Graphical Abstract

PEMAP: An Intelligence-based Framework for Post-Event Management of Transportation Systems

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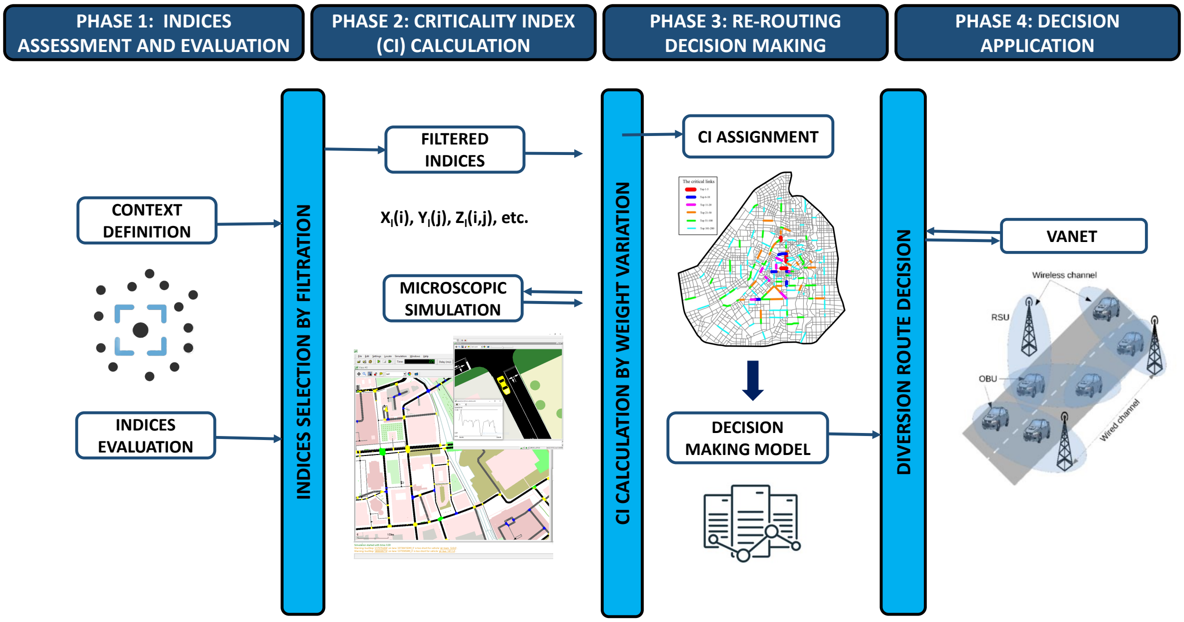

Highlights

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- An intelligence-based framework for redirecting traffic after disturbances.
- The proposed approach is based on integrating the different fields of geographic information systems, social networks, traffic simulations, data mining and artificial intelligence, as well as vehicular ad-hoc networks.
- Based on geographical information, historical data, and simulation results, intelligence is extracted and utilized to make informed decisions.

PEMAP: An Intelligence-based Framework for Post-Event Management of Transportation Systems

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ABSTRACT

In recent years, transportation systems and communities have faced major disruptions, such as heavy traffic, accidents, natural disasters, and malicious acts. Managing these disruptions and their impact on transportation systems is crucial. This paper proposes PEMAP, Post-Event MAnagement of transPortation systems, an intelligence-based framework for redirecting traffic after disturbances. PEMAP aims to ensure the swift recovery of network services despite various disruptions, benefiting transportation systems and communities. It is composed of four phases: indices selection and evaluation, criticality index calculation, diversion route decision making, and decision application. Relevant indices are evaluated and calculated into one criticality index using microscopic simulation. An intelligent model for vehicular re-routing, considering the criticality index, is then introduced. In the last phase, Vehicular ad-hoc networks (VANETs) is used to facilitate communication and implementation of rerouting decisions. The proposed implementation uses the Veins framework along with Python and C++ programming languages.

1. Introduction

Communities rely on five essential services and functions to thrive: transport services, telecommunications, power, water services, and community organizations. However, transportation services are the foundation of essential infrastructures since they grant access to other services . The organization and operation of societal and infrastructure systems are significantly impacted by transportation. A transportation network is the structure that allows movement and flow to and from different locations to perform daily life activities. With continued population growth, the need for transportation services is also growing. However, transportation systems are highly susceptible to regular minor as well as unexpected major disruptions. Transportation networks experience a wide variety of relatively transient disruptive occurrences every day, including partial flooding, poor visibility, weather-related traction difficulties, and road degradation . Additionally, these networks may experience unforeseen events like floods, earthquakes, bridge failures, and even malicious acts. These events leave serious impacts on the transportation network and the whole community as a result.

1.1. Problem Statement

Different events affect the network on different scales depending on the type of the event, its timing, and its location. For example, a 2-car accident on a minor road may partially block this road but otherwise will not really affect the functionality of the whole network. However, a multiple-car accident on a critical link (i.e bridge) at peak hour will certainly gravely affect the transportation network. Furthermore, critical links that lead to emergency spots (hospitals, fire stations, police stations, etc) or community spots (nurseries, schools, community halls, etc) if blocked, cause further panic in the community. Accordingly, critical links are links of utmost importance of whose blockage or certain level of disturbance gravely affects the whole network or a considerable part of it. Disruption of such links causes major stress on the whole network whether by blocking completely the movement from one location to another or by causing major panic.

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Data from prior traffic disturbance incidents has demonstrated that transportation authorities recovery and intervention strategies lacked predictive consequence insights ahead [1]. For example, the I-35W bridge collapse over the Mississippi River in Minneapolis on August 1^{st}, 2007, caused a sudden cut off of the daily commute for around 140,000 trips made seriously hindering the network flow pattern . Life losses and injuries were disastrous, and the monetary, time, and business losses were massive as well. Furthermore, the resulting panic-induced-changes in patterns and ignorant-rerouting caused even more damage by generating more congestion and consequent losses. In such events, the first reaction of people is to just use the closest exit to get away from the disruption, so they head for the other major road that leads to their destination. However, with the blockage of one major path, the path left will become so congested it will be blocked as well disconnecting the network even more. This is called, in the literature, as “cascading effect" [1]. Therefore, it is essential to apply a proper post-event traffic management system that insures the network resilience, particularly in the event of difficulties like high traffic volumes and significant natural disasters .

The framework PEMAP is our proposed solution for intelligent management of traffic post-disruptive-events. This solution is based on extracting important information from the urban road network (URN) and then using that knowledge to take intelligent decisions later at times of events to restore the resilience of the network.

1.2. Resilience Analysis in Transportation Systems

The study of proper swift recovery from disruptive events falls under what is called, in the literature, as “resilience analysis". Resilience is defined differently in the literature depending on the object of interest and the studied use case. In transportation studies, resilience is commonly defined as the ability of the network to swiftly and efficiently absorb the effects of disruptive events and restore functionality.Most work goals while performing resilience analysis are: impact reduction and swift recovery. However, despite defining resilience in a similar way in Urban Road Network (URN) analysis, different works evaluate and study resilience differently. The performance measurements, language, methodology, and even underlying analytical assumptions utilized in network disturbance studies may differ wildly based on the application, problem area, and the specific research objectives, according to existing research.

