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Streamlining Disaster Response: A Benchmark Study on Population Evacuation Planning with Telecommunication Network

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Abstract—In times of disaster, swift and efficient population evacuation is crucial to minimize losses. This study presents a generic framework for dynamic population evacuation (DPE), incorporating both planning and online management using vehicular communication. The framework deploys dynamic shelter allocation and traffic assignment techniques in the planning phase and combines an agent-based traffic simulator to represent the evacuation process with a vehicular ad hoc network (VANET), enabling real-time communication and decision-making among evacuees. The proposed methodology allows us to benchmark a range of evacuation strategies, focusing on identifying the most effective configuration of the framework’s objective functions for DPE planning, particularly in large-scale scenarios. Additionally, the study investigates the optimal Penetration Rate (PR) – the proportion of vehicles that are capable of communicating with each other and the infrastructure. The aim is to determine the level of vehicle connectivity that promotes the most efficient evacuation procedures. A detailed benchmark comparison is conducted of two prevalent telecommunication network architectures: the centralized VCC and the distributed Vehicular Fog Computing (VFC). Multiple insights into the performance of these systems during evacuation situations are provided. The results show that a VFC architecture is the most suitable for large-scale population evacuation.

I. INTRODUCTION AND LITERATURE REVIEW

The planning phase in disaster scenarios is crucial as it determines evacuation instructions such as the shelter destination and the path taken to reach it [1]. Traditional offline planning methods involve pre-determining these factors by solving the Shelter Allocation Problem (SAP) and using Dynamic Traffic Assignment (DTA). Solving SAP involves identifying the most suitable shelters for different groups of people, such as families with children or individuals with special needs. While DTA is a traffic management strategy that considers real-time traffic conditions to determine path flow distribution. Several studies have investigated the use of traffic assignment and shelter allocation problems for offline evacuation planning. For example, a study by [2] proposed a multi-objective DTA model for evacuation planning that considers both evacuation time and congestion. In [3], we presented a comprehensive literature review on offline Dynamic Population Evacuation (DPE) planning methods and proposed a dynamic framework to solve SAP and DTA together using a simulation-based approach. However, offline

planning alone may not be sufficient to handle the dynamic nature of an evacuation.

In this context, online DPE is defined as a process of revising the evacuees’ shelter and path choices during the evacuation process. It means evacuees can communicate during the evacuation and receive new information to revise their decisions. From a practical point of view, this process can be feasible if vehicles are equipped to connect to a vehicular ad hoc network (VANET). Generally, the concept of Vehicular Cloud Computing (VCC) and Vehicular Fog Computing (VFC) have emerged in order to support and serve all drivers’ needs, ensure their comfort and safety, and increase VANET resources [4]. VCC uses connected vehicles and cloud computing to reroute vehicles and dynamically allocate shelters during an evacuation. Therefore, online solving of the evacuation problem using VCC for rerouting vehicles and shelter reallocation may further optimize the evacuation process. Several studies have investigated the use of VCC for evacuation planning. For example, [5] proposed a safety-related message exchange protocol for highway scenarios. However, their work does not revise the SAP and DTA problems. In a study by [6], an evacuation strategy called speed strategy was applied and evaluated using the VCC architecture. This study quantified driver responses to evacuation pre-plans in emergencies. However, the authors did not propose any replanning orders to change their routes or destinations, a critical element we introduced in [7] and aim to address in this study. Regarding VFC, most studies in the literature only mention the potential of this architecture for emergency situation and do not apply it to the DPE process.

Another question to be addressed is which indicator should be optimized for the DPE problem [8]. In the literature, multiple studies have explored various key performance indicators (KPIs) used to optimize and evaluate evacuation planning. Evacuation orders serve several primary goals, which have been extensively studied by [8]. Combined KPIs that take into account multiple factors like total evacuation time, network clearance time, and total traveled distance are also proposed in the literature [9]. The combination of these KPIs for optimization is mainly defined by the weighted sum function. However, there is no proof in the literature that shows optimizing one single KPI provides the optimal evacuation plan. These varied objectives highlight the complexity of the DPE problem and the need for nuanced, multi-faceted solutions. This study seeks to further investigate the effectiveness of single versus combined KPIs

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in optimizing the DPE process, thereby contributing to the ongoing discussion in the field.

