Enhancing Evacuation Planning and Management through Vehicular Communication

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Short summary

The current study presents a novel framework that aims to solve dynamic population evacuation (DPE) problems, divided into two phases: planning and online evacuation management, utilizing vehicular communication. During the planning phase, an initial evacuation plan is created by dynamically solving the shelter allocation problem (SAP) to determine destination choices and dynamic traffic assignment (DTA) to choose the best path to the selected destinations. Once the evacuation process begins, the vehicular ad hoc network (VANET) enables communication between evacuees, providing an opportunity to update initial decisions in real-time using VANET under the vehicular cloud computing (VCC) architecture, which considers the dynamic evolution of the hazard and traffic congestion levels. We apply the proposed online DPE framework to a test case in Luxembourg City to benchmark with existing planning methods. The results demonstrate that the proposed framework surpasses existing solution methods by more than 10% in network clearance time. Furthermore, the proposed framework's performance is evaluated by changing the penetration rate of connected vehicles in VANET, which provides additional insight into the framework's effectiveness.
Keywords: Network evacuation, online disaster management, Telecommunication network, VANET, shelter allocation, dynamic traffic assignment.

1 Introduction

According to Supian & Mamat (2022), the population residing in areas prone to natural disasters and catastrophes faces danger as the frequency of such incidents is on the rise due to climate change, leading to an increase in human casualties and environmental destruction. Effective evacuation orders are necessary to reduce the impact of these disasters, which can adapt to changing hazards and the needs of evacuees in real-time. This can be achieved through telecommunication technology, particularly dynamic population evacuation (DPE), using vehicle-to-everything (V2X) communication Pan et al. (2016); J. Wang et al. (2019).

Determining the best evacuation plans requires considering the disaster's characteristics, as the evacuation orders' objectives may vary depending on the type of disaster. The most common goals of evacuation orders are to minimize the mean evacuation time or the total time Supian & Mamat (2022).

To determine the best and most effective evacuation plans, it is crucial to consider the characteristics of the disaster at hand. The type of disaster plays a significant role in determining the objectives of evacuation orders given to evacuees. Typical objectives of such orders include minimizing the mean evacuation or the total time Hajjem et al. (2017); Bayram & Yaman (2018); Bayram et al. (2015), minimizing the network clearance time Hsu & Peeta (2014); Lim et al. (2015); Zhao et al. (2016), and minimizing the total traveled distance Sheu & Pan (2014); Alçada-Almeida et al. (2009).

Since the 1970s, DTA models have been used to analyze long-term, and short-term planning problems Han et al. (2015). The reactive nature of both SAP and DTA limits their effectiveness during the evacuation process, i.e., they are more contributing to the planning phase compared to online management Pan et al. (2013). In this context, adding telecommunication technologies moves one step forward by providing effective methods for proactive rerouting when an emergency is predicted based on real-time traffic information. Since traffic conditions are very time-varying

during an evacuation process, updating evacuation guidance messages frequently and quickly is critical.
With the emergence of intelligent and connected vehicles, vehicular networks, particularly vehicular ad hoc networks (VANET), were introduced in 2001 as a part of ad hoc mobile networks Olariu et al. (2011); Zeadally et al. (2012). VANET have received much attention from research communities in the last few years since it opened new doors of research (e.g., on vehicle and road safety, traffic efficiency, etc.) in intelligent transportation systems (ITS) Al-Sultan et al. (2014); Hartenstein & Laberteaux (2008).
With the growing demands of drivers, vehicles require empowering themselves in processing power, computing resources, and storage space. Despite all the efforts made to satisfy all these requirements, VANET shows some disadvantages, such as the high costs generated by communication between vehicles due to the high mobility of vehicles Qin et al. (2012). To support and serve all drivers' needs and ensure their comfort and safety, we have to increase the resources of VANET. As a result, the concept of vehicular cloud computing (VCC) has emerged Gerla (2012); Mekki et al. (2017) to enable vehicles to harness the benefits of cloud computing to satisfy certain requirements. VCC concept refers to the use of cloud computing in VANET Gerla (2012); Mekki et al. (2017). VCC allows vehicles to use the cloud resources required for a particular period, representing the time they need to achieve their goals.
In this study, we realize that there is no study in the literature about considering vehicle rerouting in the DPE context. However, the replanning decision is a critical part of the evacuation process and can impact the success of the evacuation. This study proposes an online evacuation framework to solve the DPE problem. The proposed methodology can dynamically assign evacuees to the best shelter considering the current traffic conditions. Our model uses an initial plan for evacuation that represents the output of solving SAP and DTA based on Idoudi et al. (2022). In our model, we consider two phases of the evacuation process:

