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1 **RESILIENCE AS A SERVICE - RAAS IN TRANSPORTATION NETWORKS:**
2 **DEFINITION AND DESCRIBING THE CONCEPT**

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35 The authors declare no potential conflict of interests.

36 **AUTHOR CONTRIBUTION STATEMENT**

37 All the authors have contributed to all aspects of this study, ranging from the conception and
38 design of the methodology, analysis and interpretation of the results and discussion, and the
39 manuscript preparation.

40

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1 **ABSTRACT**

2 Urban transportation systems' structure and functionality can be affected by unexpected disrup-
3 tions due to several reasons, e.g., natural hazards, intentional attacks, accidents, etc. Resilience is
4 generally understood as the ability to recover from a disruptive event. There are multiple studies
5 in the literature focusing on resilience assessment and improving the resilience level of mobil-
6 ity services prior to disruption. However, few studies offer solutions for transportation systems'
7 operators during disruptions to reduce their impacts (e.g., recovery time). In this context, a new
8 paradigm, called Resilience as a Service (RaaS), has emerged in the field of operation management.
9 The idea of RaaS is to integrate the resource management system of different service providers
10 to improve the resilience level of the entire system and provide robust solutions for disruption
11 management. This paper proposes a definition of RaaS dedicated to transportation systems. To
12 provide a methodological example corresponding to the RaaS paradigm, we formulate a bi-level
13 optimization problem to represent a solution example that RaaS providers can deliver. The upper-
14 level model formulates the resource reallocation problem during disruption from the perspective of
15 RaaS providers, while the lower-level model considers user perspectives by calculating user equi-
16 librium, i.e., minimizing the travel cost of every user. We provide a numerical example in a real
17 test case of a French city to illustrate the benefits of implementing a RaaS solution. The results
18 show that we can reduce the average travel delay of all users by 69% compared to the absence of
19 RaaS.

20 *Keywords:* Resilience; RaaS; Mobility service; Public transport; Bi-level optimization; Simulation.

1 INTRODUCTION

2 Disruption can happen in different circumstances based on various factors, ranging from catas-
3 trophic natural hazards such as earthquakes and extreme weather conditions to man-made disas-
4 ters such as terrorist attacks, severe congestion, and road construction. They are distinguished by
5 their rapid evolution and severe effects on transportation systems during and after the impact of
6 disruption. The fact is that every distribution imposes multiple issues on the host system that can
7 be quantified by a cost. For instance, people in France lost 340 million minutes in 2018 due to
8 failures and delays (1). Making transportation systems more resilient against those disruptions
9 in order to maintain public safety and comfort has become a prioritized agenda for many urban
10 transport authorities. It is considered a critical skill to build modern and intelligent transportation
11 systems.

12 The concept of resilience was first introduced by (2) in 1973 to define an ecological sys-
13 tem's capacity to withstand disruption under stress and return to a stable condition. It was then
14 introduced in other fields, such as ecology, disaster management, risk engineering, etc. In the
15 transportation engineering and science field, resilience is defined as the ability of a transportation
16 system to maintain its structure and functionality in the face of disruptions (3). Many studies have
17 been undertaken to measure the resiliency of transportation systems based on various indicators,
18 e.g., robustness, reliability, redundancy, resourcefulness, rapidity, etc (4). However, most of the
19 works only focus on scanning the disruption and do not propose a framework able to provide
20 practical solutions in the event of disruptions. In addition, the state of the art in urban transport
21 resilience is considerably limited to investigating either one scenario of disruption or a single mo-
22 bility service (5, 6). In this study, we focus on a new paradigm in resilience that is mostly dedicated
23 to managing various types of disruption in multi-modal transportation systems.

24 The development of the transportation systems and networks in the urban areas and the high
25 mobility (population movement) require innovative solutions to increase the service reliability and
26 robustness of the system. Recently, a new paradigm is introduced in the context of resilience. It
27 is called *Resilience as a Service* (RaaS) and was first introduced in the literature, in the field of
28 cloud computing by (7). The general idea of RaaS is to support the disrupted component of the
29 system by using the operating or reserved resources of other components that are not affected by
30 perturbations.