In addition to the KPIs, another crucial aspect that warrants attention is the telecommunication network architecture within evacuation scenarios. In the literature on VANET applying to non-emergency travel, multiple studies were made to assess the impact of different telecommunication architectures on transportation systems. [10] studied the impact of different vehicular communication architectures, such as cloud computing and fog/edge computing. They presented several applications of these architectures, excluding evacuation. [11] presented a comprehensive summary and analysis of the latest research in smart transportation systems, focusing on standardization activities, protocols, applications, and security. In addition, [12] describes the essential parts of a fog computing architecture and focuses on different applications, architectures, and significant performance metrics using fog computing in vehicular networks. All the aforementioned studies addressed normal conditions. However, understanding how these architectures perform during emergencies like population evacuation is crucial, as these scenarios present unique challenges that may impact system performance. Despite this, to the best of our knowledge, there is no previous study that examines the performance of these telecommunication architectures in a population evacuation context. This study aims to fill this knowledge gap.

This study designs a generic framework for DPE that will enable the evaluation of various telecommunication network architectures in terms of their performance. The focus will be on examining objective functions that are most effective for DPE planning, particularly in large-scale scenarios. Additionally, the research will investigate the optimal Penetration Rate of connected vehicles within a cloud computing setting, aiming to identify the ideal level of vehicle connectivity for efficient evacuation processes. Furthermore, a comprehensive benchmark will be conducted to compare and assess the performance of two commonly used telecommunication network architectures. By evaluating and optimizing telecommunication systems for population evacuation, this study aims not only to enhance the scientific understanding in this area but also to provide practical insights that could contribute to improving public safety during emergencies. The results may help inform the design and implementation of evacuation strategies, guide policymaking, and serve as a foundation for future research in this area.

II. METHODOLOGY

Efficient evacuation operations are critical in emergencies and require a systematic approach to minimize evacuation time. The proposed approach consists of two phases: the initial evacuation plan (solving the SAP and DTA problems) and the online management process that considers vehicular communication. For the initial phase, we follow the methodology developed in [3]. In SAP, we minimize the overall evacuation time, which aligns with the interests of system operators who prioritize efficiency in the evacuation process.

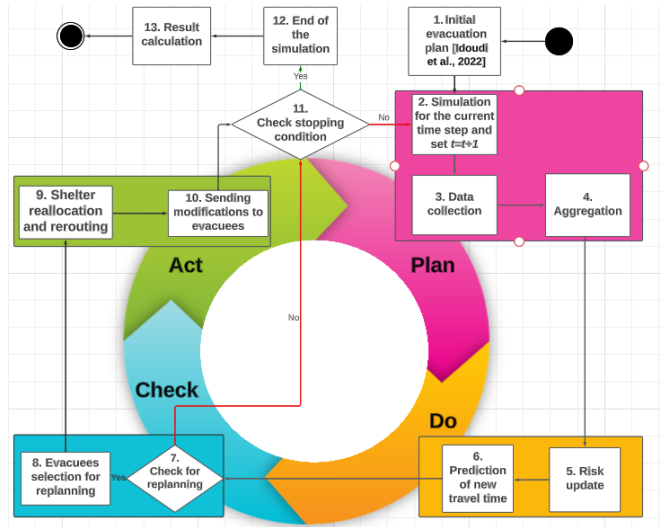


Fig. 1. Flowchart of the proposed methodological framework to address the online DPE problem using the PDCA Cycle.

Subsequently, the DTA problem addresses the concept of Stochastic User Equilibrium (SUE), considering the tendency of evacuees to prioritize their perceived minimum travel time when choosing their path to their selected shelter. By formulating and optimizing these decision problems, the evacuation process can be effectively streamlined, considering both the priorities of system operators and the preferences of individual evacuees.

