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Resilience as a Service for Transportation Networks. RaaS Definition and Basic Concepts

Rihab Amghar¹, Sara Jaber^{1,2}, S. M. Hassan Mahdavi Moghaddam², Neila Bhouri¹, and Mostafa Ameli¹

Abstract

Urban transportation systems' structure and functionality can be affected by unexpected disruptions due to several reasons, like as natural hazards, intentional attacks, accidents, etc. The conventional definition of resilience is the capacity to withstand, assimilate, adjust, and expeditiously recuperate from various forms of perturbations such as shocks, disturbances, and deliberate attacks. Though multiple studies in the literature focus on resilience assessment and improving the resilience level of mobility services prior to disruption, few studies offer solutions for transportation systems' operators during disruptions to alleviate the negative effects of disruptions, such as reducing the recovery time. In this context, a new paradigm, called Resilience as a Service (RaaS), has emerged in the field of operation management. The idea of RaaS is to integrate the available resources of different service providers to manage disruptions and maintain the system's resilience. The decision is taken under multiple conditions with respect to the benefit of each stakeholder, namely the operator, the passengers, and the authorities. This paper proposes a definition of RaaS dedicated to transportation systems. To provide a methodological example corresponding to the RaaS paradigm, we formulate a bi-level optimization problem to represent a solution example that RaaS providers can deliver. The upper-level model formulates the resource reallocation problem during disruption from the perspective of RaaS providers, while the lower-level model considers user perspectives by calculating (multimodal) user equilibrium, i.e., minimizing the travel cost of every user. We provide a numerical example in a real test case of a French city to illustrate the benefits of implementing a RaaS solution. The results show that we can reduce the average travel delay of all users by 69%, including the delay results from the proposed RaaS strategy compared to the absence of RaaS.

Keywords

Resilience, Recovery, Cooperative mobility service, Stress level, Policy making.

Introduction

Disruption can happen in different circumstances based on various factors, ranging from catastrophic natural hazards such as earthquakes and extreme weather conditions to man-made disasters such as terrorist attacks, severe congestion, and road construction. They are distinguished by their rapid evolution and severe effects on transportation systems during and after the impact of disruption. Distribution of any kind can result in a host system experiencing various issues, which can be measured by performance indicators that signify cost. For instance, people in France lost 340 million minutes in 2018 due to failures and delays (1). Making transportation systems more resilient against those disruptions in order to maintain public safety and comfort has become a prioritized agenda for many urban transport authorities. It is considered a critical skill to build modern and intelligent transportation systems.

The concept of resilience was first introduced by (2) in 1973 to define an ecological system's capacity to withstand disruption under stress and return to a stable condition. It was then introduced in other fields, such as ecology, disaster management, risk engineering, etc. In the transportation engineering and science field, resilience is defined as the ability of a transportation system to maintain its structure and functionality in the face of disruptions (3). Many studies have been undertaken to measure the resiliency of transportation systems based on various indicators, e.g., robustness, reliability, redundancy, resourcefulness, rapidity, etc (4). However, most of the works only focus on scanning

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the disruption and do not propose a framework able to provide practical solutions in the event of disruptions. In addition, the state of the art in urban transport resilience is considerably limited to investigating either one scenario of disruption or a single mobility service (5, 6). In this study, we focus on a new paradigm in resilience that is mostly dedicated to managing various types of disruption in multi-modal transportation systems.

The development of transportation systems and networks in urban areas and high mobility (population movement) requires innovative solutions to increase the service reliability and robustness of the system. Recently, a new paradigm has been introduced in the context of resilience. It is called *Resilience as a Service* (RaaS) and was first introduced in the literature in the field of cloud computing by (7). The general idea of RaaS is to support the disrupted component of the system by using the operating or reserved resources of other components unaffected by perturbations.

In this paper, we aim to define RaaS in transportation systems. To illustrate the concept of RaaS, we need to take into account the complexity and challenges of modern transportation systems. To this end, we investigate recent approaches that have similarities with RaaS. In particular, we focus on Mobility as a service (MaaS), which is a recent paradigm in transportation systems. MaaS has resemblances with RaaS contextually, but in terms of architecture, they have different objectives. The idea of MaaS is to provide integrated packages of transport, including multiple services based on travelers' needs. In other words, people can buy mobility services that are provided by the same or different operators by using just one platform and a single payment (8). MaaS has been welcomed as a sustainable alternative to car travel as it is environmentally friendly. In response to this concept's revolution that is currently taking place, some cities (e.g. Helsinki, Vienna, Tokyo) are making an effort to switch to centralized systems, even though mobility services are often provided by decentralized operators.

In the context of resilience, a new management solution is required for both, centralized and decentralized mobility services in order to maintain the highest level of service while lowering the risk of disruptions and the effects of perturbations. In this paper, we define RaaS as a management system for the different mobility service providers, enabling them to integrate their operating and reserved resources in order to reduce the recovery time from any kind of disruption. In particular, RaaS aims to empower multi-modal transportation systems by outlining a management mechanism to reduce the recovery time from a disruption event. RaaS can be interpreted as a kind of agreement between multiple mobility service providers to reallocate their operating resources during disruptions for a fast recovery of the entire system.

Paper organization

In this study, we first perform a comprehensive literature review on resilience in transportation systems in order to propose a standard definition for the RaaS paradigm. Second, to illustrate how a RaaS system can be designed and operated, we propose a mathematical framework to make an example of how a RaaS system can contribute to transportation systems. Third, we apply the proposed methodology to a real test case of public transport in the city of Rennes in France to validate our framework and show the effectiveness of RaaS in an urban area. The remainder of the paper is organized as follows. A literature review on transportation resilience and RaaS is presented in the next section. The results of the literature review lead us to propose the definition of RaaS at the end of the next section. Then, A methodological framework for RaaS is presented. Following this section, the numerical experiment and its results are detailed. Finally, we conclude this study and mention our future works in the last section.

Literature review and contribution statement

We conduct a literature review on transportation system resilience in order to cover the concept and applications of resilience in mobility systems. We then highlight the limitations in the literature. Next, we discuss disruption types and investigate how they can impact the transportation network. Based on the outcome of this review, we propose a definition of resilience as a service.