URN Resilience evaluation differs from one use case to another as it depends on the specific aspect of resilience considered in the work. This variation hinders the ability to perform a proper comparison between different approaches. Despite that, multiple works in the literature like in [2]have attempted to perform a state of art study to cover the different approaches taken and parameters used. In [2], the authors identify and classify the different resilience indices used in the literature to evaluate transportation system resilience. They classified them according to each research’s objective, type of transportation network (application domain), type of disruptive event, as well as the methodology used.

In our work, we explored the different concepts of URN resilience analysis and the different indices, methods, and evaluation parameters proposed in the literature as well as the different actions considered after acquiring this knowledge base. As a result, we were able to properly formulate our objective and propose an intelligent framework to redirect traffic post disturbances and improve URN resilience.

1.3. Contribution

In this work, we focus on post-event traffic management with the following main goal: after the occurrence of an event that affects the traffic, we want to redirect traffic in a way that avoids the blockage of what we evaluated as “critical" links. We define “criticality" of roads as a parameter that measures how crucial the link is to the functionality and efficiency of the whole network. A road with high criticality should be dealt with care so as to avoid it getting blocked. For that reason, our evaluation methods focus on the efficiency of our method in avoiding blockage and congestion on critical roads. Granted, directing traffic to mainly avoid the blockage of critical links might cause the total trip times to increase. It will, however, ensure the connectivity and robustness of the network so that no part of the network is cutout in time of emergency. Hence, the sides of resilience that we are focusing on in our study are mainly robustness and connectivity.

The novelty of our work is integrating the different fields of geographic information systems (GIS), graph theory, traffic simulations, data mining and artificial intelligence, as well as vehicular ad-hoc networks. We propose a framework to improve transportation systems by intelligently redirecting traffic post events to restore functionality. In this framework, we perform analysis of the network to come up with an index that signifies the criticality of different links in a URN. This index is then used to make informed rerouting decisions to avoid further bottle-neck scenarios as well as facilitate the flow of traffic post events. In our study, we are targeting link criticality because we believe that this value is crucial to take the proper decisions to divert traffic from bottle-necking important roads that will lead to possible disconnection of the network.

We propose an intelligence-based framework for post-event management of transportation systems (PEMAP) as an end-to-end solution for road network analysis, decision making, and rerouting post-disturbances. The framework is depicted in Figure 1 and is composed of four phases:

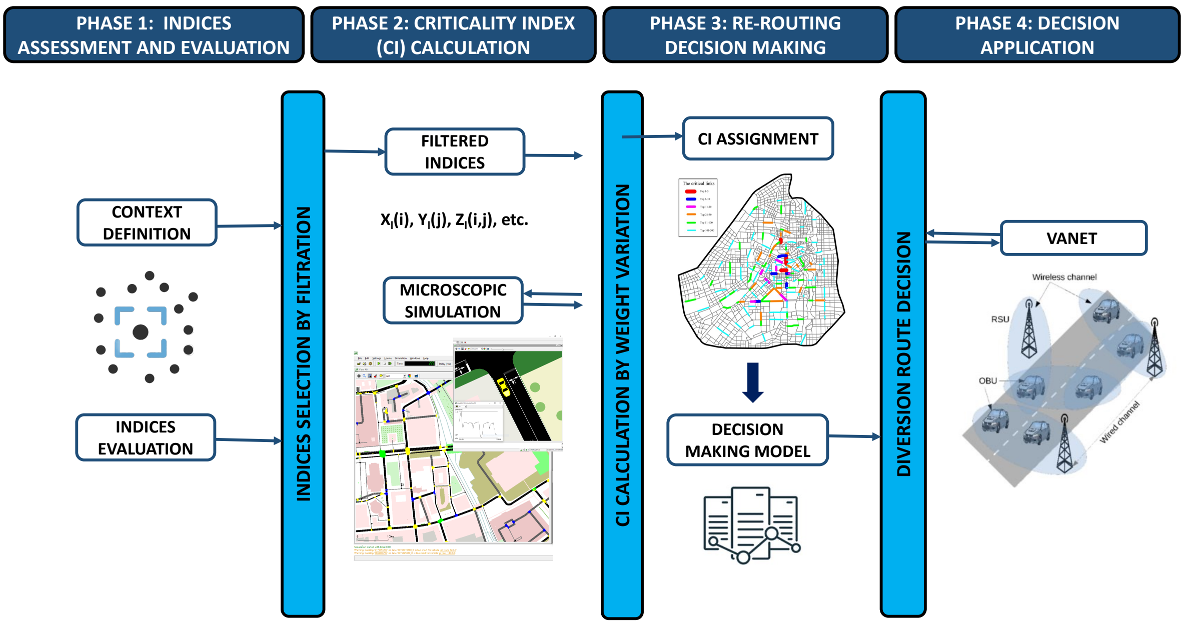

Figure 1: PEMAP architecture.

- *Indices Assessment and Evaluation*: in this phase, we study the different indices, evaluation parameters, and methods proposed in the literature, and we perform a comparative analysis to choose the ones that most fit our specific use case and application context to assess the links of the network.
- *Criticality Index (CI) Calculation*: to calculate our criticality index, we combine the different indices with proper weights using microscopic simulation. Then, in order to get the right weights for this index, we study the correlation between the CI for each road and the negative effect of removing this road using stress testing by changing the weights each time.
- *Re-routing Decision Making*: after obtaining the criticality index for each road, we propose a data mining-based model to redirect traffic after disruptions by diverting it from blocking critical roads.
- *Decision Application*: using VANETs, we simulate the application of the proposed model to improve the functionality restoration time of urban networks post-events.

The remainder of this paper is organized as follows: Section 2 presents the different phases of PEMAP framework with an overview of the different works in the literature within each phase. Section 3 presents an evaluation of our proposed framework with respect to other work in the literature as well as the experiments done to validate the work. Section 4 concludes the paper and gives directions for future work.

2. Our Framework: Post-Event MAnagement of transPortation systems (PEMAP)

Traffic redirection decisions have to take into consideration the structural as well as the dynamic states of the different links in an urban network. Roads, bridges, and tunnels, as well as other road network-related facilities, are crucial elements of the infrastructure that enable the local community business activities . Disturbances on these links are contagious-causing further network flow impediment across the network. These disruptions have grave effects on the functionality of the whole network. Hence, taking into consideration this criticality of roads, intelligent and informed decisions can be made in order to avoid further disturbance of the network. For that reason, we propose Post-Event MAnagement of transPortation systems (PEMAP) framework which is composed of the four previously mentioned phases and described in this section.

2.1. Indices Assessment and Evaluation

In the first phase of our work we study the measurement indices proposed in the literature that evaluate links based on their criticality or importance. Different approaches and views are implemented to evaluate this index. The goal from this phase is to make use of the previously proposed approaches and views. Deep research and analysis of the different indices have to be performed to select the indices for our specific application context. To achieve this, we have to go through two steps. First, we have to provide an exact definition for criticality which is done through specifying our application context. Second, based on that, we can filter and evaluate the indices proposed in the literature to select the ones that fit our line of work.

2.1.1. Context Definition

Since there is no one general definition that was used in the literature for criticality, there is a large number of works that were done proposing criticality indices. For which reason we found it mandatory to have this step for context definition to specify the exact context of the criticality index to be calculated in order to define the scope of the work to be done.