The proposed online management framework aims to address unforeseen events and adapt the initial evacuation plan in real time by utilizing the communication capabilities of vehicles. This framework leverages the power of vehicular communication to enable evacuees to receive and transmit information, allowing them to update their routes as needed. This dynamic modification of ways based on real-time information significantly enhances the efficiency and safety of the evacuation process, ensuring that evacuees can respond effectively to changing circumstances and navigate the most optimal paths to their destinations. To use VANET, a network layer is introduced to incorporate vehicular communication, enabling network congestion monitoring. This communication network is crucial in re-planning evacuation routes and shelter allocation in real-time throughout the evacuation process.

The proposed methodology is structured following Deming's Plan-Do-Check-Act (PDCA) cycle [13], illustrated in Figure 1. This visual representation provides a systematic approach for continuously improving the evacuation plan and offers an overview of the proposed methodological framework's key steps. We first detail the flowchart and subsequently, highlight the differences between VCC and VFC.

In the initial planning phase, Step 1 focuses on generating the initial evacuation plan. This stage involves solving the multi-level DTA and SAP, thereby creating an evacuation plan as described in [3]. The objective function of SAP will

be modified in the next section for our benchmark.

The PDCA cycle begins with the "Plan" phase, which simulates the evacuation process for the current time step and increments the simulation time index ($t=t+1$) in Step 2. The simulation considers the proposed plan and any new events that have occurred due to decisions made by evacuees in the previous time step. A trip-based or agent-based dynamic simulator can be used for this purpose. Step 3 focuses on data collection as part of the VCC architecture. Each vehicle (node) broadcasts data messages using its On-Board Unit (OBU) to Roadside Units (RSUs), which transmit the data to the cloud server.

In the "Do" phase, the risk measure is updated based on the data collected in Step 3. The risk calculation in Step 4 considers the vehicle's distance from a hazardous area and the congestion levels at the vehicle's location. Afterward, new travel times are predicted in Step 5, taking into account the evolving risk and congestion.

The "Check" phase verifies the need for replanning. Step 7 determines whether a vehicle should be included in the replanning process. It estimates edge density, including road speed and traffic density, based on the Greenshield model [14]. Vehicles with current edge density exceeding a certain threshold are considered to be in congestion and are thus subject to rerouting. The shelter reallocation process selects vehicles when congestion is detected in front of their original destinations. In Step 8, prioritization is given to vehicles within a risky zone with a radius of 4 km, particularly focusing on those closest to the center of the risky zone.

In the "Act" phase of the PDCA cycle, two important steps are performed. Step 9 involves shelter reallocation and rerouting, where the content of a message is prepared to be sent to targeted users, asking them to reroute their vehicles to the path with the current shortest travel time, considering their possible newly planned shelter. This step aims to optimize the evacuation routes for efficiency and safety. Step 10 focuses on sending notifications to evacuees. In this step, the cloud server communicates its decisions to the nearest RSU, which then forwards the results to the vehicles. The vehicles receive these notifications and can react accordingly based on the instructions provided. This communication process ensures effective coordination and timely response during the evacuation, leveraging cloud computing and communication capabilities to improve the overall evacuation process. Lastly, Step 11 verifies whether all evacuees have reached the shelters. If not, the PDCA cycle restarts at Step 2, ensuring continuous improvements to the evacuation process.

The aforementioned description outlines the communication process within a cloud computing architecture, which bears a resemblance to that of a fog computing architecture. However, a pivotal distinction resides in the decision-making locus. While the cloud architecture consolidates decisions at the cloud server level, the fog architecture delegates decision-making to the RSU level. This decentralization fosters prompt decision-making and diminishes dependency on the cloud server, thereby bolstering the responsiveness of the

evacuation system. Moreover, another divergence between the two architectures lies in the message aggregation process. In the cloud architecture, message aggregation is centralized at the cloud server level, while in the fog architecture, it occurs closer to the edge at the RSUs. These disparities underscore how fog computing brings decision-making and data processing closer to the network's edge, thus enhancing system agility while maintaining the overall communication framework established in the cloud computing architecture.