Transportation systems resilience

There are several studies in the literature that provide various definitions of resilience in the field of transportation systems. We present four complementary definitions. (3) defines resilience as the ability of a system to maintain its structure and function in the face of disruptions. (9) represents resilience as the ability of a system to react to stresses that challenge its performance. (10) defined a resilient transport as a system able to absorb shocks as well as accommodate slow onset long-term events. Finally, according to (5), resilience is the ability of the transportation system to resist and adapt to external or internal disturbances and then quickly return to a normal service level to meet the original travel demand. All of these definitions attempt to demonstrate that resilience is a solution to face disruptions in order to minimize their effect and return to the normal situation as fast as possible.

Resilience is also addressed in the literature as a range of concepts and definitions that play a crucial role in designing assessment tools. (5) gives some keywords to quantify resilience: redundancy, resourcefulness, rapidity, strength, and stability. (11) considered that the key parameters in resilience quantification are as follows: disruptive events, component restoration, and overall resilience strategy. In a

comparative study to highlight the importance of resilience in system infrastructure, (12) proposed a process to evaluate the system's resilience based on the entropy theory. This process is similar to how resilience is quantified, as both aim to demonstrate the system's vulnerability to disruptions.

In order to design a sustainable and resilient system, we need to consider three phases in the disruption management, before, during, and after the perturbation. In this context, (13) defined a resilient system as a system that can effectively adjust its functioning prior to, during, or following changes and disturbances.

There is a lack of a universally accepted definition of resilience which raises significant uncertainty about what is being measured, limiting the ability to compare different approaches (6). In addition, the majority of the studies refer to a single independent system, while in the real world, the multi-modality should be taken into account. In this study, we try to address the resilience concept in a multi-modal disruption situation,

Disruptions in transportation systems

Disturbances affecting transportation systems vary in nature, scale, impact, duration, and source. It is important to evaluate the costs of disruption to have a better understanding of the solution needed.

Without considering day-to-day variability, which is typically measured by travel time reliability (14), disturbances can be categorized into internal and external threats (15). The internal threats may originate from mistakes or/and accidents caused by staff or users, technical failures, components that break down, faulty constructions, overload, etc. they could also be intentional, such as labor market conflicts. External threats may be related to natural phenomena including various degrees of adverse weather and natural disasters: heavy rains, snowfalls, thunderstorms, hurricanes, volcanic eruptions, earthquakes, etc. Another threat that is considered as long-term is global warming, which is partially a consequence of human activities in the transport sector. External threats also include deliberate attacks such as sabotage, terrorism, and acts of war.

The consequences of disruptions in transportation networks vary according to many factors, including the type of disruption, duration, location, etc. Some studies divided disruption consequences into direct and indirect costs. For example, (16) proposes a framework to provide a comprehensive estimation of the indirect economic impacts of transportation disruptions. Besides, (17) conclude that the failures are not significantly related to the topological properties of the network, but to the duration of failure and passenger flow re-distributions.

In the literature, there are several approaches to measure and quantify resilience, providing different strategies to reduce the impact of disruptions, however, the perturbations are generally difficult to estimate and predict. In the urban

transportation systems, most of the studies focus on the independent systems that try to optimize their own resilience, but, in real complex urban systems, e.g. MaaS, several parts are working together and affecting each other. For these reasons, we need a framework providing resilient solutions in the face of any kind of disruption, taking into account the systems' multi-modality.

Resilience as a service (RaaS)

Recently, a new paradigm is introduced in the context of resilience. It is called *Resilience as a Service* (RaaS). It was first developed in the literature, in the cloud computing field by (7). In the mentioned paper, this concept refers to the capacity of the infrastructure to support uninterrupted functionality of the applications despite failures of components. In our paper, we extend this concept to multi-modal transportation systems.

Definition Resilience as a service (RaaS).

Resilience as a service in a transportation system is the integration of various forms of resilience services into a single service accessible on demand by the system's stakeholders. It aims to support multiple mobility services operating and correlating together in a single complex transport system in order to empower the ability of the global system to anticipate, prepare for and adapt to changing conditions and resist, respond to and recover rapidly from disruptions.

RaaS can be designed for a centralized or decentralized structure. In its decentralized form, each service provider controls their own resources independently, but they collaborate with each other in the case of a disruption. It means RaaS provides a management system for the different mobility service providers to cooperate in order to improve the resilience of the whole transportation system. Thus, it can be represented as an agreement contract between them enabling resource reallocation in the case of a disruption to reduce the recovery time and costs. In its centralized structure, all transportation services are managed under a single entity. In this case, RaaS is an additional service that can optimize all service plans together in order to respond to the disruption considering all the available modes in the network. Here, we focus on the decentralized structure to describe the concept of RaaS for a current transportation network including multiple independent providers.

In this paper, we restrict our example to a specific scenario that RaaS can offer during a disruption event. Specifically, RaaS must cover all combinations of multi-modal mobility services to sustain their structure and function in the face of disruptions, ensuring a rapid recovery capability or proposing alternative solutions to travelers. The primary objective of RaaS is to be fully prepared to cope with any exceptional events that may occur.

Problem statement

In this paper, we consider a multi-modal urban transportation system, in which we have multiple modes of transport. Each of them corresponds to a mobility service managed by different service providers. At the urban area, these transportation modes can be correlated, consequently, if a disruption happens, travelers and service providers are affected, this effect vary based on the level of service and the impact of the disruption factor. The idea of RaaS in this situation is to integrate resources of all the available services in the system, in order to empower it to face both, the infrastructure based and the service-based disruptions, and optimize the objective of all stakeholders in the system.

Figure 1 depicts the placement of RaaS and its relationship with the different stakeholders in the system. When a disruption occurs, RaaS unit is activated, and the disruption causes a cost for operators, travelers, and consequently mobility authorities. The impact on travelers indirectly influences the RaaS operations. RaaS considers the goals of travelers, by respecting the policy that comes from the authorities, then tries to increase the utility of the user in the system. In the other hand, it provides mobility operators a service to reduce their recovery time and increase their service level. In Figure 1, the direct arrows show the direct relationships between different stakeholders, while the dash arrows show the indirect relationships between the other units of RaaS.