In our work, the context and scope of the criticality index is as follows: it aims to highlight **critical** roads which are the most important and whose disruption greatly affects the whole network. For example, roads like bridges connecting two parts of the city, major roads or highways, popular roads in city center and so on. This criticality index does not aim on the other hand to highlight the vulnerability or susceptibility of roads and only their importance.

During our research, we found criticality to be even considered synonymous in some works with “vulnerability", and both were used interchangeably widening even more our pool of research. However, in our work, we make a clear distinction between criticality and vulnerability analysis as we are focusing only on the former.

Most works in the literature studying the vulnerability of roads focus on the *inherent* characteristics, which is mainly the *susceptibility* of this road to disruptive events. In the comprehensive review of resilience modeling concepts [2], the authors define it as the “susceptibility of critical components". Their definition and the works they mentioned combines the two concepts of risk (vulnerability) study and criticality (importance) study under one title, e.g. vulnerability. In the work of [3], the authors highlight this “dual characteristic" and argue that it should be decomposed into two concepts; *weakness* and *importance*.

In Table 1, the difference between criticality analysis and vulnerability is highlighted by differentiating the focus, application field, and evaluation of each of them. Both studies are crucial however depending on the context and focus of the work, one concept or the other is studied as it is more relevant.

Table 1
Difference between criticality and vulnerability.

Index	Focus on	Application Field	Evaluation
Vulnerability	Risk	Inherent	Weakness Study
Criticality	Importance	Post-event	Link Disruption Study

In our work, our focus is specifically the study of criticality as in the *importance* of the link with respect to the performance and operability of the network post disruptive events. From this importance perspective, a link is considered more critical the graver the consequences of its disruption are.

2.1.2. Indices in Literature

Different indices/measures were used in the literature. The most common indices mentioned in literature that we have come across are summarized in Table 2. Most of the works in the literature focus on betweenness centrality (BC) index [4, 5, 6, 7].Additionally, works like [5, 6]studied BC index in its unweighted and weighted forms. In [5], the authors explore six different types of weights: (1) unweighted, (2) traffic flow, (3) link length, (4) reciprocal capacity, (5) congestion, and (6) travel-time. Similarly, the work [6] explore four different types of weights for BC: (1) unweighted, (2) travel-time weighted, (3) unweighted on entry/exit nodes only, and (4) travel-time weighted from entry to exit nodes only. The work emphasizes the necessity of combining standard static topological analysis with methods for dynamic stress-testing that take demand into account so they consider demand as well to calculate their importance metric. Other works combined BC with other non-graphical indices. The work [4] combined betweenness centrality index with link length, clustering coefficient, degree, and road network connectivity indices. In [8] the authors studied weighted BC index with flow index. The work [7] studied in addition to BC and flow, length, link capacity, and congestion as well.

Table 2
Indices in Literature.

Index/Measure	Ref.
Flow	[9, 3, 7, 8, 10]
Exposure	[3]
Length	[4, 7]
Importance	[6, 3]
Road network connectivity	[4, 10]
Betweenness Centrality (BC)	[4, 5, 6, 7]
Clustering coefficient	[4]
NRI	[10, 8]
Degree	[4]
Congestion	[7]
Link capacity	[7, 10]
Weighted BC	[5, 6, 8]

Conversely, other works didn't consider BC at all [9, 10, 3, 11, 8]. Works like [9]consider only flow index while [3] considers demand as well.

2.2. Criticality Index (CI) Calculation

Several criticality indices have been proposed in the literature and are presented in Table 3. Despite some of these works having a different naming for criticality (i.e. vulnerability), their definitions conform with what we previously defined in our context definition as criticality. Two perspectives stood out for us during our research. The first perspective considered the impact of the link disruption in terms of the travel cost [10, 3, 7]. The second perspective evaluated criticality of a link depending on the analysis of diversion routes [9, 1].

The authors in [10] believed that a fundamental change in network design is crucial, so they presented a system-wide approach and defined a new measure, network robustness index (NRI), for criticality analysis which represents the change in *simulated* travel-time cost resulting from the closure of a link. In the work of [3], four metrics were derived based on the change in the *generalised* travel cost. In [7], however, the authors studied two *aggregated* indices by integrating various vulnerability indices, physical-based or operational-based, and weighting them using stress tests. On the other hand, the authors of [9] considered that a non-critical link in normal conditions may become very critical when neighboring links are disrupted and flow is redirected to it. For that reason, they introduced flow and impact based measures to study the importance of a link as an alternative route. Similarly, in [1], supporting vulnerability was introduced which represents the criticality of a link as one that allows reconnecting the network after the disruption of a major link. They used this measure in their calculation of segment vulnerability index which is the criticality of the link based on the availability of diversion routes. Their main concern was to avoid “cascading effect" post disturbances and to reach equilibrium flow in such situations.

Indeed, both perspectives are interesting to us because we are targeting critical links as critical in their ownselves in normal conditions as well as post disturbances as important diversion routes. In our work, we explore, analyze, and evaluate the indices used in literature in order to filter the most prominent indices and combine them into on criticality index using microscopic simulation..

Table 3
Criticality Indices in Literature.

Ref.	Year	Criticality Index	Measures	Context	Data
[10]	2006	• Network Robustness Index (NRI)	• Traffic flow • Traffic capacity • Network connectivity	Metric that evaluates difference in travel-time cost caused by rerouting traffic in the system post a link's disturbance	Three hypothetical road networks, each with different levels of connectivity
[3]	2006	• Demand weighted importance • Unsatisfied demand importance • Demand-weighted exposure • Unsatisfied demand exposure	• Travel cost • Travel demand	Operational measures to study link importance and site exposure derived based on the increase in generalised travel cost when links are closed	Network and travel data of northern Sweden as extracted from the Swedish national travel demand model system SAMPERS (2001)
[9]	2010	• Flow-based redundancy importance • Impact-based redundancy importance	• Net amount of rerouted flow • Total delay incurred when the link itself is closed	Metrics to study importance of road links as backup alternatives	Swedish national travel demand model system SAMPERS (2001)
[1]	2022	• Segment vulnerability index • Supporting vulnerability	• Shortest path distance • Diversion path distance	Indices for measuring network vulnerability when facing disruptions based on the availability of diversion routes that could allow reconnecting the affected segment	Malaysian Peninsular from OSM data (static)
[7]	2014	• Physical-based aggregated vulnerability index • Operational based aggregated vulnerability index	• Link capacity, • Traffic flow, • Link length, • Link free flow and • Traffic congestion density	Aggregated indices by combining different vulnerability attributes and assigning weights by stress testing	Synthetic road transport network of Delft city

2.2.1. Filtered Indices

Figure 2 visualizes the distribution of the different indices mentioned in the literature reviewed which we went over in the previous phase. The indices filtered are the indices chosen by us depending on the context explained and the criticality index definition. For our work, we choose to study the most prominent indices in the literature which are highlighted in the distribution pie chart:

- **Betweenness Centrality (BC) Index:** measures the importance of a specific link in facilitating traffic flow between pairs of nodes in a transportation network. Thus, it can identify links that act as critical connectors between different regions or nodes. While the traditional edge betweenness centrality considers unweighted networks, there is also the option of calculating a weighted betweenness centrality, which takes into account the weights or costs associated with the links. Indeed, the betweenness centrality of a link can be calculated using graph theory algorithms.Accordingly, the BC formula can be expressed as follows:

$$\text{Betweenness Centrality} = \sum_{s \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{1}$$