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

43 In the context of resilience, a new management solution is required for both, centralized
44 and decentralized mobility services in order to maintain the highest level of service while low-
45 ering the risk of disruptions and the effects of perturbations. In this paper, we define RaaS as a

1 management system for the different mobility service providers, enabling them to integrate their
2 operating and reserved resources in order to reduce the recovery time from any kind of disruption.
3 In particular, RaaS aims to empower multi-modal transportation systems by outlining a manage-
4 ment mechanism to reduce the recovery time from a disruption event. RaaS can be interpreted
5 as a kind of agreement between multiple mobility service providers to reallocate their operating
6 resources during disruptions for a fast recovery of the entire system.

7 In this study, we first perform a comprehensive literature review on resilience in transporta-
8 tion systems in order to propose a standard definition for the RaaS paradigm. Second, to illustrate
9 how a RaaS system can be designed and operated, we propose a mathematical framework to make
10 an example of how a RaaS system can contribute to transportation systems. Third, we apply the
11 proposed methodology to a real test case of public transport in the city of Rennes in France to
12 validate our framework and show the effectiveness of RaaS in an urban area. The remainder of
13 the paper is organized as follows. A literature review on transportation resilience and RaaS is pre-
14 sented in Section 2. The results of the literature review lead us to provide the definition of RaaS
15 in Section 2. A methodological framework for RaaS is presented in Section 3. The numerical
16 experiment and its results are detailed in Section 4. Finally, we conclude this study and mention
17 our future works in Section 5.

18 LITERATURE REVIEW AND CONTRIBUTION STATEMENT

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

23 **Transportation systems resilience**

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

34 Resilience is also addressed in the literature as a range of concepts and definitions that play
35 a crucial role in designing assessment tools. (5) gives some keywords to quantify resilience: re-
36 dundancy, resourcefulness, rapidity, strength, and stability. (11) considered that the key parameters
37 in resilience quantification are as follows: disruptive events, component restoration, and overall re-
38 siliance strategy. After doing a comparative study to highlight the importance of resilience in the
39 system infrastructure, (12) proposed a process to evaluate the resilience of the system base on the
40 entropy theory, it is defined similarly to how resilience is quantified, as they both are trying to show
41 how the system is vulnerable against the disruptions.

42 In order to design a sustainable and resilient system, we need to consider three phases
43 in the disruption management, before, during, and after the perturbation, according to (13), a

1 resilient system is able effectively to adjust its functioning prior to, during, or following changes
2 and disturbances.

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

8 **Disruptions in transportation systems**

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

12 Disturbances can be categorized into internal and external threats (14). The internal threats
13 may originate from mistakes or/and accidents caused by staff or users, technical failures, compo-
14 nents that break down, faulty constructions, overload, etc. they could also be intentional, such as
15 labor market conflicts. External threats may be related to natural phenomena including various de-
16 grees of adverse weather and natural disasters: heavy rains, snowfalls, thunderstorms, hurricanes,
17 volcanic eruptions, earthquakes, etc. Another threat that is considered as long-term is global warm-
18 ing, which is partially a consequence of human activities in the transport sector. External threats
19 also include deliberate attacks such as sabotage, terrorism, and acts of war.

20 The consequences of disruptions in transportation networks vary according to many fac-
21 tors, including the type of disruption, duration, location, etc. Some studies divided disruption
22 consequences into direct and indirect costs. For example, (15) proposes a framework to provide
23 a comprehensive estimation of the indirect economic impacts of transportation disruptions. The
24 cost can be related to many reasons, (16) conclude that the failures are not significantly related
25 to the topological properties of the network, but to the duration of failure and passenger flow re-
26 distributions.

27 In the literature, there are several approaches to measure and quantify resilience, providing
28 different strategies to reduce the impact of disruptions, however, the perturbations are generally
29 difficult to estimate and predict. In the urban transportation systems, most of the studies focus
30 on the independent systems that try to optimize their own resilience, but, in real complex urban
31 systems, e.g, MaaS, several parts are working together and affecting each other. For these reasons,
32 we need a framework providing resilient solutions in the face of any kind of disruption, taking into
33 account the systems' multi-modality.