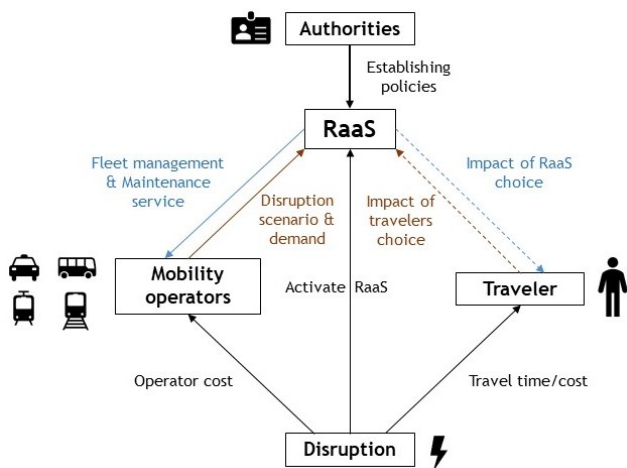


Figure 1. Relationship between the different stakeholders.

In order to formulate the problem taking into consideration the different perspectives, we used a bi-level mathematical model. According to (18), the bi-level programming model has much more advantages compared with the traditional single-level programming model: first, it can be used to analyze two different and even conflict objectives at the same time in the decision-making process, second, the multiple-criteria decision-making methods of bi-level programming can reflect the practical problem better, and third, the bi-level

programming methods can explicitly represent the mutual-action between the system managers and the customers, i.e., different stakeholders.

In this work, we use a bi-level optimization, in order to consider the problem solved by RaaS. Different perspectives and goals of the stakeholders should be taken into consideration. For this reason, RaaS aims to minimize the allocation of resources as well as achieve user equilibrium (19). This interaction can be represented through the following bi-level programming problem. (20).

$$\begin{aligned} \min_x \quad & F(x, y) \\ \text{s.t.} \quad & G(x, y) \leq 0 \end{aligned} \quad (1)$$

Where $y=y(x)$ is implicitly defined by the lower-level problem:

$$\begin{aligned} \min_y \quad & f(x, y) \\ \text{s.t.} \quad & g(x, y) \leq 0 \end{aligned} \quad (2)$$

The idea of bi-level optimization is to represent the problem as a model consisting of two sub-models, an upper-level and a lower-level. Equation 1 represents a generic form of the upper-level, in which $F(x, y)$ is the objective function of upper-level decision-makers, and x is the decision vector of the upper-level decision-makers, $G(x, y)$ is the constraint set of the upper-level. Equation 2 defines the generic representation of a lower-level problem, in which $f(x, y)$ is the objective function of lower-level decision-makers, y is the decision vector, and $g(x, y)$ is the constraint set of the lower-level.

$y(x)$ denotes the response function, i.e., the reaction. It connects the upper and lower-level decision variables. The lower-level solution determines the value of y in the upper-level problem, making the two programming models interdependent on each other (18).

The problem defined by RaaS service, involves two main sets of decision-variables: the first set is related to service providers, and the other to travelers. In the next section we will present our mathematical model in details.

Methodological framework

In this section, we formulate a small management unit of RaaS as a bi-level mathematical model. The upper-level model considers the objectives of RaaS providers. Note that these objectives indirectly serve the goals of service providers and authorities. In the upper-level model, we aim to find the best resource reallocation for all mobility services in a disruption event.

Let us represent the resources with two components, the number of assigned vehicles to scheduled services and the maintenance or supporting units. The assignment problem

at the upper-level is about assigning these two resources to defined services in order to serve the demand. The objectives of the model are minimizing: (i) the resources used by the undisrupted services with respect to their demand, (ii) recovery time, and (iii) the difference between the current (disrupted) service level and the normal level. Optimizing the upper-level leads us to find the optimal values for the supply side in which more resources are reallocated to the disrupted service in order to reduce the recovery time and increase the service level toward the normal situation. Afterward, we represent the decision-making process of the travelers in the lower-level model. Recall that the goal of this model is to achieve user equilibrium. Therefore, the objective function is formulated as minimizing the travel cost of every traveler (21). The decision variable in this level is the assignment variable, which denotes the decision of travelers about choosing their travel mode among the available transportation modes (22).

We proceed first by presenting the analytical formulation of the problem. Then we deploy an agent-based simulator and propose a practical framework based on our bi-level model for multi-modal transportation systems.

Analytical formulation of the RaaS management unit

To reduce the complexity of the mathematical model in presentation, we define the model in a single time interval, wherein a single or multiple disruptions are already affecting the system. The duration of an interval can be differed based on the evolution of the disruption(s) and the effective period of the decisions made by stakeholders. Thus, we factor out the index of time in our formulation. In addition, we simplify the definition of travel time and avoid defining the dynamics of the multi-modal traffic system, which is out of the scope of this study. We formulate the travel time and the impact of maintenance units on disruptions in a generic, deterministic, and simplified manner. The employed notations in this study are summarized in Table 1.

Upper-level model: The upper-level model is formulated from the perspective of RaaS providers. Before presenting the model, let us define a disrupted scenario δ as the network state in which a disruption affects one or more links (23). The travel time of mode j for Origin-Destination (OD) pair w , denoted by t_j^w , is a function of the basic (i.e., normal or undisrupted) travel time ($t_j^{w,b}$) and the impact factor of effective disruption(s), Equation 3 is the main equation for calculating the travel time:

$$t_j^w = f(t_j^{w,b}, \sum_{\forall \delta} \frac{R_j^\delta}{\lambda_j^w} \cdot y_j^{w,\delta}) \quad \forall w \in W, j \in M \quad (3)$$

$$t_j^w = t_j^{w,b} \sum_{\forall \delta} \frac{R_j^\delta}{\lambda_j^w} \cdot y_j^{w,\delta} \quad \forall w \in W, j \in M \quad (4)$$

where, R_j^δ denotes maintenance (recovery) units needed for mode j to make disruption δ ineffective. $y_j^{w,\delta}$ is a binary variable showing if mode j on w is affected by disruption δ or not. This binary variable is defined in Equation 5. The fraction in Equation 4 denotes the relation between the basic travel time and the impact of disruption. This fraction can be reduced by using the maintenance units (recovery resources). This equation is an example of Equation 3. Note that R_j^δ can have various values based on the disturbances that disruption δ imposes on the system.