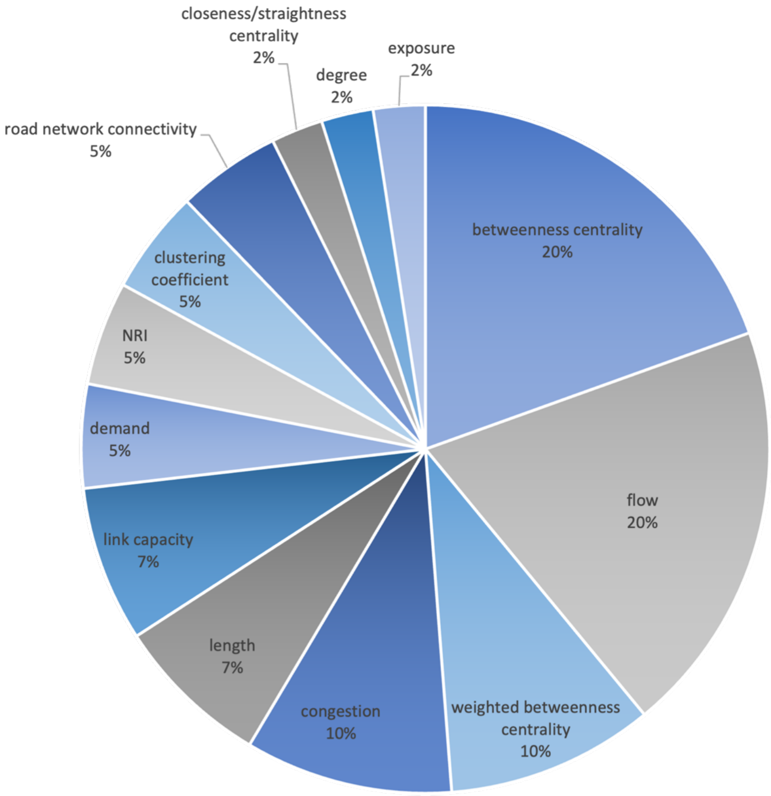

Figure 2: Indices Distribution in Literature.

where σ_{st} is the total number of shortest paths between all pairs of two distinct nodes s and t in the network, and $\sigma_{st}(v)$ is the number of those shortest paths that pass through the link v. The sum is taken over all pairs of distinct nodes s and t.

On the other hand, the formula of the weighted BC may differ depending on the specific weighting scheme used for the links. Mostly, the weighted BC involves summing the weights of the edges along the shortest paths passing through the link of interest. Thus, the calculation will depend on the weights assigned to the links and the method used for incorporating them into the betweenness centrality.

Indeed, the calculation of BC, whether weighted or unweighted, requires graph theory algorithms that compute the shortest paths between all pairs of nodes in the network. Once the shortest paths are obtained, the number of shortest paths that pass through the specific link is considered. This measure provides insights into the importance of the link in terms of its influence on traffic flow and network connectivity.

- **Flow Index:** it measures the relationship between traffic volume and link capacity thus, providing insights into congestion or link utilization. Flow index is calculated as follows:

$$\text{Flow Index} = \left(\frac{\text{Traffic Volume}}{\text{Link Capacity}}\right) \times 100 \tag{2}$$

where the traffic volume represents the current traffic volume of a link and the link capacity denotes the maximum traffic volume that the link can handle under ideal conditions. Subsequently, the traffic volume can be obtained based on the traffic counts, the historical data and the simulation results. Whilst, the link capacity is estimated through field observations, traffic simulation models, and analytical formulas.

- **Congestion Index:** it is a situation where traffic demand exceeds the available capacity on a link. This results in reducing vehicle speeds, increasing travel times and degrading network performance. Congestion assessment is typically based on a set of predefined thresholds or criteria related to the transportation network. For instance, if the flow index exceeds a certain threshold (e.g., 80%), the link is considered congested. As a result, the formula for congestion itself varies depending on the specific threshold or criteria set for the network.

- **Link Capacity Index:** it represents the maximum traffic volume that a link can handle under ideal conditions, without significant congestion or delays. Basically, link capacity index is determined through field observations, traffic simulation models, or analytical formulas that consider various factors such as lane width, speed limit, and roadway characteristics. Thus, the link capacity formula is calculated depending on the specific models or approaches used for the estimation.

- **Demand Index:** it refers to the amount of traffic or the number of vehicles that seek to travel through a link or the transportation network within a given time period. It is typically obtained from traffic data sources, such as traffic counts or historical data, and expressed as the number of vehicles per unit of time (e.g., vehicles per hour). Indeed, the demand index varies based on factors such as time of day, day of the week, or specific events. Historical data, traffic counts, travel surveys, or travel demand models can be used to acquire the necessary information for demand calculation.

- **Length Index:** it measures the relative length of a link compared to other links in the transportation network. Length index provides insights into the spatial characteristics of the network and the connectivity between nodes. Mathematically, the length index is calculated by dividing the length of a specific link by the average length of all links in the network. The formula for the length index is shown as follows:

$$\text{Length Index} = \frac{\text{Length of the Link}}{\text{Average Length of all Links}} \tag{3}$$

  where the link length represents its physical distance or geographical span, and the average length of all links provides a reference value for comparison. More specifically, the link length is mostly obtained from geographic information systems (GIS) or through manual measurements on maps. Whilst, the average length of all links in the network can be calculated by summing up the lengths of all links and dividing it by the total number of links.

The above link indices provide valuable insights into the performance, congestion, importance, and spatial characteristics of individual links in transportation networks. Their calculations involve various data sources, such as historical data, traffic counts, travel surveys, simulation models, and geographic information systems (GIS).

2.2.2. CI Calculation

Taking these filtered indices, we propose combining them into one Criticality Index (CI). Subsequently, CI is calculated as a function of the different filtered indices where each index has a specific weight.

Mathematically, let's consider l as a specific link of a URN U. Let's also consider that we were able to filter n indices in the previous phase: X_1, X_2, ..., X_n. Each of these indices is calculated as a function of some number of characteristics (i.e. i, j, ..., z) of l with respect to the whole network U. Accordingly, the criticality index of l with respect to U ($CI_{l/U}$) is calculated as follows:

$$CI_{l/U}(i,j,...,z) = \alpha \times X_{1l/U}(i,j) + \beta \times X_{2l/U}(j,...,z) + ... + \theta \times X_{nl/U}(i,j,z) \tag{4}$$

where α, β, and θ are the respective weights of each filtered index.

In order to determine and calibrate these weights, we propose to use the concept of stress testing and evaluation used in [7, 8]. For this purpose, we remove (block) links of the network, and we study the negative effect of this removal. If the link is critical, the effect should be graver. Hence, the weights for the indices have to be changed and calibrated to reach the best correlation between the resulting CI and the negative effect of removal for a specific link. The flowchart in Figure 3 shows how this process is done.

