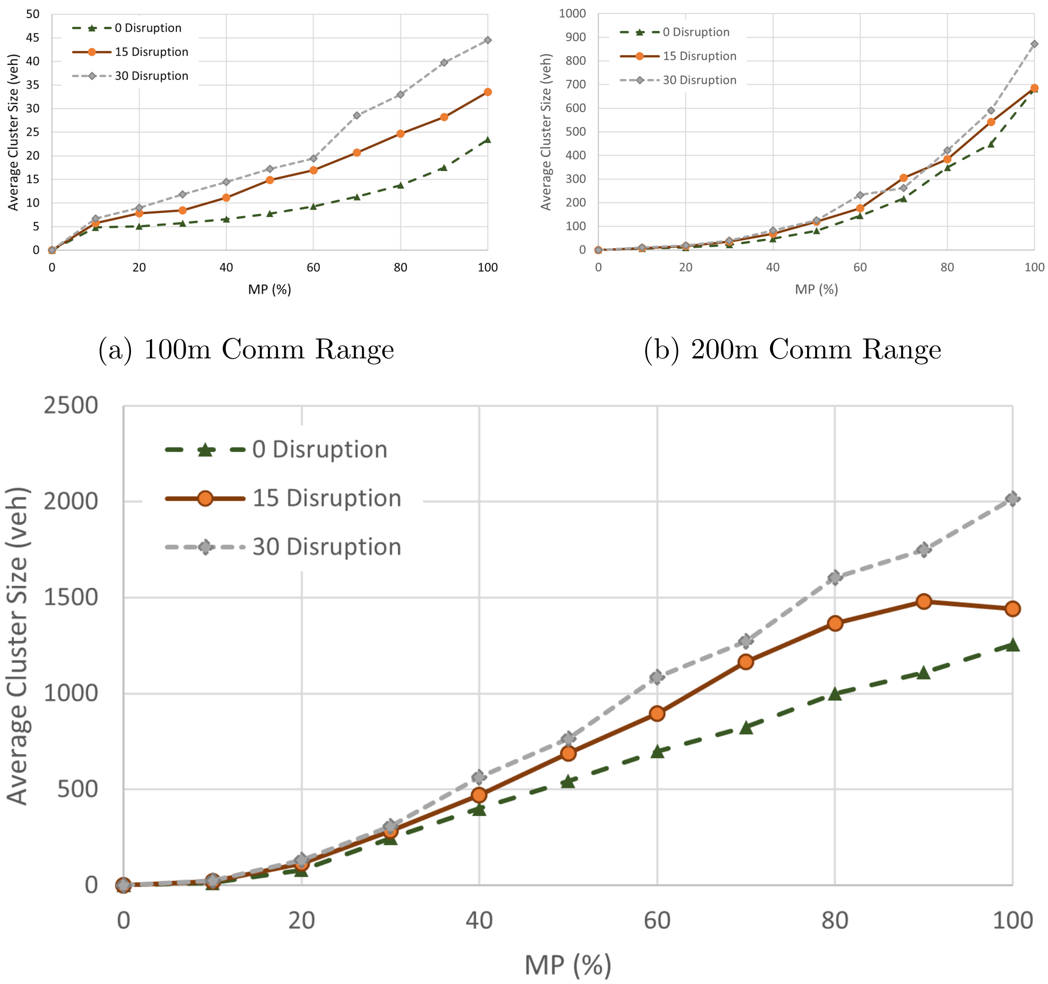
(h) λ_3 - 200m Comm Range



(i) λ_3 - 300m Comm Range

Figure 4.4: Network Coverage with varying levels of MP for λ_1, λ_2 and λ_3 vehicle arrival rates.

To have an insight into the VANET clustering dynamics under varying scenarios, the study analyzes the average cluster size and average number of clusters in the network under the predefined simulation conditions. Figure 4.5 presents the average cluster size under different traffic intensity and MP levels. The figure shows that the average cluster size ranges between 2 to 4 vehicles at MP range of 20% to 70% regardless of the traffic intensity. However, the average cluster size starts to dramatically increase at higher MP levels where it reaches 7 and 11 vehicles at low and high traffic intensity respectively.