This methodology outlines a comprehensive approach for dynamic population evacuation using vehicular communication and different network architectures. By integrating planning, real-time adjustments, and dynamic decision-making, the framework ensures an efficient evacuation process. Next, two city-scale case studies will be presented, applying this framework to demonstrate the potential of the methodology under different configurations, allowing a comprehensive cross-comparison of different optimization and VANET configurations by evaluating their effectiveness.

III. CASE STUDIES

This section provides an overview of the hardware and software components deployed in implementing the proposed solution and conducting the experiments. Two distinct networks were utilized for the experiments: the LuST scenario, which represents Luxembourg City [3], and the network of Mill Valley City in California. The experiments were conducted on a laptop with a processing speed of 1.7 GHz and 16 GB of RAM, which facilitated the generation of all the results. The solution was implemented using a simulation-based DTA method, employing the SUMO simulator [15]. SUMO facilitated the calculation of the C-logit model and travel time prediction. The planning phase was optimized using the SAP model implemented with ILOG CPLEX version 12.9. To simulate vehicular communication, the Veins/Omnet++ simulator was utilized to implement the fog and cloud computing architectures, which were based on previous works [16].

Figure 2 illustrates the evacuation network maps of Luxembourg City (covering an area of 155.95 km²) and Mill Valley City (encompassed a total length of residential roads spanning 337 km), serving as the simulation environments. In the LuST scenario, we focus on the affected population in the central region, as shown in Figure 2(a). Further information about this scenario can be found in [7]. Similarly, the real evacuation scenario of Mill Valley (Figure 2(b)) is detailed in [17]. The Veins project was integrated to incorporate the vehicular communication layer into the traffic network graph. The vehicular communication network in the OMNET++ simulator is depicted in Figures 2(c) and 2(d).

IV. NUMERICAL RESULTS

The proposed methodology is applied to both case studies using the scenario setting presented in [7] and [17]. In this section, we begin by examining the influence of SAP's objective on the effectiveness of evacuation planning. Subsequently, we conduct a sensitivity analysis to determine

the optimal penetration rate of connected vehicles. Finally, we compare the VCC and VFC architectures to determine the most appropriate vehicular communication architecture for this specific application.

A. SAP objective function

In [7], we have determined the effect of telecommunication compared to just planning on the success of the evacuation process, and we noted that planning also contributed a lot to this success. Hence, here we modify our planning methodology, especially the model adopted in formulating the SAP. Recall that most studies that are discussed in Section I are using the formulation of the p-median problem proposed in [18]. The p-median problem aims to minimize the total evacuation time. However, there is a similar formulation, known as the p-center model aims to determine the optimal location for shelters, such that the maximum travel time between any demand point and shelters is minimized. In other words, it minimizes the network clearance time [19]. The research question is which objective function is more suitable for the DPE problem. Note that both models are known to be NP-hard [8].

Initially, we address the SAP by utilizing the p-median problem in [3]. Here, a weighted sum operator is defined for the objective function, and we are progressively transitioning toward the p-center problem in order to minimize the time required for clearance. Hence, we define the following objective function for the SAP:

$$\min z = w_{ct} \cdot \max_{\forall os} \{t_{os}^\alpha * a_{os}\} + w_{tt} \frac{\sum_{o \in O} \sum_{s \in S} t_{os}^\alpha * a_{os}}{|M|} \quad (1)$$

This formulation allows us to capture both the p-median and the p-center problem. If we set $w_{tt} = 0$, the problem becomes a p-center problem, whereas if we set $w_{ct} = 0$,

it turns into a p-median problem, subject to the condition $w_{tt} + w_{ct} = 1$. In Equation 1, M represents the set of all evacuees. α denotes the time interval, $\alpha \in T$. Furthermore, a_{os} denotes the number of evacuees allocated to a particular origin-destination pair os , and t_{os}^α stands for the minimum experienced travel time for the os pair within the time interval α . It is important to note that we have refrained from introducing any modifications to the DTA model deployed for directing evacuees toward their specified destinations, as determined by the shelter allocation solution. It means the congestion evolution will impact our results. For example, the pure clearance time optimization for SAP does not necessarily result in minimum clearance time for our test cases after DTA calculation and dynamic simulation. This fact emphasizes the complexity of the problem and the impact of dynamic traffic conditions.