$$y_j^{w,\delta} = \begin{cases} 1 & \text{If disruption type } \delta \text{ happens to mode } j; \\ 0 & \text{Otherwise.} \end{cases} \quad (5)$$

$t_j^{w,b}$ should be calculated separately for fixed scheduled and on-demand mobility services. For fixed scheduled services (e.g. bus, shuttle bus, etc.), $t_j^{w,b}$ in Equation 4 is calculated by Equation 6, where the basic travel time is a function of the free flow travel time.

$$t_j^{w,b} = f t_j^w \frac{h_{\max}^w}{\pi_j^w} \quad \forall w \in W \quad (6)$$

where $f t_j^w$ denotes the free flow travel time of mode j for w , h_{\max}^w is the maximum headway [time] of a service on w , and π_j^w is the number of modes j assigned to w . For on-demand services (e.g. taxi, etc.), $t_j^{w,b}$ is calculated by replacing headway with travel time from i to the point of passenger demand while considering the impact of congestion and competence with other taxis on the arrival time of on-demand service (24). The fraction in this equation aims to represent the time period of service, i.e., the inverse of the frequency of mode j for w .

The mathematical formulation of the upper-level model is as follows:

$$\min_{\pi_j^w, \lambda_j^w} \alpha z_1(\pi_j^w) + \beta z_2(\lambda_j^w) + \gamma z_3(x_{ij}^w) \quad (7a)$$

$$\text{s.t.} \quad \sum_{j \in M} \pi_j^w C_j (1 - y_j^w) \geq D^w \quad \forall w \in W, \quad (7b)$$

$$\sum_{w \in W} \pi_j^w \leq N_j \quad \forall j \in M, \quad (7c)$$

$$\sum_{j \in M} \lambda_j^w \leq M_j \quad \forall j \in M, \quad (7d)$$

$$\lambda_j^w \leq R_j^\delta y_j^{w,\delta} \quad \forall \delta, j \in M, \quad (7e)$$

$$\pi_j^w, \lambda_j^w \geq 0 \quad \forall j \in M. \quad (7f)$$

where z functions are calculated by the following formula:

$$z_1(\pi_j^w) = \frac{\sum_{w \in W} \sum_{j \in M} \pi_j^w (1 - y_j^w)}{\sum_{j \in V} N_j} \quad (8)$$

Table 1. Table of notations

W	Set of all Origin-Destination pairs in the network.
M	Set of all transportation modes in the network.
P_w	Set of all the passengers travel on Origin-Destination pair w .
w	Index of the Origin-Destination pair, $w \in W$.
i	Index of the passenger, $i \in P_w$.
j	Index of the transportation modes, $j \in M$.
δ	Index of the disruption scenario.
N_j	Total number of available modes j .
M_j	Total number of available maintenance units corresponding to mode j .
ft_j^w	free-flow travel time of mode j for w
U_i^w	Utility function of user i , traveling for w .
tc_i	Total cost of user i .
C_j	Capacity of transportation mode j .
D^w	Total demand for Origin-Destination pair w .
π_j^w	Number of modes j assigned to Origin-Destination pair w .
λ_j^w	Number of maintenance units corresponding to mode j assigned to Origin-Destination pair w .
x_{ij}^w	Binary variable; it is set to 1 if user i chooses transportation mode j ; 0 otherwise.
$y_j^{w,\delta}$	Binary parameter; it is set to 1 if disruption type δ happens to mode j ; 0 otherwise.
t_j^w	Travel time of a mode j for Origin-Destination pair w .
$t_j^{w,b}$	Travel time in the basic (i.e., normal) condition.
tc^b	Vector of user's travel cost in the basic situation.
x^b	Distribution of users' mode choice in the basic situation. Maintenance
R_j^δ	(recovery) units needed for mode j to make disruption δ ineffective.
ft_j^w	The free flow travel time of mode j for Origin-Destination pair w .
h_{\max}^w	Maximum headway for Origin-Destination pair w .

$$z_2(\lambda_j^w) = \frac{\sum_{w \in W} \sum_{j \in M} \lambda_j^w (1 - y_j^w)}{M_j} \quad (9)$$

$$z_3(x_{ij}^w) = \frac{-\sum_{w \in W} \sum_{i \in P_w} U_i^w(tc_i, x_{ij}^w)}{\sum_{w \in W} \sum_{i \in P_w} U_i^w(tc^b, x^b)} \quad (10)$$

Equation 7a presents the objective function of the system for the RaaS providers, it includes three main components. The first (Equation 8) is related to minimizing the non-disrupted service resources used by service providers, where π_j^w is the number of modes j assigned to OD pair w , and N_j is the total number of available modes j . The second component (Equation 9) is about minimizing the maintenance resources for the non-disrupted lines, where λ_j^w is the number of maintenance units corresponding to mode j assigned to OD pair w , and M_j is the total number of available maintenance units corresponding to mode j . The main idea of the two first components is to take into account the objective of the disrupted service providers, by providing extra resources for a fast recovery. We multiply these components with $(1 - y_j^w)$ shown in Equation 11 to eliminate all the disrupted lines from the objective function, it is a binary value determining either

a mode j is disrupted by any type of disruption or not, where $y_j^{w,\delta}$ is also a binary variable represented in Equation 5. The third component (Equation 10) aims to minimize the difference between the total utility of the normal and the disrupted situation. Here, we include the variables originating from the lower-level. $U_i^w(\cdot)$ is the utility function of user i , traveling for w . The three components are integrated into a single objective function with a weighted sum, the weights are denoted by α , β , and γ , where $\alpha + \beta + \gamma = 1$. In Equation 7a we try to normalize each component of the objective function.