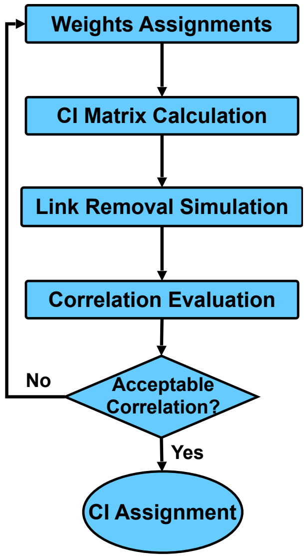

Figure 3: CI Weights Calibration.

2.2.3. *Microscopic Simulation for CI Weights Calibration*

Two main approaches were taken in the literature for the evaluation of a calculated criticality index. The first approach is usually demand-insensitive and strictly topological. In this approach criticality is evaluated using a number of graph-theory measures.

For example, in [4] the authors used shortest path length as an index for evaluating the criticality of roads after link removal. They considered the most significant links as those whose removal causes the greatest rise in the shortest path between two specified node locations. The authors in [5] quantified the amount of change in the performance of a network using the size of the giant component: number of nodes in the largest set of connected nodes of the network etc.

On the other hand, the second approach involves using a micro-simulator to insert disturbances into the network and measure how much it can adapt to them. This approach models variations in demand while evaluating traffic network performance. In transportation evaluation, microsimulation is a prevalent and cutting-edge technology that offers a practical and immersive approach. By allowing for observation of near-realistic scenarios even after modifications, it has gained wide adoption in literature [12, 13, 14, 10, 8, 7, 15, 16, 17].

We opted to use microsimulation in this work, as it captures various aspects that the former approach misses, such as congestion, speed fluctuations, accidents, and post-roadblock recovery. These aspects are essential to our context and contribute to the realism of the application.

Different simulation tools and approaches were taken in the literature summarized in Table 4. In the previously mentioned work [10], the authors used TransCAD to study the temporal effect of a link removal. In the work of [7], the authors proposed combining multiple vulnerability attributes into a single index considering both physical and operational characteristics. To do this, they used fuzzy logic and exhaustive search using the micro-simulation tool OmniTrans to determine the weight of each fuzzified metric. Another work, [8], proposed a new approach that takes into consideration traffic flow betweenness index (TFBI) to evaluate criticality of links. To reduce the computation time compared to full-scan methods, they proposed a two step approach where they evaluate first the traffic flow betweenness and rerouted travel demand metrics and then calculate the criticality index by calibrating the weight of the two metrics using MATLAB R2014a software for simulation.

An interesting concern that is usually raised in these simulation approaches is addressed in the work of [11], which is how the disruption of roads is simulated. The traditional approach used in most works is the complete removal of the link. However, they propose another link disruption modeling approach where they use a high percentage capacity reduction of the link instead of complete removal i.e. 99% capacity reduction.

In our work, we propose using SUMO simulator for micro-simulation as it is the most flexible open source tool and it has a good support with VANET frameworks (i.e Veins), which will be used in our last application phase.

Table 4
Microscopic simulation tools in literature.

Ref.	Micro-Simulation Tool	Application	Licenses
[12, 13]	*PTV Vissim*	Multi-modal	Commercial
[14]	*FLO-2D*	Field-specific (floods)	Commercial
[10]	*TransCAD*	Travel demand forecasting	Commercial
[8]	*MATLAB R2014a*	Multi-modal	Commercial
[7]	*OmniTrans*	Multi-modal and multi-temporal	Commercial
[15, 16, 17]	*SUMO*	Multi-modal and multi-temporal	Open-source

2.2.4. Evaluation Measures

The evaluation of the negative effect post-link-disruption in microscopic simulations has been studied differently in the literature depending on the use case. As shown in Table 5, the most used evaluation parameter is the difference in time/cost between normal condition and after link removal [9, 10, 7, 8]. In the work of [1], the authors focused additionally on the connectivity reliability.

Table 5
Evaluation Measures in Literature.

Ref.	Evaluation Measure
[9, 10, 7, 8]	Time/cost difference
[1]	Connectivity reliability
[12]	Volume/capacity ratio & average (volume, speed, and delay time) traveling across alternate bridges
[14]	Length of overlapping sections with critical routes
[13]	Length of failure road link & total parking delay

In the work of [12], however, the authors used volume/capacity ratio and average (volume, speed, and delay time) traveling across alternate bridges for evaluation. On the other hand, in [14], the length of the sections overlapping with the routes providing critical services was the evaluation parameter considered. In the work of [13], the authors evaluated the results of their approach in terms of decrease in the length of failure road link and the total parking delay.

As for evaluation parameters, we will be mainly considering time cost, but we will explore other use-case-related parameters that will better reflect our use case.

2.3. Re-routing Decision Making

The most common routing protocol used is the shortest (fastest) path provided by typical vehicle navigation systems like Google maps. In a normal use case, when an event occurs that causes people to reroute, they depend on the typical vehicle navigation systems i.e. Google Maps to take another route. However, these systems provide all users with the same routes without considering the whole network flow. Such solutions suggest routes depending only on the fastest route they can come up with for this specific user at that specific instant. This causes all the users to be redirected to the same alternative route (fastest) creating a bottle neck there as well. Hence, rerouting systems have to be more predictive of the state of the network flow and be at least one step ahead of it.

2.3.1. Importance of Proactive Rerouting

A better solution than providing the shortest path to every individual vehicle on its own, would be to consider the whole network flow of cars; their origins, their destinations, their criticality factor, etc. Now, both of these solutions have their advantages and disadvantages. The first kind of solutions are easy to implement, but, as mentioned before, when every car is provided the same "fastest route", that route will no longer be the fastest, and, post-disrupting-events, all the main roads will be blocked from the sudden increase in flow. That's why they've been called "selfish" in the literature. Also, these solutions are reactive as they consider only the conditions of the roads at that moment, so they fail to respond to the different events that may occur. On the other hand, the other kind of routing, called "altruistic" in literature, provides a proactive global solution that considers future moves of vehicles. However, ironically, this solution has a fairness issue where some cars will get faster routes comparably. Also, these solutions are harder to apply because they need real-time information regarding all car origins and destination as well as the conditions of the roads which present much higher complexity. An optimal solution for this is a system that balances between the benefits of the selfish and the altruistic approaches.

2.3.2. Rerouting Protocols in Literature

We did not come upon any other work in the literature that makes use of the criticality index specifically for rerouting decisions post-disruptive-events. However, many works studied rerouting traffic to avoid congestion by proposing rerouting algorithms that studied each car's choices and provided the best route considering the whole network. Some of these interesting works are summarized in Table 6.

Table 6
Rerouting Protocols in Literature.

Ref.	Year	Objective	Focus	Algorithm
[18]	2016	Aid drivers in making the most appropriate next road choice to avoid unexpected congestion	Car's destination and local traffic conditions	Next Road Rerouting (NRR)
[15]	2012	Traffic re-routing to avoid congestion	Popularity of roads based on future vehicle positions	Multi-path load balancing considering future vehicle positions (EBkSP)
[19]	2018	Investigating how neural network can yield a better optimal path than simple shortest path algorithms (proof of concept)	Structural and graphical characteristics of roads	Neural Networks

A new two-step rerouting system (NRR) is introduced in the work of [18] that proposes using heuristic rerouting decision making based on a cost function that considers the car destination as well as local traffic conditions. In this work, the authors are motivated to provide a solution that helps drivers to take the best route to avoid unexpected congestion by balancing between the altruistic and selfish solutions using a two-step approach. Further more, in the work of [15], a new rerouting strategy is introduced (EBkSP) that focuses on balancing the loads between the different routes by rerouting traffic to the paths with lowest "popularity". On the other hand, the work of [19] investigates using neural networks for decision making to make locally optimal choices. Contrary to basic heuristics, neural networks can consider variables such as the length of a road section, the centrality of an edge, and the speed restriction.