We conducted a sensitivity analysis on the network of Luxembourg City and the Mill Valley network, where we systematically adjusted both the w_{tt} and w_{ct} variables to observe their impact on clearance time and mean speed of the network during the evacuation planning phase.

Figure 3 displays the variation in clearance time across different scenarios with varying objective functions for Luxembourg City. The figure highlights that employing a pure p-median formulation with $w_{tt} = 1.0$ and $w_{ct} = 0.0$ yields the most favorable results in terms of clearance time. Furthermore, the figure demonstrates that the simulations having total travel time weights ranging from 0.2 to 0.8 have the same clearance time, which can be explained by the fact that these weights generate the same solution to the SAP problem, which could be expected for the medium-scale problem. In Figure 3, the mean speed of the network is depicted. A higher value of mean speed indicates better performance in terms of the efficiency of the evacuation process. The graph reveals a combination of the two objectives with weights ranging from 0.2 to 0.8 that result in more efficient use of the network.

The results for the Mill Valley network are presented in Figure 3. This figure shows that going for a mixed p-center and p-median formulation with $w_{tt} = 0.1$ and $w_{ct} = 0.9$ gives the best output in terms of clearance time. Regarding the mean speed of the network, the results show optimizing

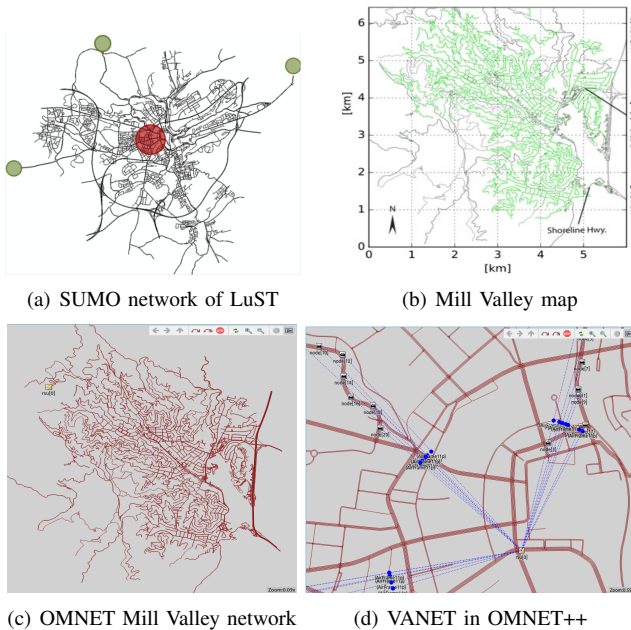


Fig. 2. VANET maps of Luxembourg and Mill Valley network

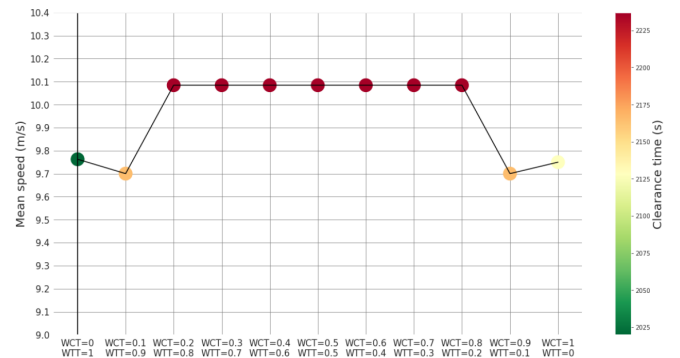


Fig. 3. Network mean speed and clearance time variation over different objectives of SAP of Luxembourg City.