- Planning phase, considering the initial evacuation plan solving both SAP and DTA problems, and
- Online evacuation management phase, which employs vehicular cloud computing technology to modify the initial evacuation plan by shelter reallocation and rerouting evacuees according to the dynamics of the network and evolution of the risk due to the disaster status.

Our methodology includes rerouting evacuees based on their distance from the risky zone and the density of vehicles on the way toward the shelters, considering their communication capacity. We implement the designed framework for a city-scale real test case to validate the model and compare the evacuation results in the presence and absence of telecommunication technology. In addition, we perform a sensitivity analysis on the penetration rate of equipped vehicles that can use the VANET.
The rest of the paper is organized as follows. In the next section, we present the framework to solve the evacuation problem. 3 is dedicated to presenting the case study and optimization scenarios. We discuss the results in 4 and present the concluding remarks in 5.

2 Methodology

The resolution of the DPE problem through our model involves two primary steps: constructing an evacuation plan by addressing the issues of SAP and DTA and providing real-time guidance to reroute vehicles as necessary in congested areas. In this section, we will provide a detailed account of the sequential process for executing each step of our formulation.
To provide an initial plan for planning purposes and in the dynamic setting, we adopt the methodology used in Idoudi et al. (2022). However, we aim to modify the planning model to adopt a stochastic user equilibrium (SUE) instead of a pure user equilibrium (UE) solution. We introduce a network layer for vehicular communication to capture network congestion for the online evacuation management phase. Using this communication network, we can re-plan evacuation routes and shelter locations during the evacuation process and provide real-time instructions to evacuees. We employ a cloud computing scheme to implement this methodology, which is advantageous due to its low implementation cost compared to fog or edge architectures, as noted in Gaouar & Lehsaini (2021).
Figure 1 depicts the proposed methodology of our study in the Plan-Do-Check-Act (PDCA) diagram format. The steps of the framework are detailed as follows:

Table 1: The steps of the methodological process described in Figure 1

Start:	
Step 1.	**Initial evacuation plan:** This step corresponds to solving the multi-level DTA and SAP to generate an evacuation plan. The SAP is going for system optimal (SO), and the DTA is formulated under SUE Idoudi et al. (2022).
Plan:	
Step 2.	**Simulation for the current time step and set t=t+1:** This step corresponds to simulating the evacuation process that could be the same as proposed by the plan, or new events could occur due to several decisions made by evacuees in the previous time step. We have also to increment the simulation time index.
Step 3.	**Data collection:** This is the first part of our cloud computing architecture wherein each vehicle (node) broadcasts data messages, using their OBU, to RSUs that send it to the cloud server.
Step 4.	**Aggregation:** In this step, we aggregate messages from different RSUs. An evacuee could be connected to more than one RSU and broadcast his message to all RSUs in his range of communication
Do:	
Step 5.	**Risk update:** In this step, we update the risk based on data from step 3. The considered risk consists of two main components: the vehicle's distance from a hazardous area and the congestion levels of the vehicle's location.
Step 6.	**Prediction of new travel times:** In this step, the travel time of edges might change according to the risk and congestion evolving by Step 4. In this step, we use a prediction model to predict new travel times.
Check:	
Step 7.	**Check for replanning:** This step is for deciding whether a user i is concerned by the rerouting process or not. For user i we estimate edge density, including the road speed and traffic density based on the Greenshield model Pan et al. (2016).
Step 8.	**Evacuees selection for replanning:** This step corresponds to selecting vehicles that to go to another safe destination or have to be rerouted before getting inside a congested edge (road). For shelter reallocation, we select vehicles if there is congestion in front of their original destinations, and the server asks them to go to a less congested destination.
Act:	
Step 9.	**Shelter reallocation and rerouting:** In this step, we prepare a message to the targeted users to ask them to reroute to the path with the current shortest travel time having their planned shelter as a safe destination.
Step 10.	**Sending notification to evacuees:** The step represents the second essential part of our cloud computing scheme where the cloud server sends its decisions to RSUs that forward the results to vehicles to react accordingly.
End:	
Step 11.	**Check stopping condition:** This step checks if all the demand is evacuated, go to 12 otherwise go to 2.
Step 12.	**End of the simulation:** In this step, we end the simulation of the evacuation process,
Step 13.	**Result calculation :** In this step and after ending the simulation, all results are then calculated in terms of packet delay ratio, end-to-end delay, and other measures.