2.3.3. Criticality Index in Rerouting Decision Making

We believe that a rerouting protocol that is makes use of the calculated CI, based on a CI weighted links map, will be able to make more intuitive and intelligent decisions. Since the criticality index combines static (betweenness centrality, length, capacity) and dynamic (flow, congestion, demand) indices that offer insight that is crucial to make informed decisions. With a rerouting protocol that recognizes criticality of links, it will be able to take this criticality to produce rerouting decisions that focus on maintaining the availability of the most critical links which will in turn maintain the connectivity and reliability of the network. For this reason, in our work, we study the integration of the criticality index into redirection decision making. Since no other work is done specifically to do this, we explore and look into the interesting rerouting protocols previously mentioned modifying the cost function or scope to consider mainly the CI of links.

2.4. Decision Application

Traffic management systems proposed in the literature have different approaches for application of proposed strategies. Traffic light control systems and automobile navigation systems are the two most popular methods for handling congestion used in the literature. However, both solutions are unable to effectively handle en-route occurrences [18]. In order to apply the rerouting decisions, we propose using Vehicular Ad-Hoc Networks (VANETs)

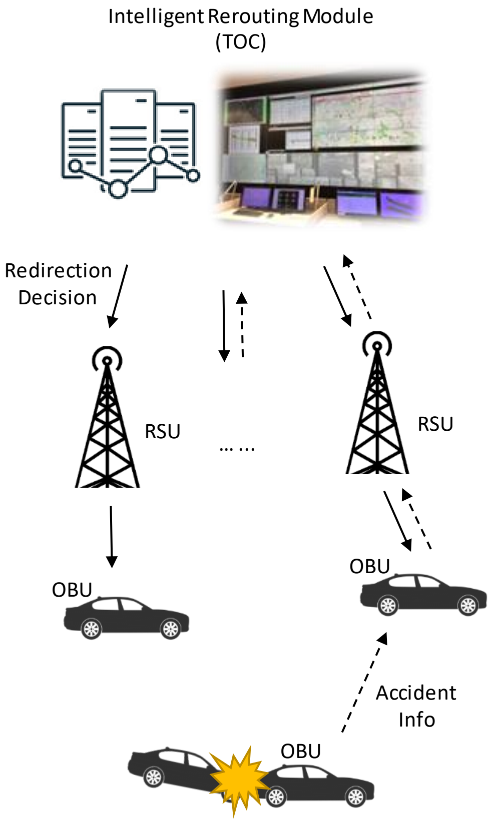

Figure 4: VANET Communication for Event & Decision Relay.

to communicate disturbances to authorities and transfer the decisions to the cars to redirect them to the proper paths. VANETs are networks composed of mobile devices, car on-board units (OBUs), and stationary devices, road-side units (RSUs) and trusted authorities (TAs) i.e. Traffic Operation Centers (TOCs). These networks have two main kinds of communication: vehicle-to-vehicle communication (V2V) between cars and vehicle-to-infrastructure (V2I) communication between cars and RSUs or TAs.

In our work, we make use of both kinds of communication to inform authorities of unexpected events as soon as possible as well as to request and relay redirection routes from TOC to vehicles as shown in Figure 4. When an accident or event occurs, the information is communicated between cars until it reaches the closest OBU. The OBU will then communicate this message to the TOC which replies with the proper diversion route decisions made using the Intelligent Rerouting Module. The RSU then relays these decisions to the affected vehicles.

Many works in the literature used VANETs to improve transportation systems. In the work of [20], the authors propose a VANET-based distributed, cooperative system for traffic congestion sensing and information dissemination without requiring human involvement, to reroute incoming traffic and lessen congestion. Similarly, in the work of [21], the authors use VANETs for congestion avoidance. Using VANET communication, they work on determining the best route to cut down on travel time and fuel usage by examining the valuable and reliable real-time traffic data. In [22], to efficiently enable real-time information exchange among automobiles, road-side units (RSUs), and a vehicle-traffic server, the authors provided a real-time route planning algorithm that aims to enhance a road network overall spatial efficiency and lower the overall cost of a car trip in order to prevent traffic jams with the use of both vehicular ad hoc networks (VANETs) and cellular systems of the public transportation system. Additionally, in [23], the authors focus on the development of a novel strategy for mobile node journeys in vehicle environments that may gather data for warning of dangerous or emergency situations by utilizing on-board sensors. On the other hand, the authors of [24] introduce a plan to use vehicle-to-vehicle communication to lessen traffic congestion using continuously broadcast beacons to monitor flow of traffic and alert other drivers of potential traffic jams. Vehicles that get this notice are expected to maintain a wider distance from the vehicle in front of them. Their approach however targeted highway use cases only.

In this work, we will use VANETs to communicate disruptive events to trusted authorities as well as relay the redirection decisions received from the proposed model in real-time. This approach ensures rapid notification and recovery post-events.

3. Evaluation

For the evaluation of this framework, each phase has to be implemented in turn and the iterative results will be compared to the state of art approaches. That is because the novelty of our proposed framework is that no other work in the literature proposes a similar end-to-end solution that combines the study of criticality index using the different fields mentioned and the post-event decision making and application using Data Mining and VANET.

To evaluate our proposed framework several tools and technologies are needed. In order to calculate the criticality index, an “accident" or road blockage have to be simulated to analyze the effect of this blockage. Instead of testing this by real life example, events can be simulated. For a long time now, micro-simulation tools have been used to test multiple transportation approaches in the literature. Furthermore, for decision making an intelligent model has to be calculated and implemented. We chose to do this using Python and C++ languages. For the last phase of VANET simulation and testing, a combination of a micro-simulation tool and VANET network simulation tool have to be used. For that purpose we chose to use Veins framework that combines the two most popular open-source tools, SUMO simulator and OMNet++. SUMO simulator is also the chosen micro-simulation tool to be used in the CI calculation phase.

3.1. Proposed Framework vs State-of-Art: Similarities and Dissimilarities

Despite our work being the only work in the literature that introduces such an end-to-end solution concept, we have come upon some interesting works in the literature that took a similar approach in one or more aspect of our work. We have summarized the similarities and dissimilarities in Table 7.

Table 7
Comparison of frameworks proposed in literature with similar concept to PEMAP.

Ref	Year	Similarities to our work	Dissimilarities from our work
[12]	2022	Studied importance of links and taking actions accordingly	The actions they took were to increase “inherent" resilience (preventive)
[14]	2020	Proposed an approach to direct waste transportation focusing on clearing “critical routes" after floods	Dealt with waste transportation only, and their definition of critical routes was based only on those connecting critical services
[25]	2019	Integrated analyzing dynamic and topological characteristics of links and used stress testing	The approach is purely analytical; no post-event solution studied

In the work of [12], they make a similar assumption that having better knowledge of the traffic conditions of roadways helps absorb sudden traffic surges. In their work, they recognize “crucial links" and focus on increasing the resiliency of the network in case of these links failure, specifically bridges. However, the actions they take are to improve the “inherent" resilience which falls on the side of preventive measures not post events. On the other hand, in [14], the authors propose an approach to reroute waste transportation post-floods to mainly decrease overlapping of those routes with what they identified as critical routes. However, their evaluation of critical routes mainly focused on routes that provide critical services not the structural and dynamic characteristics of roads. In [25], the authors identify the difference between analyzing dynamic and topological (static) characteristics and they propose an approach to integrate both metrics by weighing the different indices and assessing and highlighting the effect of area-wide disruptions using stress testing. Their work though is purely analytical and does not propose a post-event management solution to recover from disruptions.