34 **Resilience as a service (RaaS)**

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

40 **Definition** (Resilience as a service). *Resilience as a service in a transportation system is the in-*
41 *tegration of various forms of resilience services into a single service accessible on demand by the*
42 *system's stakeholders. It aims to support multiple mobility services operating and correlating to-*
43 *gether in a single complex transport system in order to empower the ability of the global system to*

1 *anticipate, prepare for and adapt to changing conditions and resist, respond to and recover rapidly*
2 *from disruptions.*

3 RaaS can be designed for a centralized or decentralized structure. In its decentralized form, RaaS
4 provides a management system for the different mobility service providers to cooperate in order to
5 improve the resilience of the whole transportation system. It can be represented as an agreement
6 contract between them enabling resource reallocation in the case of a disruption, to reduce the
7 recovery time and costs. In its centralized structure, RaaS is an additional service that can optimize
8 all service plans together in order to respond to the disruption considering all the available modes
9 in the network.

10 In this paper, we limit our example to the solution that RaaS can provide during the disrup-
11 tion, in this context, RaaS should cover all the combinations of the multi-modal mobility services
12 to maintain their structure and function in the face of disruptions, and guarantee a fast repair ability.
13 Or suggest alternative solutions to the travelers. Its principal role is to be prepared to cope with
14 any kind of exceptional event.

15 **Problem statement**

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

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

33 In order to formulate the problem taking into consideration the different perspectives, we
34 used a bi-level mathematical model. According to (17), the bi-level programming model has
35 much more advantages compared with the traditional single-level programming model: first, it
36 can be used to analyze two different and even conflict objectives at the same time in the decision-
37 making process, second, the multiple-criteria decision-making methods of bi-level programming
38 can reflect the practical problem better, and third, the bi-level programming methods can explic-
39 itly represent the mutual- action between the system managers and the customers, i.e., different
40 stakeholders.

41 In this work, we use a bi-level optimization, in order to consider the problem solved by
42 RaaS. Different perspectives and goals of the stakeholders should be taken into consideration. For
43 this reason, RaaS aims to minimize the allocation of resources, as well as achieve user equilibrium.

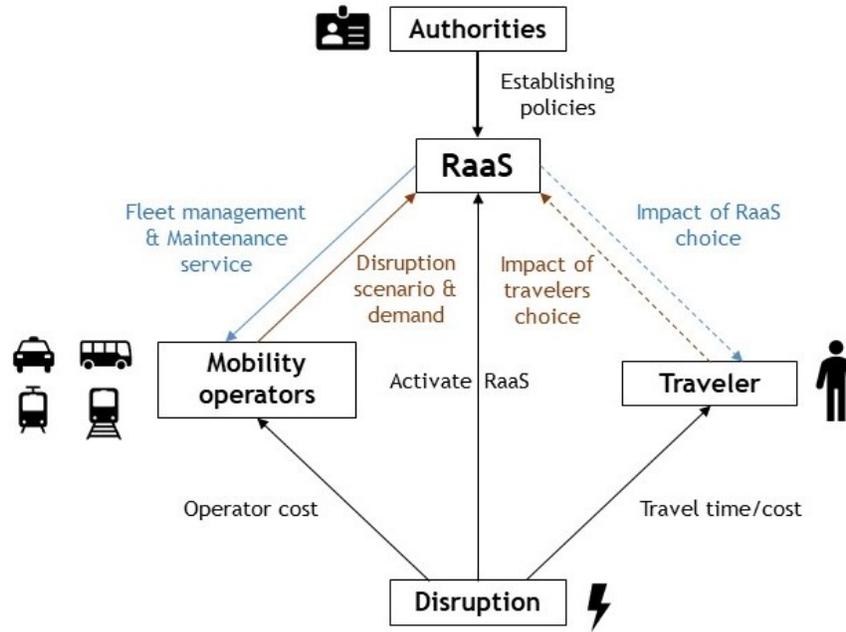


FIGURE 1: Relationship between the different stakeholders.

- 1 This interaction can be represented through the following bi-level programming problem. (18).