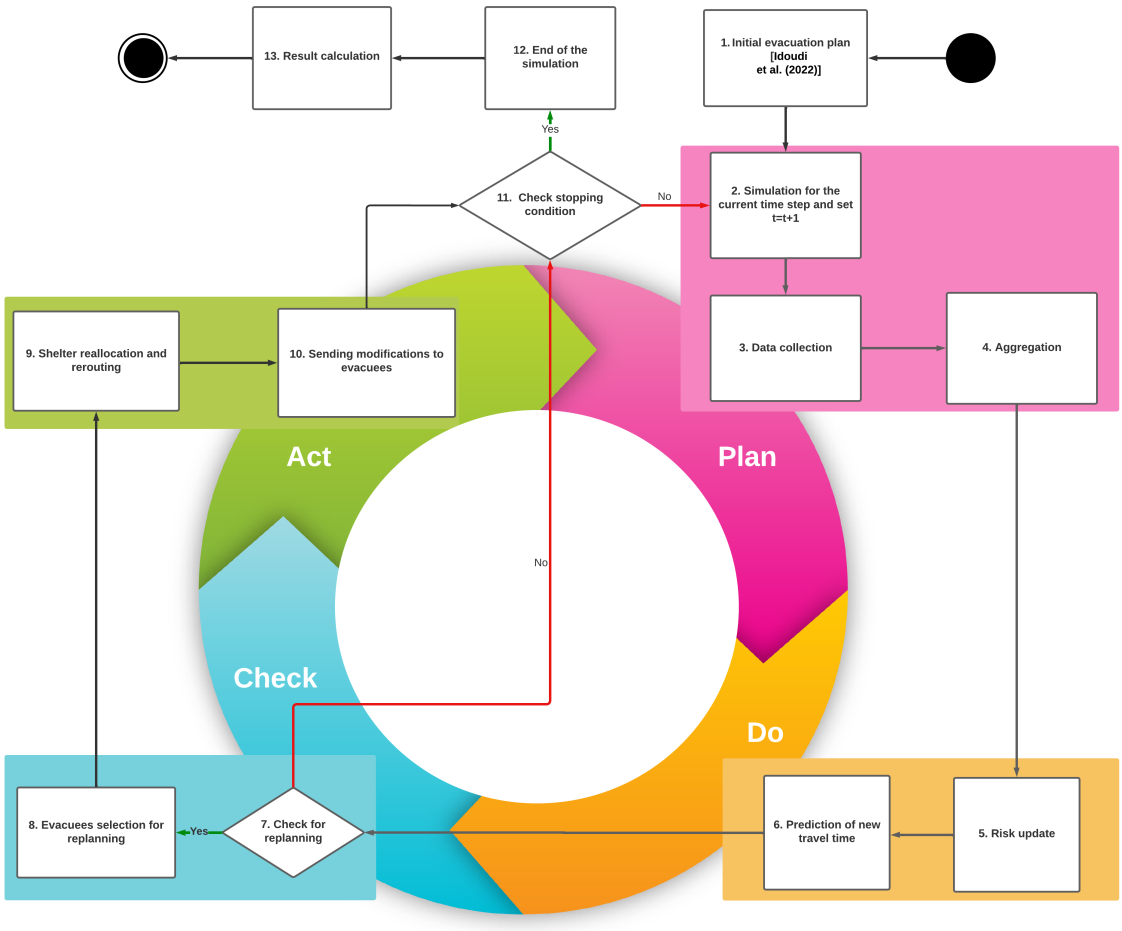


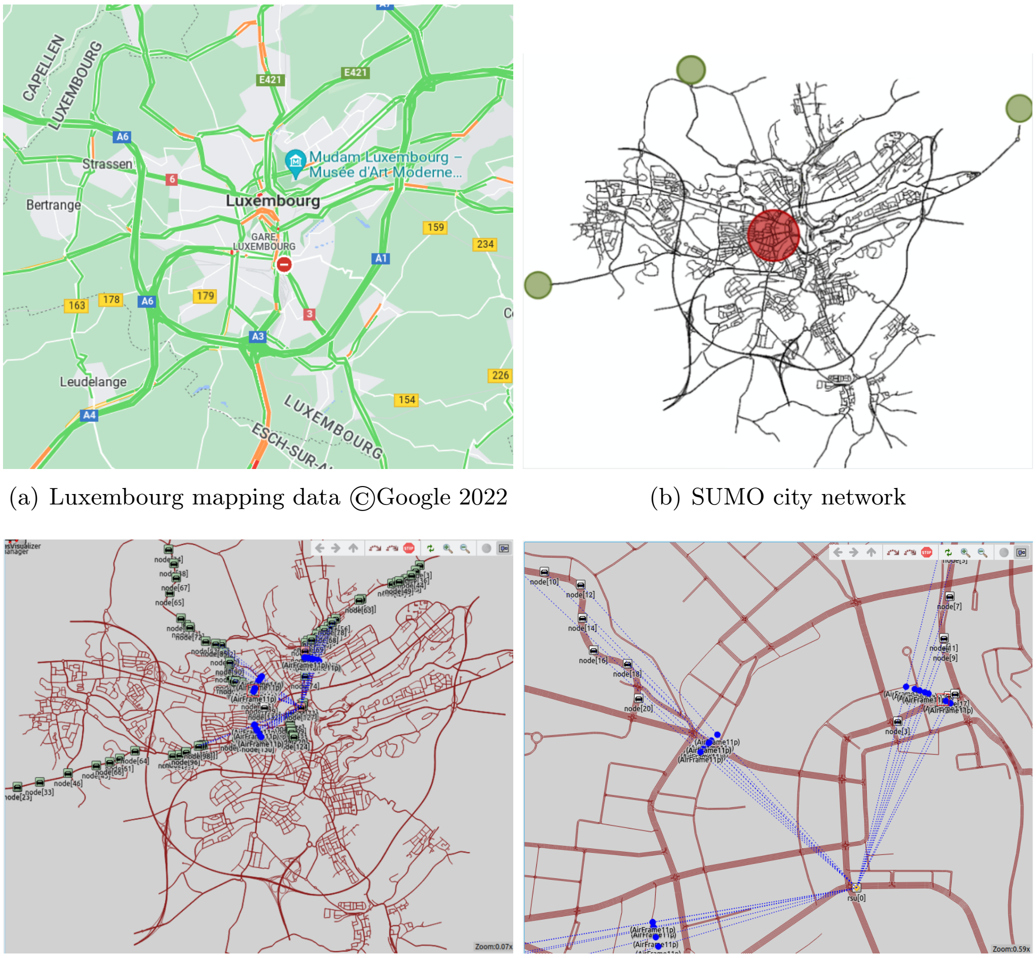
Figure 1: flowchart of the solving the DPE problem

3 Numerical experiments

In the preceding section, we introduced our framework for addressing the online DPE problem. This section will apply the methodology to an actual network to validate the proposed solution. We will begin by describing the selected test case, followed by discussing the experimental design.