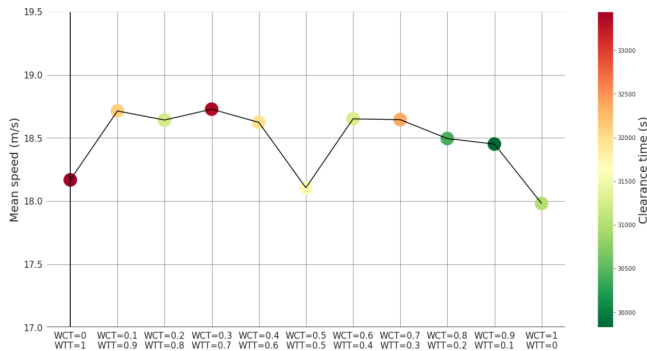


Fig. 4. Network mean speed and clearance time variation over different objectives of SAP of Mill Valley City

clearance time provides less mean speed for the network. Note that higher mean speed does not provide minimum clearance time as the departure time distribution of evacuees is not uniform. In addition, Figure 4 shows that there is no correlation between mean speed and clearance time, as all scenarios have different values for clearance time measures.

The two optimization approaches, namely minimizing total evacuation time and minimizing clearance time, both play a significant role in the SAP formulation to address the DPE problem. However, the effectiveness of these approaches can vary greatly depending on the specific scenario or test case. Our analysis reveals a noteworthy observation - a configuration with $w_{tt} = 0.2$ and $w_{ct} = 0.8$ appears to yield effective results across diverse test cases, both medium and large-scale.

B. Penetration rate sensitivity analysis

While assuming that 100% of evacuees use connected vehicles may be unrealistic at present, it is a potentially attainable scenario in the future. Hence, multiple penetration rate values for connected vehicles are considered for both test cases. Note that, This sensitivity analysis is applied to scenarios with the best weights for each case determined in the previous section. The connected vehicles are chosen randomly when considering a certain percentage of penetration rate. Only this specific percentage is responsible for transmitting positioning information and receiving online orders. Consequently, the cloud server exclusively monitors and guides this subset of vehicles. The proposed evacuation framework is executed for five penetration rate values, and the results are presented in Tables I and II for the LuST and Mill Valley scenarios, respectively.

Table I presents the different values of the performance measures used for multiple penetration values. The table clearly shows that the case of a 100% of penetration rate is the best scenario in the LuST network. Table I also illustrates acceptable values of Packet Delivery Ratio (PDR) measure for 70%, 50%, 30%, and 10% scenarios. This PDR level means that around 75% generated packets are received correctly in the range of network infrastructure and without the need for retransmission. Also, the delay measure is crucial, especially in this case dealing with population evacuation.

The average end-to-end delay of packets considering the VCC architecture employed is around 203 ms.

TABLE I
DIFFERENT PENETRATION RATE PERFORMANCE MEASURES

Metrics	PR 100%	PR 70%	PR 50%	PR 30%	PR 10%
Network clearance time(s)	1775	1833	1846	1873	1923
Mean evacuation time(s)	1071.54	1081.17	1084.90	1081.17	1102.28
Average travel delay (ATD)	205.47	220.24	219.68	228.88	234.47
Average evacuation delay (AED)	229.04	243.58	243.58	252.49	254.34
End-to-end delay (ms)	205.30	203.75	202.77	201.17	200.25
Packet Delivery Ratio	74.20%	75.80%	76.24%	75.50%	76.44%

Table II shows multiple values of the penetration rate of vehicles in the large-scale scenario of Mill Valley City. The large network and the high demand considered put limitations on simulating penetration rate high values. In this Table II, we compare scenarios with 0%, 10%, 20%, 30%, and 40%. Results demonstrate that the evacuation process is optimized using vehicular communication, with a difference of more than 2 hours in terms of clearance time between scenarios with PR=0% and PR=40%.

TABLE II
DIFFERENT PENETRATION RATE PERFORMANCE MEASURES

Metrics	PR 40%	PR 30%	PR 10%	PR 00%
Network clearance time(s)	23311	23387	23683	29826
Mean evacuation time(s)	14502.9	14570.34	14572.84	14719.26
Average travel delay (ATD)	520.29	511.37	363.99	449.57
Average evacuation delay (AED)	1204.16	1075.49	1004.29	942.92
End-to-end delay (ms)	405.30	403.75	401.17	-
Packet Delivery Ratio	70.20%	71.80	72.50	-

The outcomes presented in Table I and II demonstrate a noteworthy enhancement in the quality of the final solution achieved through the scenario with only PR=30%, where both planning and online guidance models are utilized. The results concerning End-to-End delay and PDR indicate that with a 30% penetration rate, we achieve a latency-sensitive application that exhibits limited delay and a high PDR value, thereby meeting acceptable standards as the higher value than 30% for the PR does not improve the results significantly.