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

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

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

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

- 10 $y = y(x)$ is the response function or the reaction, it connects the upper and the lower-
 11 level decision variables, the response function is obtained by solving the lower-level problem and
 12 replacing the variable y in the upper-level problem with the relationship between x and y , the two
 13 programming models are dependent one another (17).

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

1 METHODOLOGICAL FRAMEWORK

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

6 Let us represent the resources with two components, the number of assigned vehicles to
 7 scheduled services and the maintenance or supporting units. The assignment problem at the upper
 8 level is about assigning these two resources to defined services in order to serve the demand. The
 9 objectives of the model are minimizing: (i) the resources used by the undisrupted services with
 10 respect to their demand, (ii) recovery time, and (iii) the difference between the current (disrupted)
 11 service level and the normal level. Optimizing the upper level leads us to find the optimal values
 12 for the supply side in which more resources are reallocated to the disrupted service in order to
 13 reduce the recovery time and increase the service level toward the normal situation. Afterward,
 14 we represent the decision-making process of the travelers in the lower-level model. Recall that the
 15 goal of this model is to achieve user equilibrium. Therefore, the objective function is formulated
 16 as minimizing the travel cost of every traveler (19). The decision variable in this level is the
 17 assignment variable, which denotes the decision of travelers about choosing their travel mode
 18 among the available transportation modes.

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

22 Analytical formulation of the RaaS management unit

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

31 *Upper-level model*

32 The upper-level model is formulated from the perspective of RaaS providers. Before presenting
 33 the model, let us define a disrupted scenario δ as the network state in which a disruption affects
 34 one or more links (20). The travel time of mode j for OD pair w , denoted by t_j^w , is a function of the
 35 basic (i.e., normal or undisrupted) travel time ($t_j^{w,b}$) and the impact factor of effective disruption(s),
 36 equation 3 is the main equation for calculating the travel time:

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

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

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 OD 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 OD pair w .
π_j^w	Number of modes j assigned to OD pair w .
λ_j^w	Number of maintenance units corresponding to mode j assigned to OD 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 OD 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.
R_j^δ	Maintenance (recovery) units needed for mode j to make disruption δ ineffective.
ft_j^w	The free flow travel time of mode j for OD pair w .
h_{\max}^w	Maximum headway for OD pair w .

1 where, R_j^δ denotes maintenance (recovery) units needed for mode j to make disruption δ ineffec-
2 tive. $y_j^{w,\delta}$ is a binary variable showing if mode j on w is affected by disruption δ or not. This
3 binary variable is defined in equation 5. The fraction in equation 4 highlights the relation between
4 the basic travel time and the impact of disruption, which can be reduced by using the maintenance
5 units (recovery resources), this equation is an example of the equation 3. Note that R_j^δ can have
6 various values based on the disturbances that disruption δ imposes on the system.
7 (21)

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

8 $t_j^{w,b}$ should be calculated separately for fixed and on-demand mobility services. For fixed
9 scheduled services (e.g. bus, shuttle bus, etc.), $t_j^{w,b}$ in equation 4 is calculated by equation 6, where
10 the basic travel time is a function of the free flow travel time, the maximum headway corresponding

1 to the service, and the number of the available in the system for an origin-destination pair. For on-
 2 demand services (e.g. taxi, etc.), $t_j^{w,b}$ is calculated by replacing headway with travel distance from
 3 i to the point of passenger demand while considering the impact of congestion and competence
 4 with other taxi on the arrival time of on-demand service.

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

5 where ft_j^w denotes the free flow travel time of mode j for w , h_{\max}^w is the maximum headway [time]
 6 of a service on w , and π_j^w is the number of modes j assigned to w . The fraction in this equation
 7 aims to represent the time period of service, i.e., the inverse of the frequency of mode j for w .