Case study

We implement our proposed solution on a realistic network of Luxembourg city. The LuST scenario provides the network. We have used a laptop with 1.7 GHz. and 16 GB of RAM to generate all the results. We employed a solution method using the simulation-based DTA. For this, we performed all simulations by SUMO simulator, and we calculated the C-logit model and the travel time prediction by SUMO Lopez et al. (2018). In addition, we used ILOG CPLEX version 12.9 to implement the SAP model and solve it. To simulate the scenario considering vehicular communication, we used the Veins/Omnet++ simulator and a cloud computing architecture based on works done in Z. Wang et al. (2020).
We applied our methodology to the realistic network of Luxembourg city Codeca et al. (2015). Please refer to Idoudi et al. (2022) for the network and evacuation scenario characteristics.
Figure 2(a) presents the evacuation network map of Luxembourg. Figure 2(b) presents the real network of Luxembourg with the size of 155.95 km^2 and the traffic network graph considered by Veins for dynamic simulation. We examine a hypothetical threat in the center zone affecting people of that region colored in red in Figure 2(b). We do not assume any super source nodes (risky nodes) in this study. Four origin nodes are considered evacuation sources in the risk zone (see Figure 2c in Idoudi et al. (2022)). Vehicles carrying people should be evacuated to safe destinations (shelters), colored in green in Figure 2(b), and placed at the border of the network. We set the duration of each planning departure time interval (η) to 20 minutes for the simulation, considering the network's size. The demand at each node is 200 vehicles at each period. We have selected four



(a) Luxembourg mapping data ©Google 2022 (b) SUMO city network

(c) OMNET++ communication network (d) Communication between nodes in VANET

Figure 2: Vehicular communication map of Luxembourg city

origin nodes and four shelters, each with a capacity to hold 1500 evacuees. Therefore, the total demand is 600 vehicles per origin for the planning horizon (H). Figure 2(c) shows the vehicular communication network in the OMNET++ simulator. Figure 2(d) illustrates the message exchange process between vehicles and the network infrastructure.

Study optimization scenarios

In this study, we design four scenarios to investigate the impact of planning and online orders on the DPE problem. The scenarios are detailed below:

- **Scenario P+C: Scenario with both planning and vehicular communication:** This scenario follows the proposed framework (demonstrated in Figure 1).
- **Scenario P: Scenario with the initial plan only:** This scenario illustrates the case of just planning for evacuation without any communication between vehicles or vehicles to RSUs. It means that we do not reroute evacuees during the evacuation process; they just follow the initial plan.
- **Scenario C: Scenario with vehicular communication only:** This scenario is the same as Figure 1) except in step 1 where evacuees consider the nearest shelter and choose their routes following the SUE.
- **Scenario N: Naive scenario without any optimal plan and vehicular communication:** This scenario represents the case where the system operators do not provide guidelines for evacuees. It means the evacuees choose the nearest shelter and their routes following the SUE.

4 Results

In this section, the results for the four mentioned scenarios were executed on the synthetic demand profile. Table 2 presents the results for the four scenarios. The results show a significant improvement in the quality of the final solution obtained by scenario P+C wherein we used both planning and online guidance models. For instance, the reduction of more than 18 minutes (39%) in the network clearance time compared to the naive scenario. Also, there is an improvement of more than 3 minutes (10%) between scenario P+C and scenario P. Results show that scenario P represents the second-best solution. The comparison between scenarios P+C and P proves that new orders handling new events not expected in planning create a more successful evacuation operation.
Besides, scenario C provides a better solution than scenario N, meaning that using the telecommunication network can improve the evacuation solution, even without any planning phase. This observation could prove the effectiveness of online communication and highlights the importance of giving new orders to evacuees to revise their route choice during the evacuation process. Inspecting the result for scenario P and scenario C, we can observe that planning contributes more than telecommunication during the evacuation operation. One of the reasons behind this observation is that in scenario C the shelter allocation was done without considering the congestion level. We have monitored scenario C to have a better view and understand more of the effect of online evacuation guidance. We observe that allocating all users to the same nearest shelters in all evacuation operation generate congestion that cannot be escaped even by using online vehicle rerouting. That is why different shelters, like in scenario P in each state, will ensure that we assign evacuees to the closest destinations in terms of time-dependent shortest path and not distance measure.