C. Vehicular communication architectures

In this section, we use the results of the previous sensitivity analysis sections about SAP's best objective and a realistic penetration rate value of PR=30%. Our focus lies in modifying the vehicular communication architecture and investigating its impact on the success of evacuation operations. Therefore, we conduct a comparative analysis between two well-known architectures, namely Vehicular Fog Computing (VFC) and Vehicular Cloud Computing (VCC), to assess the effects of this alteration. By examining these architectures, we aim to understand how changes in the communication infrastructure can influence the overall efficiency and effectiveness of evacuation operations. VFC and VCC are two distinct architectures for vehicular communication, each offering unique characteristics and advantages. Due to its proximity to vehicles, VFC offers lower latency and faster response times for real-time applications. Fog nodes in VFC can process and analyze data locally, reducing the need for data transmission to remote cloud servers. In contrast, VCC

TABLE III
DIFFERENT ARCHITECTURES PERFORMANCE MEASURES

Scenarios Metrics / Telecom. architecture	Luxembourg City		Mill Valley City	
	VCC	VFC	VCC	VFC
Network clearance time (s)	1873.00	1948.00	23387.00	23488.00
Mean evacuation time (s)	1081.17	1110.53	14570.34	14541.81
Average travel delay (ATD)	228.88	221.11	511.37	431.70
Average evacuation delay (AED)	252.49	265.28	1199.52	1108.12
End-to-end delay (ms)	201.17	0.24	403.75	0.24
Packet Delivery Ratio	75.50%	65.01%	75.80%	49.88%

introduces higher latency as data has to travel to distant cloud data centers for processing and storage.

As expected, Table III reveals an increase in network clearance time, 3.9% for medium scale and 0.4% for the large scale, when deploying the fog computing architecture. However, it also demonstrates a significant decrease in the end-to-end delay. We can conclude that fog computing can achieve comparable results to cloud computing in terms of transportation performance while offering the advantage of reduced latency. This finding highlights the potential of fog computing in delivering efficient and timely communication in transportation systems, bridging the gap between local processing capabilities and the need for real-time data analysis and decision-making.

V. CONCLUSIONS

This study has made an attempt to address the dynamic population evacuation (DPE) problem by introducing a comprehensive framework incorporating both strategic planning and online management via vehicular ad hoc networks (VANET). An analysis of various models used in evacuation planning and VANET (Vehicular Ad hoc Network) creation and execution in the context of evacuations is presented. We propose a generic framework following the PDCA improvement cycle for the DPE problem. The model is implemented for city networks, namely Luxembourg City and Mill Valley, and a complete analysis is conducted to find the best configuration of the model for real applications. Our sensitivity analysis suggests that the choice of the objective function for the DPE problem can have significant implications for evacuation efficiency. The results recommend that the pure p-median approach for minimizing total evacuation time is suitable for medium-scale scenarios, and a weighted objective showing better performance for large-scale evacuations. Another noteworthy finding is that even a low penetration rate (e.g., 30%) of connected vehicles can provide substantial benefits in managing the online DPE, leading to better utilization of network capacity. In our analysis of vehicular communication architectures, we found that the Vehicular Fog Computing (VFC) implementation results in lower message transmission delay, with clearance time outcomes comparable to a centralized architecture deploying Vehicular Cloud Computing (VCC). This study recommends: (i) the configuration $w_{tt} = 0.1$ and $w_{ct} = 0.9$ for the SAP calculation and (ii) using VFC for the telecommunication architecture for the DPE problem.

We acknowledge that our study focused only on rerouting and shelter reallocation. Future work could extend this

framework to encompass various modes of transportation and apply it to specific types of disasters. There is also potential to delve into user behavioral reactions to evacuation orders, which could provide additional insights for enhancing evacuation efficiency.

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