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

$$\min_{\pi_j^w, \lambda_j^w} \quad \alpha \frac{\sum_{w \in W} \sum_{j \in M} \pi_j^w (1 - y_j^w)}{\sum_{j \in V} N_j} + \beta \frac{\sum_{w \in W} \sum_{j \in M} \lambda_j^w (1 - y_j^w)}{M_j} + \gamma \frac{-\sum_{w \in W} \sum_{i \in P_w} U_i^w(tc_i, x_{ij}^w)}{\sum_{w \in W} \sum_{i \in P_w} U_i^w(tc^b, x^b)} \quad (7a)$$

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

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

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

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

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

9 Equation 7a presents the objective function of the system for the RaaS providers, it includes
 10 three main components. The first is related to minimizing the non-disrupted service resources used
 11 by service providers, where π_j^w is the number of modes j assigned to OD pair w , and N_j is the
 12 total number of available modes j . The second component is about minimizing the maintenance
 13 resources for the non-disrupted lines, where λ_j^w is the number of maintenance units corresponding
 14 to mode j assigned to OD pair w , and M_j is the total number of available maintenance units corre-
 15 sponding to mode j . The main idea of the two first components is to take into account the objective
 16 of the disrupted service providers, by providing extra resources for a fast recovery. We multiply
 17 these components with $(1 - y_j^w)$ shown in Equation 8 to eliminate all the disrupted lines from the
 18 objective function, it is a binary value determining either a mode j is disrupted by any type of dis-
 19 ruption or not, where $y_j^{w,\delta}$ is also a binary variable represented in Equation 5. The third component
 20 aims to minimize the difference between the total utility of the normal and the disrupted situation,
 21 in this component, we include the variables originating from the lower level, where $U_i^w(\cdot)$ is the
 22 utility function of user i , traveling for w . The three components are integrated in a single objective
 23 function with a weighted sum, the weights are denoted by α , β , and γ , where $\alpha + \beta + \gamma = 1$. In
 24 Equation 7a we try to normalize each component of the objective function.

25 The constraint Equation 7b forces the non-disrupted mobility services to serve all their
 26 demand, we exclude the disrupted services as they are already perturbed, and cannot fully serve

1 their demand, where D_w is the total demand for OD pair w . The constrains of Equation 7c and
 2 Equation 7d aim to conserve the total number of the available mobility services and maintenance
 3 resources, where N_j is the total number of available modes j , and M_j is the total number of avail-
 4 able maintenance units corresponding to mode j . The constraint in Equation 7e ensures, that we
 5 cannot add more recovery resources than what a disrupted service needs, where R_j^δ is the main-
 6 tenance units needed for mode j to make disruption δ ineffective. The last constraint presented
 7 in the Equation 7f is the positivity condition on the decision variables, which are π_j^w and λ_j^w . As
 8 mentioned in Equation 1, the input of the objective function of the upper-level comes from the
 9 lower-level.

$$y_j^w = 1 - \prod_{\forall \delta} (1 - y_j^{w,\delta}) \quad \forall j \in M \quad (8)$$

10 *Lower-level model of the RaaS bi-level mathematical model*

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

$$\min_{x_{ij}^w} \quad tc_i = \sum_{j \in M} x_{ij}^w t_j^w \quad \forall w \in W, i \in P_w \quad (9a)$$

$$\text{s.t.} \quad \sum_{i \in P_w} x_{ij}^w \leq C_j \pi_j^w \quad \forall w \in W, j \in M, \quad (9b)$$

$$\sum_{j \in M} x_{ij}^w = 1 \quad \forall w \in W, i \in P_w, \quad (9c)$$

$$\sum_{i \in P_w} \sum_{j \in M} x_{ij}^w = D^w \quad \forall w \in W, \quad (9d)$$

$$x_{ij}^w \in 0, 1 \quad \forall w \in W, i \in P_w, j \in M. \quad (9e)$$

13 where

$$x_{ij}^w = \begin{cases} 1 & \text{If user } i \text{ assign to mode } j; \\ 0 & \text{Otherwise.} \end{cases} \quad (10)$$

14 In this level, the objective function is presented in Equation 9a, it aims to minimize the total
 15 cost of each traveler, to reach the user equilibrium, where x_{ij}^w is the assignment of a traveler i to a
 16 transportation mode j , it is a binary variable expressed in the Equation 10, it takes the value of 1
 17 if a traveler i is assigned to a transportation mode j ; and 0 otherwise, and t_j^w is the travel time of a
 18 mode j in a pair w .