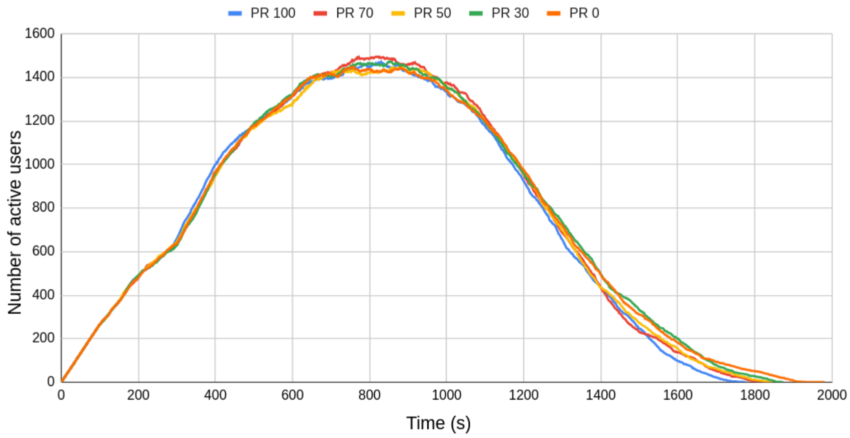
Table 2: Performance metrics

Metrics / Scenario	P+C	P	C	N
Network clearance time(s)	1775.00	1980.00	2765.00	2835.0
Mean evacuation time(s)	1071.54	1093.70	1407.92	1447.61
Average travel delay (ATD)	205.47	220.62	341.63	349.78
Average evacuation delay (AED)	241.32	366.65	366.65	392.12

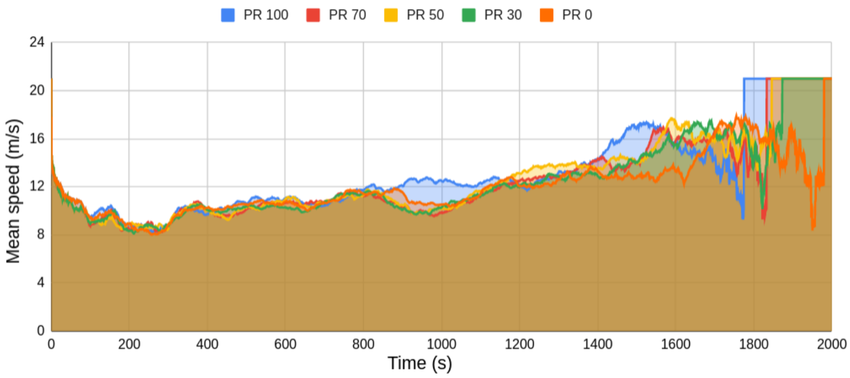
The decrease in mean evacuation time in 2 shows that the online DPE improves the evacuation solution. Compared to the second best, the proposed model used in scenario P+C generates better ATD for evacuees with more than 6% of reduction. The improvement is remarkable for AED (34%). We mention that including telecommunication network gives us some errors and delays in sending and receiving messages. In both cases, P+C and C, we have around 205.30 ms for the end-to-end delay and PDR around 74%.