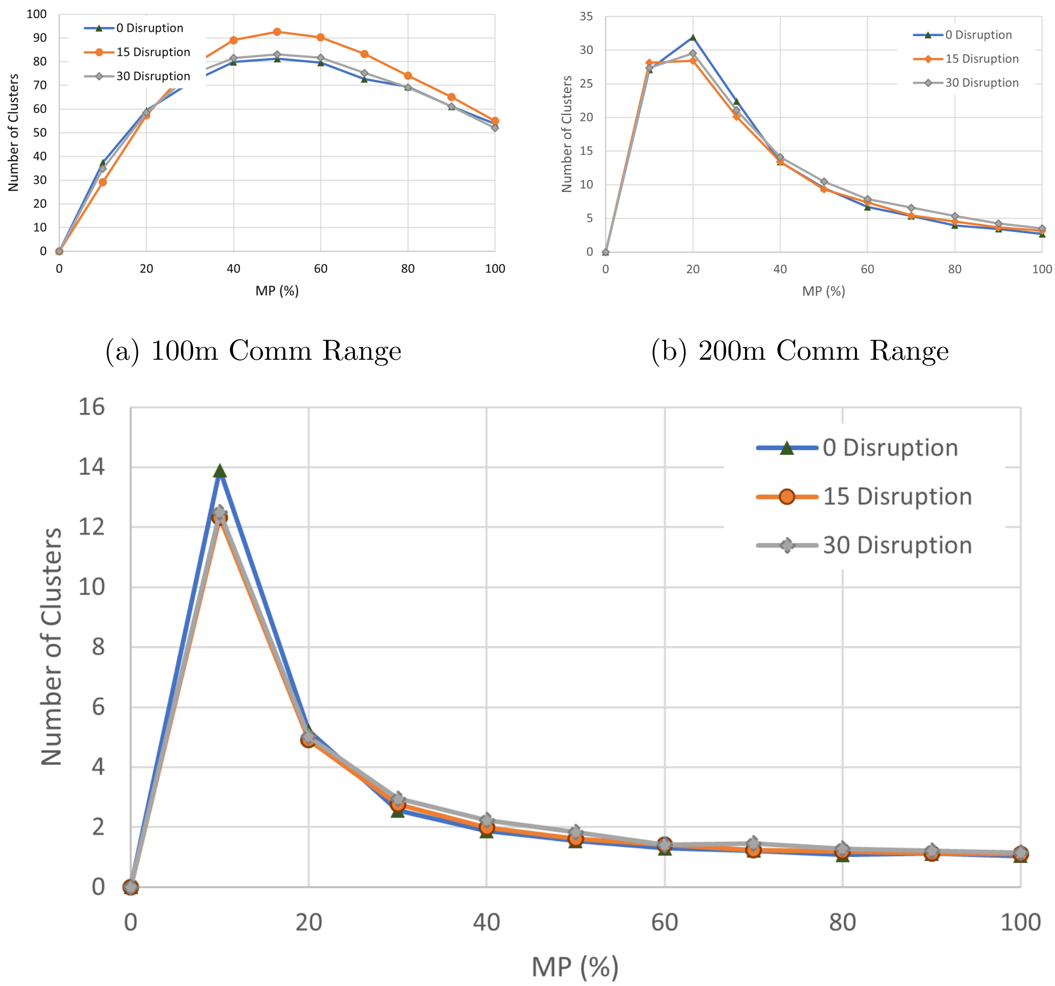
(a) 100m Comm Range

(b) 200m Comm Range

(c) 300m Comm Range

Figure 4.5: VANET Average Cluster Sizes under varying levels of network disruption and MP for the λ_1 vehicular inter-arrival rate

The average number of clusters presented in Figure 4.6 reflects the cluster formation over different MP levels. The curves show a bell-shaped trend. Where the maximum number of clusters is achieved earlier and earlier the larger the communication range. After the maximum number of clusters is achieved, it



(a) 100m Comm Range

(b) 200m Comm Range

(c) 300m Comm Range

Figure 4.6: Number of Clusters under varying levels of network disruption and MP for the λ_1 vehicular inter-arrival rate

starts to drop again. This behavior is attributed to the formation of larger clusters from the smaller ones as a result of higher MP levels. The figure also reflects that the number of clusters is highly affected by the traffic intensity where the possibility of clusters merging into a larger one is higher at higher traffic flow. On the other hand, lower congestion scenario, the curves are flatter in comparison to the aforementioned scenario where the average number of clusters maintains a relatively steady value at MP level range between 50% and 80% at higher communication ranges.