3.2. Proposed Framework vs State-of-the-Art: A Comparative Study

In order to emphasize the novelty previously mentioned, we summarize the works proposed in the literature in the following Table 8. All of the surveyed works cover one or two phases where as our proposed framework is the only end-to-end solution that covers the four different phases.

Table 8
Phases Covered in Literature vs in PEMAP

Ref.	Phases covered			
	Phase 1	*Phase 2*	*Phase 3*	*Phase 4*
[1]	X	X		
[3]		X		
[7]	X	X		
[8]	X	X		
[9]	X	X		
[10]		X		
[12]	X			
[13]	X	X		
[14]	X		X	
[15]			X	
[18]			X	
[19]			X	
[20]				X
[21]			X	X
[22]			X	X
[23]				X
[24]				X
[25]	X	X		
PEMAP*	X	X	X	X

*Our proposed approach.

While the process of disruption management has attracted considerable research attention, much of it has been directed at the pre-disruption stage. Most of the works in the literature studying criticality analysis do not use this value for post-disruptive events management. Rather, these works focus on fixing inherent and structural states of the links to improve resilience. PEMAP on the other hand focuses on the post-disruption stage along with its management. The unpredictability of disruption magnitude and nature suggests that the post-disruption management process may be as important, if not more so, than pre-determined pre-disruption strategies. An effective post-disruption management process would directly affect actual ability to recover from sudden and serious disruptions.

Moreover, in our work, we make use of the study and the analysis of the characteristics and graph-based metrics of links in urban road networks in order to make rerouting decisions. On the other hand, the approaches proposed in the literature focus on real-time and do not consider the structural and graphical aspects of links to handle re-directions accordingly.

3.3. Experiments

To evaluate our proposed framework several tools and technologies are needed. In order to calculate the criticality index, an “accident" or road blockage have to be simulated to analyze the effect of this blockage. Instead of testing this by real life example, events can be simulated. For a long time now, micro-simulation tools have been used to test multiple transportation approaches in the literature. Furthermore, for decision making an intelligent model has to be formulated and implemented. We chose to do this using Python and C++ languages. For the last phase of VANET simulation and testing, a combination of a micro-simulation tool and VANET network simulation tool have to be used. For that purpose we chose to use Veins framework that combines the two most popular open-source tools, SUMO simulator and OMNet++. SUMO simulator is also the chosen micro-simulation tool to be used in the CI calculation phase.

3.3.1. Data and Simulation Scenario

Using SUMO simulator, we had two options: either to create a scenario from scratch, or to use a well created and tested scenario provided by the SUMO community. In our work, we decided to do the latter because it allows our work and results to be compared to those of others' using the same scenario. Further more, creating a SUMO scenario from scratch that is as realistic as possible is time consuming and out of the scope of this work. Instead we decided to make use of the existing realistic scenario LuST [16] of the city of Luxembourg. A scenario of Monaco, MoST [17], is also used in our work to validate the ability of our framework to be applied to different cities of different sizes and transport nature. The variation and numbers of both scenarios are shown in Table 9.

Table 9
SUMO Simulation Scenario Numbers

Ref.	Year	Name	City	Area	Total Nodes	Total Edges	Total Trips
[16]	2017	LuSTScenario	Luxembourg	155.95 km2	2,247	5,779	215,526
[17]	2018	MoSTScenario	Monaco	22 km2	2,004	4,404	7,990

As can be seen, despite the number of nodes and edges being close, the other numbers in the scenarios vary greatly. That is because the scenario of Luxembourg simulates traffic across a much bigger city. Further more, it simulates traffic for a whole day with the realistic traffic variation shown in Figure 5. The figure shows the variation of the traffic at different times of the day and highlights how the scenario realistically depicts traffic at peak (rush) hours.

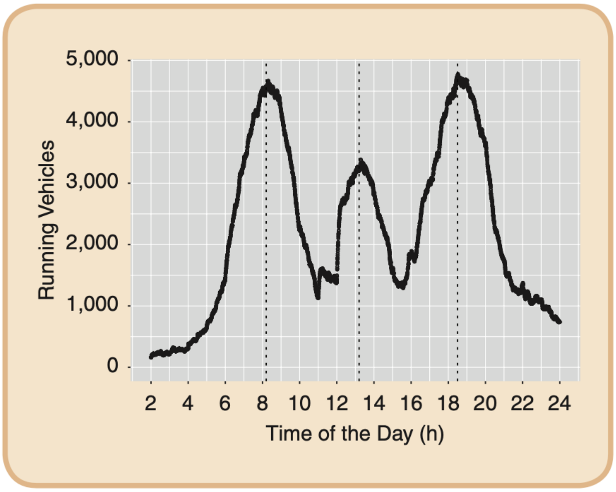

Figure 5: Luxembourg SUMO Traffic (LuST) Scenario: Traffic Demand [16].

3.3.2. Results

Using Python sumolib and networkx libraries we were able to parse and extract the graph of each city. The graph generated is a multi-bi-directional graph with the edges representing the roads of the city and the nodes representing intersections between roads. In our work, we considered lanes with the same starting and ending points as one edge to avoid redundancy.

Taking both scenarios, we extracted the graphical representation of the city roads as mentioned, as well as the traffic flow and trips which we analyzed and used to apply our approach. We calculate for each edge (road) the different indices mentioned previously. Figure 6 shows the criticality of links based on unweighted betweenness centrality (BC). Figure 7 shows a clear difference in criticality evaluation after adding length index.

In Figure 8, BC is used along with length and speed which are used to calculate the cost of each link. On the other hand, Figure 9 shows the map of Luxembourgh weighted by flow extracted from the simulation results.

After that we apply our algorithm to calculate the criticality indices and the results are shown in Figure 10 and Figure 11 of the cities of Luxembourg and Monaco respectively.

Figure 6: Unweighted BC Weighted Map of Luxembourg.

Figure 7: BC, Length Weighted Map of Luxembourg.

The variation between the results in Figures 6, 7, 8, and 9 in comparison to those in Figure 10 show how our work provides an edge and more realistic results by better highlighting critical roads at the center of the city and in main roads.

4. Conclusion

In this paper, we have proposed a framework called PEMAP that allows to redirect traffic post disruptive events based the intelligence extracted from the criticality analysis of the different links in the urban road network. The proposed framework is made of the four phases: indices assessment and evaluation, criticality index calculation, re-routing decision making, and decision application. In the first two phases of criticality analysis, we use the fields of

Figure 8: BC, length and speed (cost) Weighted Map of Luxembourg.