Sensitivity analysis on penetration rate

The sensitivity analysis on the penetration rate is performed on the Luxembourg city map. Assuming that 100% of the evacuees are using connected vehicles is not currently realistic, and it can be reachable in the future. That is why we should consider multiple penetration rate values. In the case of x% of penetration rate, we select connected vehicles with a random distribution. Only this x% is sending positioning information and receiving online orders. Thus, the cloud server sees and guides only this x% of the vehicles.
Figure 3(a) illustrates the change in the number of vehicles evacuating in the network for five scenarios. The curves shown in this figure represent different penetration rate values.
Figure 3(b) follows the results of the distribution of accumulation of users in the network. In addition, Figure 3(b) depicts the evolution of the mean speed in the evacuation operation. The maximum network speed limit is the free-flow speed (21 m/s) attained when the network does not have any vehicles. The network speed illustrated by Figure 3(b) shows that having a 100% penetration rate is the fastest curve by arriving at the free-flow speed in the shortest time. Also, the figure presents the result of the mean speed variation of other penetration rates showing that there is not a huge difference between 70% and 30% penetration rate on network clearance time (the arrival to the free-flow speed). Figure 3(b) shows that adding the communication layer, even with different penetration rates, positively affects the evacuation process. It means that the online solving of DPE uses the network's capacity better than just planning. We conclude that using 30% of the penetration rate is more realistic, and its results are comparable to having 100%.



(a) Number of active users in the network variation



(b) Network mean speed variation

Figure 3: Performance measures variation over different penetration rates

5 Conclusions

The timely evacuation of affected populations during a disaster is critical in reducing the overall impact of the event. In this paper, we focus on the dynamic population evacuation (DPE) problem and propose a framework for effectively modeling and optimizing the evacuation process to save as many lives as possible in a faster and more efficient manner. We divide the evacuation problem into two parts: the first part involves creating an optimal evacuation plan that considers dynamic shelter allocation and traffic assignment, while the second part involves considering new orders for the online guiding system.

Our framework captures the dynamics of the evacuation process by using a traffic simulator to build an evacuation planning process to determine shelters and routes. We then perform an online management procedure during the evacuation, allowing vehicles to send and receive data to update their routes. To achieve this, we use a cloud computing architecture comprising vehicles, roadside units (RSUs), and a distant cloud server.

We apply our methodology to the real-world networks of Luxembourg and show that our proposed model outperforms the model with only evacuation planning by reducing the network clearance time by more than 10% in the medium-scale network of Luxembourg. Our framework also effectively improves network capacity in terms of speed even at a low penetration rate of connected vehicles. We consider only rerouting and shelter reallocation to manage the online evacuation process in this study, and currently, we are working on a real large-scale test case of evacuation in California state in USA. We also plan to perform a sensitivity analysis on the shelter allocation objective to search for the best objective that minimizes more the clearance time measure. As future work could consider departure times before and during the evacuation, as well as the behavioral reactions of users to evacuation orders. We also aim to extend our framework to include other modes of transport, such as buses. Additionally, we aim to improve our framework by implementing a more accurate travel time predictor.

References

Alçada-Almeida, L., Tralhão, L., Santos, L., & Coutinho-Rodrigues, J. (2009). A multiobjective approach to locate emergency shelters and identify evacuation routes in urban areas. *Geographical analysis*, *41*(1), 9–29.

Al-Sultan, S., Al-Doori, M. M., Al-Bayatti, A. H., & Zedan, H. (2014). A comprehensive survey on vehicular ad hoc network. *Journal of network and computer applications*, *37*, 380–392.

Bayram, V., Tansel, B. Ç., & Yaman, H. (2015). Compromising system and user interests in shelter location and evacuation planning. *Transportation research part B: methodological*, *72*, 146–163.

Bayram, V., & Yaman, H. (2018). Shelter location and evacuation route assignment under uncertainty: A benders decomposition approach. *Transportation science*, *52*(2), 416–436.

Codeca, L., Frank, R., & Engel, T. (2015). Luxembourg sumo traffic (lust) scenario: 24 hours of mobility for vehicular networking research. In *2015 ieee vehicular networking conference (vnc)* (p. 1-8). doi: 10.1109/VNC.2015.7385539

Gaouar, N., & Lehsaini, M. (2021). Toward vehicular cloud/fog communication: A survey on data dissemination in vehicular ad hoc networks using vehicular cloud/fog computing. *International Journal of Communication Systems*, *34*(13), e4906.