The constraint Equation 7b forces the non-disrupted mobility services to serve all their demand, we exclude the disrupted services as they are already perturbed, and cannot fully serve their demand, where D_w is the total demand for OD pair w . Constrains 7c and 7d aim to conserve the total number of the available mobility services and maintenance resources, where N_j is the total number of available modes j , and M_j is the total number of available maintenance units corresponding to mode j . The constraint in Equation 7e ensures, that we cannot add more recovery resources than what a disrupted service needs, where R_j^δ is the maintenance

units needed for mode j to make disruption δ ineffective. The last constraint presented in Equation 7f is the positivity condition on the decision variables, which are π_j^w and λ_j^w . As mentioned in Equation 1, the input of the objective function of the upper-level comes from the lower-level.

$$y_j^w = 1 - \prod_{\forall \delta} (1 - y_j^{w,\delta}) \quad \forall j \in M \quad (11)$$

Lower-level model: The lower-level model is from the perspective of the travelers, it aims to reach users' equilibrium, its mathematical formulation is expressed as follows:

$$\min_{x_{ij}^w} \quad tc_i = \sum_{j \in M} x_{ij}^{w,j} t_{ij}^w \quad \forall w \in W, i \in P_w \quad (12a)$$

$$\text{s.t.} \quad \sum_{i \in P_w} x_{ij}^w \leq C_j \pi_j^w \quad \forall w \in W, j \in M, \quad (12b)$$

$$\sum_{j \in M} x_{ij}^w = 1 \quad \forall w \in W, i \in P_w, \quad (12c)$$

$$\sum_{i \in P_w} \sum_{j \in M} x_{ij}^w D^w = D^w \quad \forall w \in W, \quad (12d)$$

$$x_{ij}^w \in \{0, 1\} \quad \forall w \in W, i \in P_w, j \in M. \quad (12e)$$

where

$$x_{ij}^w = \begin{cases} 1 & \text{If user } i \text{ assign to mode } j; \\ 0 & \text{Otherwise.} \end{cases} \quad (13)$$

At this level, the objective function is formulated in Equation 12a, which seeks to minimize the total cost incurred by each traveler to achieve the user equilibrium. In this equation, x_{ij}^w denotes the assignment of traveler i to transportation mode j , and is expressed as a binary variable in Equation 10, taking a value of 1 if the traveler is assigned to mode j , and 0 otherwise. Additionally, $t_{w,j}$ represents the travel time of mode j in pair w .

The constraint presented in Equation 12b aims to ensure that the capacity of the service is conserved by guaranteeing that the sum of all passengers assigned to mode j is less than or equal to its capacity, where C_j represents the capacity of mode j . The constraint in Equation 12c ensures that each traveler is assigned to only one mode. Additionally, Equation 12d concerns demand, ensuring that the total number of users traveling in the system is equal to the demand for each OD pair w , where D_w represents the total demand for OD pair w .

In this paper, we present a mathematical model designed for a multimodal urban transportation system. Due to the large number of parameters involved, which arise from the various modes of transportation and their complex interactions, an exact analytical solution is not feasible. The

use of heuristic methods would require making assumptions and simplifications that may not be realistic or accurate. Instead, we have chosen a simulation-based approach, which allows us to incorporate the time dimension in the calculations and capture the dynamics of the multimodal transportation system. With a traffic simulator, we provide all the input data needed and also capture the dynamics of the multimodal transportation systems.

Simulation-based framework for the RaaS management unit

In our work, we combine the bi-level programming model with an agent-based simulation. In the case of a disruption, the simulator provides the travel time of the users and the dynamics of the system during the service duration. At the upper-level, the third component of the objective function, which is based on the travel cost of users, is calculated. At the lower-level, the simulation handles the lower-level by calculating the user equilibrium and providing the distribution of the users over different modes.

The proposed iterative process includes the steps detailed in the flowchart in the Figure 2. The description of each step is highlighted as follows:

Step 1 **Disruption identification:**

This step corresponds to identifying the disrupted network, the scenario of perturbation, and the demand of users. In our process, the disruption can be the absence or the delay of service, and the impact is measured by the simulation.

Step 2 Traffic simulation: This step corresponds to simulating the traffic where the perturbation is identified. The objective here is to measure the disruption's impact on travelers, by determining the effect on travel time and capturing the system's dynamics.

Step 3 Update the cost functions: This is the first part of the upper-level resolution, where all the cost functions and indicators are updated. The measure is changed in the utility and the cost of different agents in the system,

Step 4 Upper-level convergence test: In this step we check the convergence of the objective function of the upper-level if a disruption happens, the first two components of the objective function are eliminated, we use the indicator shown in Equation 14 which is the disruption utility, that is designed to determine how far we are from the normal situation, the best value for this equation is 1, meaning that we are in the normal situation, the difference between this indicator and the value of 1 shows the level of disruption. The number of iterations is limited as shown in Equation 14.

Step 5 Solve the fleet management problem: In this step, we solve the fleet management problem (formulated in Equation 7). We obtain the optimum values of π^w and