The results show that smart routing using an infrastructure-less vehicular communication network, represented by VANETs, has the potential to improve the traffic performance during unplanned traffic network disruption in a congested urban network scenario. While vehicle connectivity will start to surface at a relatively high MP level, it has the potential to double the traffic throughput accompanied by an increase in the MTT by 50% even at 30% network disruption.

4.3 Comparison with Infrastructure Aided Approach

In this section the proposed approach is compared to different work that leverages pre-existing infrastructure. The trade-off between probability of failure with respect to reliance on infrastructure and the decrease in the performance of a completely infrastructure-less approach is what this section investigates.

The work to be compared is [20]. The objective of the proposed system in [20] is to clear the network in a shorter time by better utilizing the network resources while taking into consideration the road capacities. In this model, road links are weighted based on travel time. Road link capacities and current traffic conditions are used as constraints in the optimization problem. Vehicles are employed as sensors to compute travel times of the links and send this information to the Traffic Management Center (TMC) in real-time. The TMC periodically optimizes the traffic assignment. Subsequently, routes for vehicles are created/updated based on the latest optimized assignments. To test the model,a real network with calibrated traffic is used.

In [20], the MP used is a constant 60%; however, the vehicular density is varied.

In order to compare [20] to the approach presented in this work, the achieved MTTs are compared for the same scenario of MP of 60% with varying vehicular density.

The difference between infrastructure-less and infrastructure aided achieved MTTs show the largest differential at lower vehicular density. However, by looking at the improvement rates of both implementations, one can notice that the infrastructure-less approach's improvement rate is 49.5% at λ_1 slightly less than that of the infrastructure aided approach's improvement rate which is 53.57%, but for the rest of the arrival rates the infrastructure-less approach provided better improvement rate than that of the infrastructure aided approach, being 22.17% for the infrastructure-less at λ_2 while 13.77% for the work in [20]. At λ_3, the work in [20] offers a negative improvement rate of -9.81%; however, the work proposed in this thesis offers improvement of 7.91% even at this low vehicular density. The performance improvement presented by [20] for λ_1 is the highest that work provided with higher vehicular densities providing a maximum of 44.1%.

Thus, the infrastructure-less approach provides almost similar performance to that of the infrastructure aided vehicle routing approach.

Chapter 5

Conclusion

In this thesis, a novel design of a routing algorithm that leverages information dissemination through VANETs was targeted to tackle the following challenges: (1) mitigating the effects of crises in urban areas, (2) evaluate a network-based simulator for crises in urban areas.

This work proposed a VANET-based infrastructure-less evacuation system and also tested the system in an ABMS environment mirroring a realistic network with realistic vehicular behavior. The main benefit of these VANETs, information dissemination, is leveraged to share network-state information between CVs within the network in real-time. This was aimed towards decreasing the overall clearance times of the vehicles within a network that could be affected by an emergency and have disruption to crucial links thus rendering these links inaccessible. The positive impact and improvement of this infrastructure-less solution were proven with the results presented in the previous section after having put the solution in different scenarios with different MPs, communication ranges, vehicular density, and disruption rates.

To further justify the motivation behind this work, a comparison was conducted with another approach that leverages preexisting infrastructure. This comparison was done to validate the trade-off between the performance boost provided by infrastructure and the robustness offered by the infrastructure-less approach proposed in this work. The improvement rates offered from the infrastructure aided approach was within 5% of the improvement rate provided by this work in the best case, and was 18% worse than the infrastructure-less approach in other cases. Therefore, completely relying on VANETs for emergency evacuation is a feasible and justifiable solution.

A future extension of this work might be to investigate the impact of introducing pedestrians into the network to further bolster the communication network by increasing the network coverage of this infrastructure-less approach.

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