Gerla, M. (2012). Vehicular cloud computing. In *2012 the 11th annual mediterranean ad hoc networking workshop (med-hoc-net)* (pp. 152–155).

Hajjem, M., Bouziri, H., Talbi, E.-G., & Mellouli, K. (2017). Intelligent indoor evacuation guidance system based on ant colony algorithm. In *2017 ieee/acs 14th international conference on computer systems and applications (aiccsa)* (pp. 1035–1042).

Han, K., Szeto, W., & Friesz, T. L. (2015). Formulation, existence, and computation of boundedly rational dynamic user equilibrium with fixed or endogenous user tolerance. *Transportation Research Part B: Methodological*, *79*, 16–49.

Hartenstein, H., & Laberteaux, L. (2008). A tutorial survey on vehicular ad hoc networks. *IEEE Communications magazine*, *46*(6), 164–171.

Hsu, Y.-T., & Peeta, S. (2014). Risk-based spatial zone determination problem for stage-based evacuation operations. *Transportation research part C: emerging technologies*, *41*, 73–89.

Idoudi, H., Ameli, M., Van Phu, C. N., Zargayouna, M., & Rachedi, A. (2022). An agent-based dynamic framework for population evacuation management. *IEEE Access*, *10*, 88606–88620.

Lim, G. J., Rungta, M., & Baharnemati, M. R. (2015). Reliability analysis of evacuation routes under capacity uncertainty of road links. *Iie Transactions*, *47*(1), 50–63.

Lopez, P. A., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.-P., Hilbrich, R., ... Wießner, E. (2018). Microscopic traffic simulation using sumo. In *The 21st ieee international conference on intelligent transportation systems.* IEEE. Retrieved from https://elib.dlr.de/124092/

Mekki, T., Jabri, I., Rachedi, A., & ben Jemaa, M. (2017). Vehicular cloud networks: Challenges, architectures, and future directions. *Vehicular Communications*, *9*, 268–280.

Olariu, S., Khalil, I., & Abuelela, M. (2011). Taking vanet to the clouds. *International Journal of Pervasive Computing and Communications*, *7*(1), 7–21.

Pan, J., Popa, I. S., & Borcea, C. (2016). Divert: A distributed vehicular traffic re-routing system for congestion avoidance. *IEEE Transactions on Mobile Computing*, *16*(1), 58–72.

Pan, J., Popa, I. S., Zeitouni, K., & Borcea, C. (2013). Proactive vehicular traffic rerouting for lower travel time. *IEEE Transactions on vehicular technology*, *62*(8), 3551–3568.

Qin, Y., Huang, D., & Zhang, X. (2012). Vehicloud: Cloud computing facilitating routing in vehicular networks. In *2012 ieee 11th international conference on trust, security and privacy in computing and communications* (pp. 1438–1445).

Sheu, J.-B., & Pan, C. (2014). A method for designing centralized emergency supply network to respond to large-scale natural disasters. *Transportation research part B: methodological*, *67*, 284–305.

Supian, S., & Mamat, M. (2022). Insurance as an alternative for sustainable economic recovery after natural disasters: A systematic literature review. *Sustainability*, *14*(7), 4349.

Wang, J., Shao, Y., Ge, Y., & Yu, R. (2019). A survey of vehicle to everything (v2x) testing. *Sensors*, *19*(2), 334.

Wang, Z., Zheng, S., Ge, Q., & Li, K. (2020). Online offloading scheduling and resource allocation algorithms for vehicular edge computing system. *IEEE Access*, *8*, 52428–52442.

Zeadally, S., Hunt, R., Chen, Y.-S., Irwin, A., & Hassan, A. (2012). Vehicular ad hoc networks (vanets): status, results, and challenges. *Telecommunication Systems*, *50*(4), 217–241.

Zhao, X., Ren, G., & Huang, Z.-f. (2016). Optimizing one-way traffic network reconfiguration and lane-based non-diversion routing for evacuation. *Journal of Advanced Transportation*, *50*(4), 589–607.