j

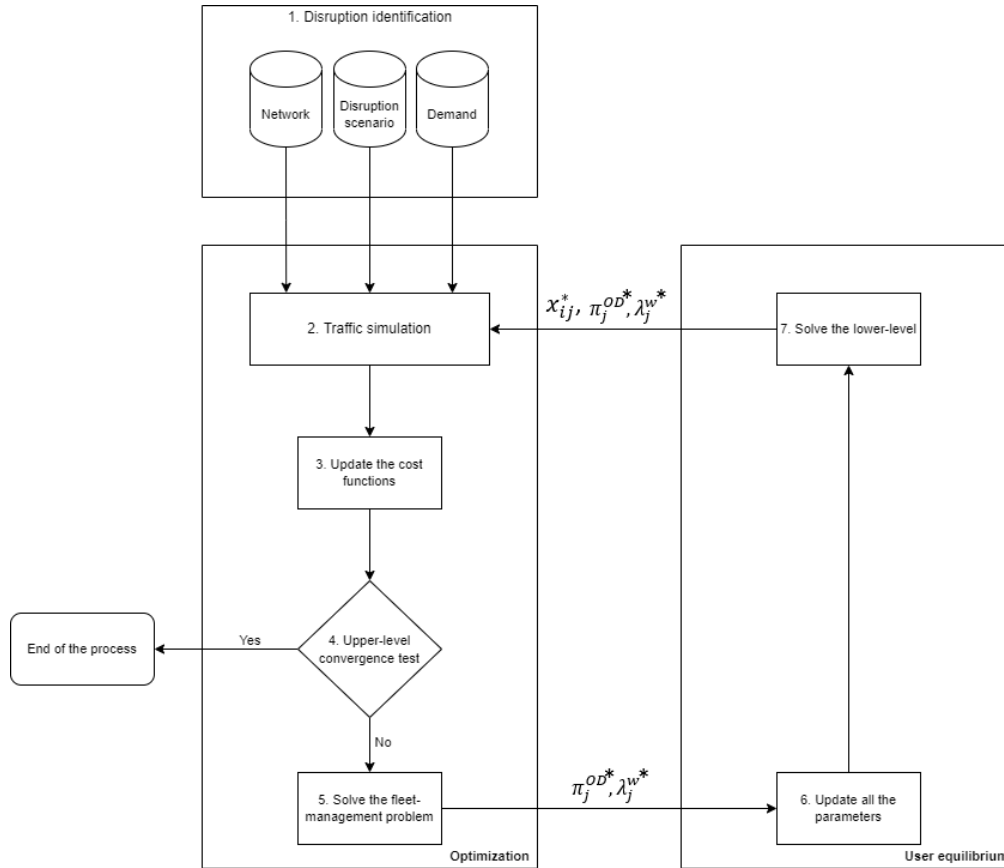


Figure 2. Flowchart of the simulation-based framework.

λ_j^w that will be used as lower-level inputs. Note that λ_j^w has impacts on t_j^w in the formulation of lower-level (Equation 12).

Step 6 Update lower-level parameters: This step is for updating all the lower-level inputs which characterize the supply side based on the optimum values that come from Step 5.

Step 7 Solve the lower-level: This step corresponds to finding a network for user equilibrium, for the targeted transportation system including all the users. After finding the equilibrium solution, x_{ij}^* we go to Step 2.

$$1 - \frac{\sum_{w \in W} \sum_{i \in P_w} U_i^w(tc_i, x_{ij}^w)}{\sum_{w \in W} \sum_{i \in P_w} U_i^w(tc^b, x^b)} \leq \epsilon \quad \forall \epsilon > 0 \quad (14)$$

Test network and Results

The numerical results are obtained by simulation of a bus network where two different operators are supposed to operate.

Agent-based traffic simulation

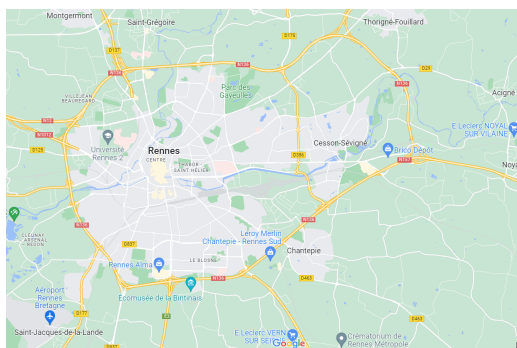
MATSim (Multi-Agent Transport Simulator), which is an open-source simulator that provides a framework to

implement large-scale activity-based transport simulations is used. In MATSim, network attributes (e.g. flow capacity and free speed) can be changed during the simulation to represent disruption events. In this study, we use MATSim to capture the dynamics of the multi-modal system during a disruption event in a single-day model.

MATSim has different modules working together to simulate traffic dynamics (25). Mobsim (mobility simulation module) is in charge of simulating the network loading (26). In every iteration, MATSim will take control of the lower-level, and calculate the user equilibrium based on an iterative algorithm. Each agent selects a plan from its memory based on user equilibrium principle, in order to optimize the initial demand. The plan's selection is done by the mean of a utility function that generates a score and associates it to each plan in the scoring module. The replanning module is responsible for the plan modification for each agent, and the user equilibrium is calculated in this module. The replanning process in our context is carried out based on (27)'s shortest path algorithm and (28)'s assignment algorithm to reroute users and converge to an equilibrium.

The network

To provide an example to illustrate how the proposed RaaS framework performs in a disrupted scenario, we implement our methodology for the network of Rennes city (Figure 3a) in France and its surrounding area. The Rennes metropolitan area's transport service is made up of a metro line, and 150 bus lines (regular and scholar) serving 43 municipalities. Rennes' network is built of 22384 edges and 32995 links. There are 1529 transit stops serving 73 regular bus lines. These lines serve 711 kilometers of surface and about 280000 daily trips. Figure 3 represents the Rennes transport map, Figure 3a is the real map of Renne, and Figure 3b is the network captured by MATSim. We used the web map OSM (OpenStreetMap) to obtain the geographical and topological data of this region, and the GTFS (General Transit Feed Specification) file provided by Rennes Metropole* in July 2022. The OSM data provides us with the activity facilities to be used in creating our OD demands, and the GTFS data is used to create the public transport fleet in the simulated area. By gathering and processing the data we obtain a multi-modal network containing the infrastructure on which the vehicles and agents can move around in the simulation, and the transit schedule file and vehicles file needed to integrate the public transport mode in the simulation.



(a) Rennes mapping data ©Google 2022



(b) MATSim city network

Figure 3. Network map of Rennes city

The application Scenario

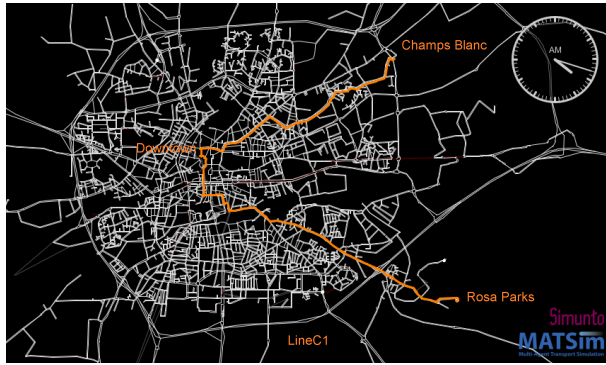
The scenario consists of simulating the traffic of Rennes and its surroundings in different circumstances, i.e., normal traffic and disrupted traffic. The disruption event is a fleet failure mainly applied to the bus line that connects Chantepie (a suburb of Rennes) to Rennes' downtown. It means that the passengers in Chantepie will not be able to go directly to Rennes. We are using a subpopulation of almost 1% to simulate the traffic between Chantepie and Rennes. The bus capacities are respected, and there is no traffic congestion in the simulated network. This simplification makes it easier to study the impact of the fleet failure disruption event on the passengers and the operators as well. We apply the RaaS methodology to this disruption case and solve the bi-level optimization problem. Note that we do not consider any extra or reserved fleet available in the period of disruption. Therefore the RaaS provider needs to reallocate the resources used by other services. Thus, we expect that the model, based on the number of passengers in the disrupted line, suggests sending one or more busses from other lines to disrupted travelers. The sent busses should be coming from the nearest bus station, in which the passengers will wait for the next bus to begin their trip.