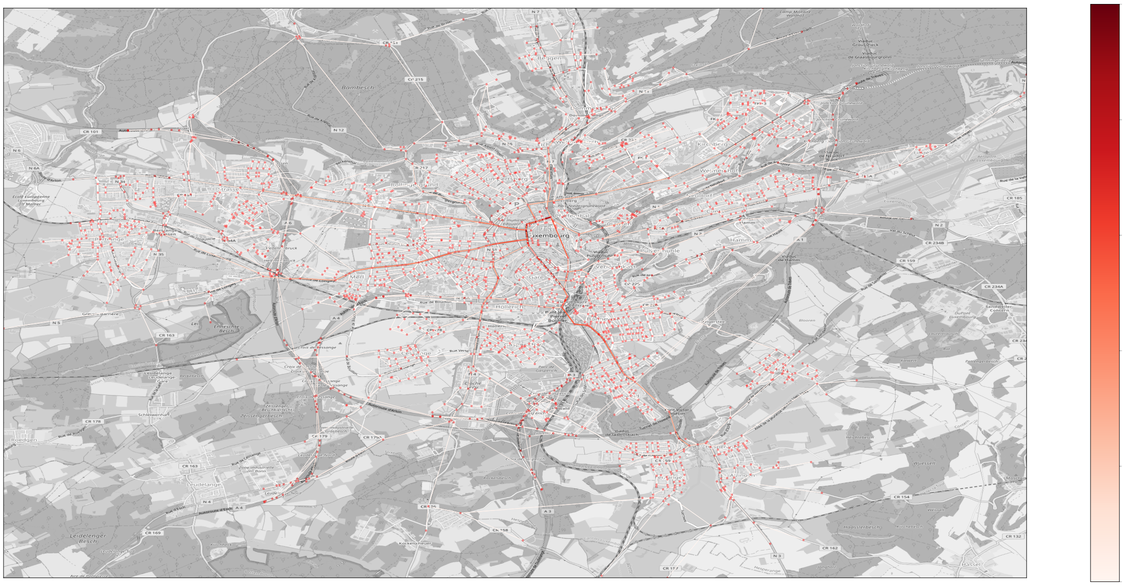

Figure 9: BC, Flow Weighted Map of Luxembourg.

geographic information systems, graph theory, microscopic simulation, and social networks. In the last two phases, we use data mining for decision making and VANET for real-time application.

We also emphasized in this work the novelty of this work which is the combination of different fields into one end-to-end system that performs analysis and decision making for post-event traffic management. In order to provide such framework, we explored the literature of each field individually and its contributions to intelligent transportation systems. We, then, properly defined our problem statement and purpose as well as distinctly emphasized our understanding of criticality analysis in order to perform an analysis of the existing works and approaches. We also performed comparative evaluation with existing works and provided experiment results to further validate the proposed framework.

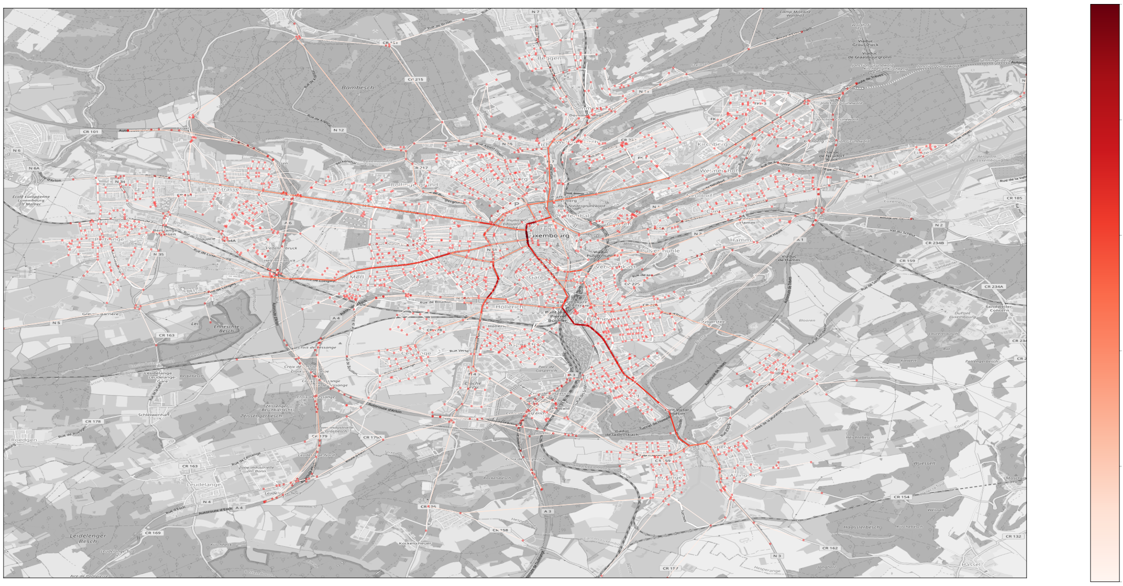

Figure 10: Criticality Index Weighted Map of Luxembourg.

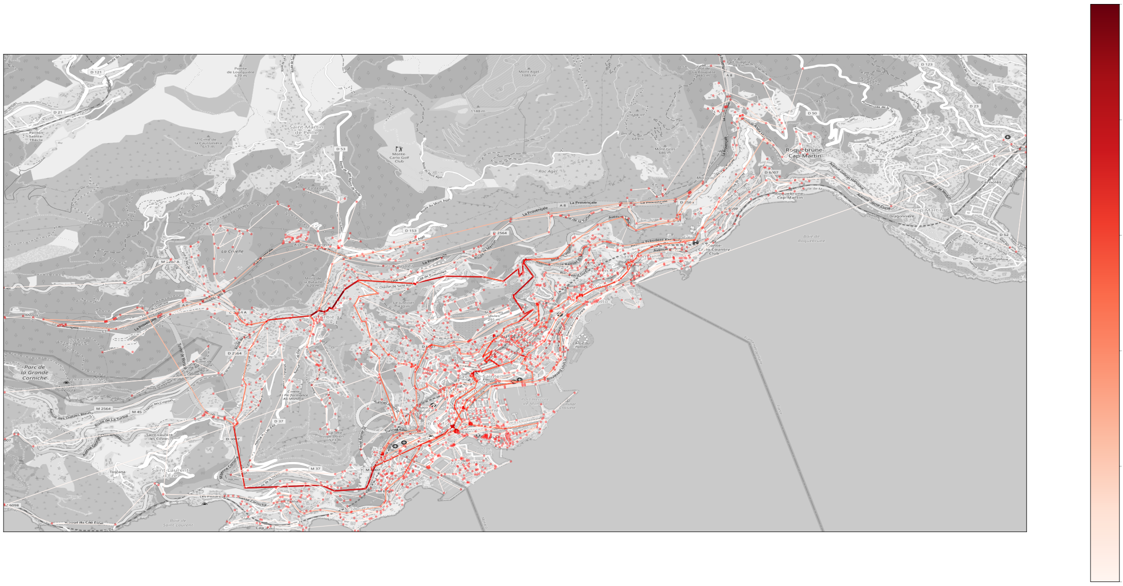

Figure 11: Criticality Index Weighted Map of Monaco.

In the future work, we intend to continue studying the applying the different phases of PEMAP framework. This work is the first in a series to realize PEMAP. We'll take each phase in our next works, study the state of art, and implement our approach.

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