Figure 4a displays in orange an example of LineC1 that goes from Rosa Parks in Chantepie to Champs Blanc in Cesson Sévigné via Rennes' downtown. It travels 13.692 kilometers and serves 39 stops. When LineC1 is disrupted, our methodology proposes to reallocate a bus from Line11. In other words, Line11 is passing by the nearest stop (called Forum) to rescue LineC1. Line11 is shown in yellow in Figure 4b. It goes from La Poterie in Rennes to ZI Ouest in Vesin-Le-Coquet via Rennes' downtown, making a traveling distance of 15.889 kilometers and serving 41 stops. The taken bus will make the route from the terminus of Line11 (La Poterie) to the terminus of LineC1 (Rosa Parks) to rescue the passengers, making an additional distance of 6.845 kilometers and an additional travel time of 23 minutes 23 seconds. This additional travel time made by Line11 from La Poterie (Line11 terminus) to Rosa Parks (LineC1 terminus) will cause an additional waiting time for passengers using LineC1 at Rosa Parks.

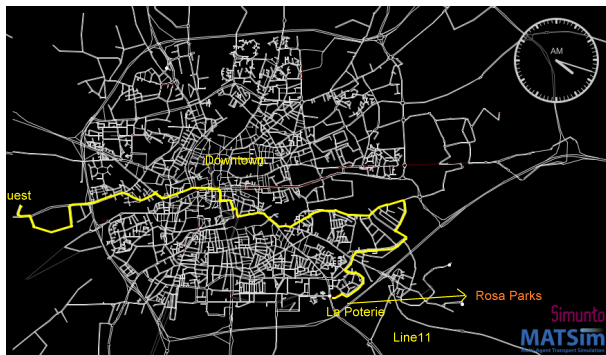
In order to evaluate the effectiveness of the RaaS strategy, we need to compare the scenario of disruption with and without the RaaS solution. In addition, we need to consider the normal scenario (no disruption) as the reference/baseline scenario to measure the cost and benefits of RaaS. Thus, the analysis should be carried out for the three following cases:

1. Normal Situation: Simulate public transport demand in a normal situation.
2. Disruption: Simulate the public transport demand in a disruption situation without RaaS.

*<https://data.rennesmetropole.fr>



(a) LineC1, in orange, is the disrupted line



(b) Line11, in yellow, is selected by RaaS providers to rescue LineC1

Figure 4. Disrupted scenario and the RaaS solution

3. RaaS: Simulate public transport demand in a rescue situation (application of RaaS).

Results

To understand how travel time, waiting time, and traveled distance by passengers and vehicles are impacted, we conducted simulations for three different cases (i.e. normal situation, disruption without RaaS and disruption with RaaS). Table 2 outlines the results of these simulations for bus LineC1 during normal operations and during the disruption without and with the help of RaaS units.

Within the simulation of RaaS decision model at upper-level, the impact of the disruption on LineC1 is investigated. To minimize the impact, Line11, the nearest bus to disruption point is interrupted and necessary fleet is dispatched to rescue the passengers of disrupted lineC1. This intervention resulted in reduction of the travel time of passengers of LineC1 by more than 50 minutes (from 1:35:16 (h:m:s) in the disruption situation to 45:12 (m:s) when the line C1 is rescued by units of Line11.

The traveled distance is also decreased from 8775 meters to 7106 meters which is exactly the traveled distance in the normal situation because it eliminates the walking distance done by passengers in the disruption situation to reach the

nearest bus station. In the absence of RaaS, the delay in the average travel time would be 56 minutes. When we apply RaaS, the delay is 6 minutes for LineC1 and 11 minutes for Line11, which gives a total delay of 17 minutes. Consequently, the average travel time of all users would be reduced by 69%. While we have an important gain in rescuing LineC1 by Line11, there is a cost to be paid by Line11, however, it is negligible compared to the time saved for line C1.

Discussion

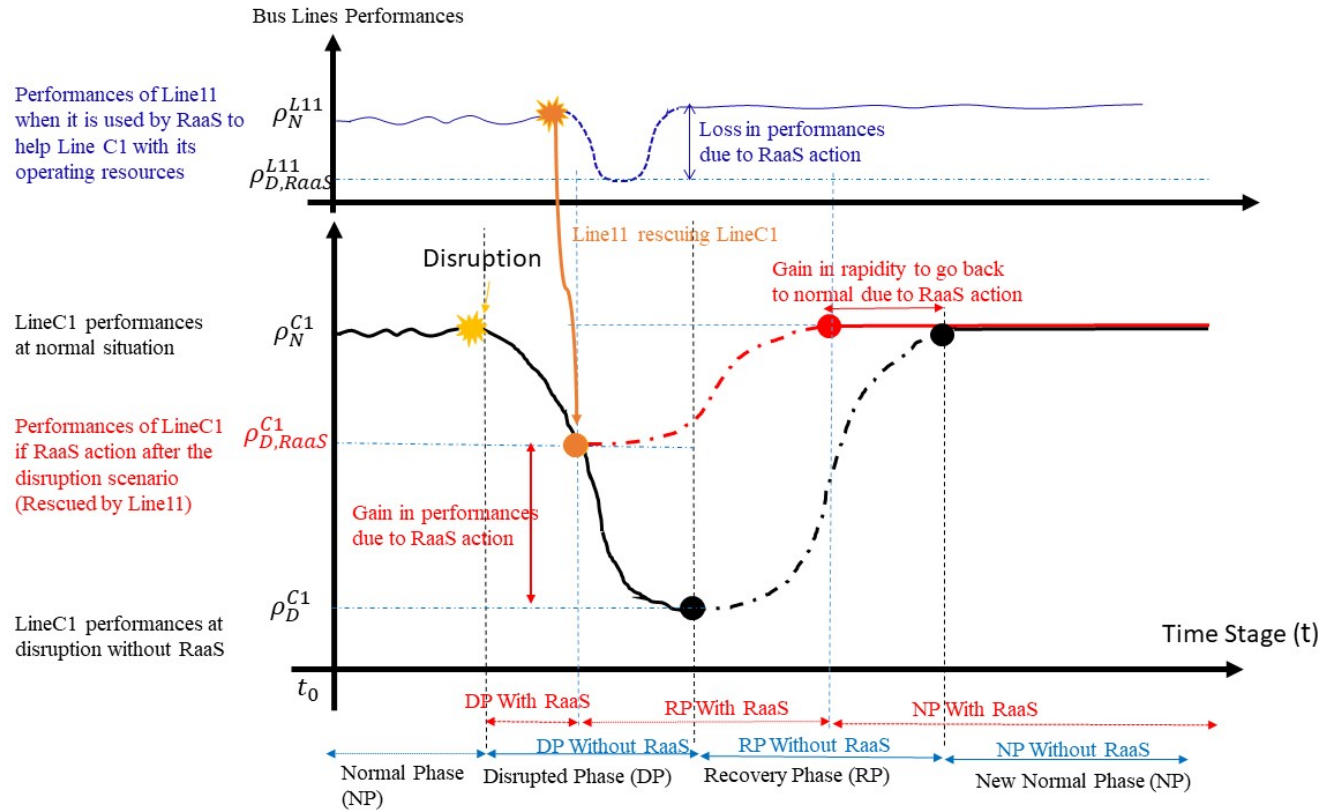
Figure 5 illustrates the performance differences between the two bus lines, providing insights into the resilience of transportation systems (29). The performances (e.g. speed, capacity) with respect to the occurrence time of the disruptive event can be divided into three stages: pre-disruption, during-disruption, and post-disruption periods. In the pre-disruption stage, the system operates in a normal state as planned (ρ_N performances). When a disruptive event occurs, the system performances decline and the degradation continues. Without any help, the performances drop to the threshold value (ρ_D). When the negative effects of the disruption are restored, a new cycle of system performance begins. The new normal phase may be different from the first one. As Shown in Figure 5, at the lower part, when Line11 rescues LineC1 (the RaaS is active), the performance of line C1 does not drop to ρ_D^{C1} . But to the better level of ($\rho_{D,RaaS}^{C1}$ shown in Table 2, average passengers' travel time improved by more than 50 minutes. Normally LineC1 and Line 11 belong to different bus operators. If there were a backup fleet in the second company (e.g., an additional set of vehicles ready but not planed for a service), RaaS would have only benefits. However, in our example, Line11 does not serve its passengers to help LineC1. Therefore, the drawback is a longer travel time for passengers of Line11 of 10 minutes (Figure 5, upper part). But as one can see, the global travel time of all passengers improved. The cost (the average travel time) for all passengers is 23 minutes and 23 seconds). The disturbances are less spread over time, which means RaaS makes the disrupted and recovery phases less significant compared to the situation where RaaS is not used).

Conclusions

In this paper, we provided a definition of a new paradigm in resilience for transportation systems, which is called Resilience as a Service (RaaS). The idea behind this concept is to propose a framework that aims to integrate the different forms of resilience services into one single resilience service. Taking into account the benefits of the transportation systems stakeholders, this framework considers the complex transportation systems in order to have a fast recovery from any kind of disruptions. In order to elaborate on the concept

Table 2. Summary of the simulation results for the disrupted LineC1 and the rescuing Line11 in different scenarios.

Scenario \ Indicator	LineC1			Line11		The operating cost of RaaS
	Normal Situation	Disruption	Rescued by Line11	Normal Situation	During LineC1 Disruption	
Average Travel Time	0:39:16	1:35:16	0:45:12	0:32:01	0:43:02	0:23:23
Average Waiting Time	0:15:15	0:22:38	0:23:32	0:06:13	0:17:13	-
Traveled Distance in Meters	7106	8775	7106	9695	9695	6845

**Figure 5.** The schematic of performances of LineC1 and Line11 with and without RaaS

of RaaS, and the way this management service works, we provided an example representing one management unit of RaaS in multi-modal urban transportation systems. To reach this objective, we proposed a bi-level mathematical model. The upper-level problem directly fulfills the RaaS providers' goals, which are partially aligned with the benefits of service providers and authorities. The objective of this level is to find the best resource re-allocation for all mobility services in the case of a disruption. The lower-level model represents the decision-making process of the traveler in order to achieve user equilibrium. After formulating the lower-level, we extended the bi-level programming model to a simulation-based framework to address practical test cases. The framework optimizes the objectives of both levels, and the summary of the proposed framework is shown in the Figure 2.

In order to examine the feasibility and the effectiveness of our solution method, we deployed an agent-based simulator and conducted a case study on the city of Rennes. One

of the key findings of this study is that by disrupting a mobility service that operates at the nominal level, we might use some new resources to help another fully disrupted mobility service. Our test case demonstrates that the benefit of applying the proposed method in reducing the average travel delay of all users is about 70%.

This work has several limitations; for example, in order to clearly illustrate and describe the concept of RaaS, we only take into account a management issue of bus providers for our test case. Other RaaS units (e.g. re-routing models in case of infrastructure disruption) should be considered. Also, including all the transportation services in the urban area (e.g., shared vehicle services, taxis, trains, etc.) will be more interesting for the RaaS service and challenging as it will extend our model to other modes. It will increase the computation time and complicate the simulation-based framework. Besides, we did not address the impact of the rescue plan on the recovery time, which could be an interesting question to be investigated.

This study opens a new door to resilience research. One of the interesting future works could be investigating other applications of RaaS, including the urban area and other transportation systems, e.g., air mobility, maritime mobility, etc. And also illustrate more complex methods by including the dynamical traffic models inside the bi-level program.

Author Contribution Statement

All the authors have contributed to all aspects of this study, ranging from the conception and design of the methodology, analysis, interpretation of the results, and the manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

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