19 The constraint in Equation 9b ensures that the some of all the passengers assigned to a
 20 mode j should be less than the capacity of the service, its objective is to conserve the capacity of
 21 the service, where C_j is the capacity of a mode j . The constraint in Equation 9c guarantees that each
 22 traveler is assigned to only one mode. The constraint in Equation 9c is about the demand, the total
 23 number of users traveling in the system should be equals to the demand for each origin-destination
 24 w , where D_w is the total demand for OD pair w .

1 In this paper, our mathematical model is designed for a multimodal urban transportation
 2 system, in this case, the solution is not analytically feasible because of the large number of param-
 3 eters, for this reason, we use the simulation-based approach, to do so, we incorporate the traffic
 4 simulator, in order to provide all the input data needed, and also capture the dynamics of the mul-
 5 timodal transportation systems.

6 **Simulation-based framework for the RaaS management unit**

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

13 The iterative process including the steps is detailed in the flowchart represented in the
 14 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 a 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, by this step we aim to measure the impact of the disruption on travelers, by determining how the travel time is affected, and we also capture the dynamics of the system.

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 the equation 11 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.

$$\frac{\sum_{w \in W} \sum_{i \in P_w} U_i^w(tc_i, x_{ij}^w)}{\sum_{w \in W} \sum_{i \in P_w} U_i^w(tc^b, x^b)} \quad (11)$$

Step 5. **Solve the fleet management problem:** In this step, we solve the fleet management problem, we obtain the optimum values of π_j^w and λ_j^w that will be used as inputs of the lower-level. Simulation-

Step 6. **Update lower-level parameters:** This step is for updating all the lower-level inputs which characterise the supply side, based on the optimum values that come from the 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 the step 2.

1 TEST NETWORK AND RESULTS

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

4 Agent-based traffic simulation

5 MATSim (Multi-Agent Transport Simulator), which is an open-source simulator that provides a
6 framework to implement large-scale activity-based transport simulations is used. In MATSim,
7 network attributes (e.g. flow capacity and free speed) can be changed during the simulation to
8 represent disruption events. In this study, we use MATSim to capture the dynamics of the multi-
9 modal system during a disruption event in a single-day model.

10 MATSim has different modules working together to simulate traffic dynamics (22). Mob-
11 sim (mobility simulation module) is in charge of simulating the network loading (23). In every
12 iteration, MATSim will take control of the lower level, and calculate the user equilibrium based
13 on an iterative algorithm. Each agent selects a plan from its memory based on user equilibrium
14 principle, in order to optimize the initial demand. The plan's selection is done by the mean of
15 a utility function that generates a score and associates it to each plan in the scoring module. The
16 replanning module is responsible for the plan modification for each agent, and the user equilibrium
17 is calculated in this module. The replanning process in our context is carried out based on (24) to
18 reroute users and converge to an equilibrium.

19 The network

20 To provide an example to illustrate how the proposed RaaS framework performs in a disrupted
21 scenario, we implement our methodology for the network of Rennes city (Figure 3a) in France
22 and its surrounding area. The Rennes metropolitan area's transport service is made up of a metro
23 line, and 150 bus lines (regular and scholar) serving 43 municipalities. Rennes' network is built
24 of 22384 edges and 32995 links. There are 1529 transit stops serving 73 regular bus lines. These
25 lines serve 711 kilometers of surface and about 280000 daily trips. Figure 3 represents the Rennes
26 transport map, Figure 3a is the real map of Renne, and Figure 3b is the network captured by
27 MATSim. We used the web map OSM (OpenStreetMap) to obtain the geographical and topological
28 data of this region, and the GTFS (General Transit Feed Specification) file provided by Rennes
29 Metropole¹ in July 2022. The OSM data provides us with the activity facilities to be used in
30 creating our Origin-Destination demands, and the GTFS data is used to create the public transport
31 fleet in the simulated area. By gathering and processing the data we obtain a multi-modal network
32 containing the infrastructure on which the vehicles and agents can move around in the simulation,

¹<https://data.rennesmetropole.fr>

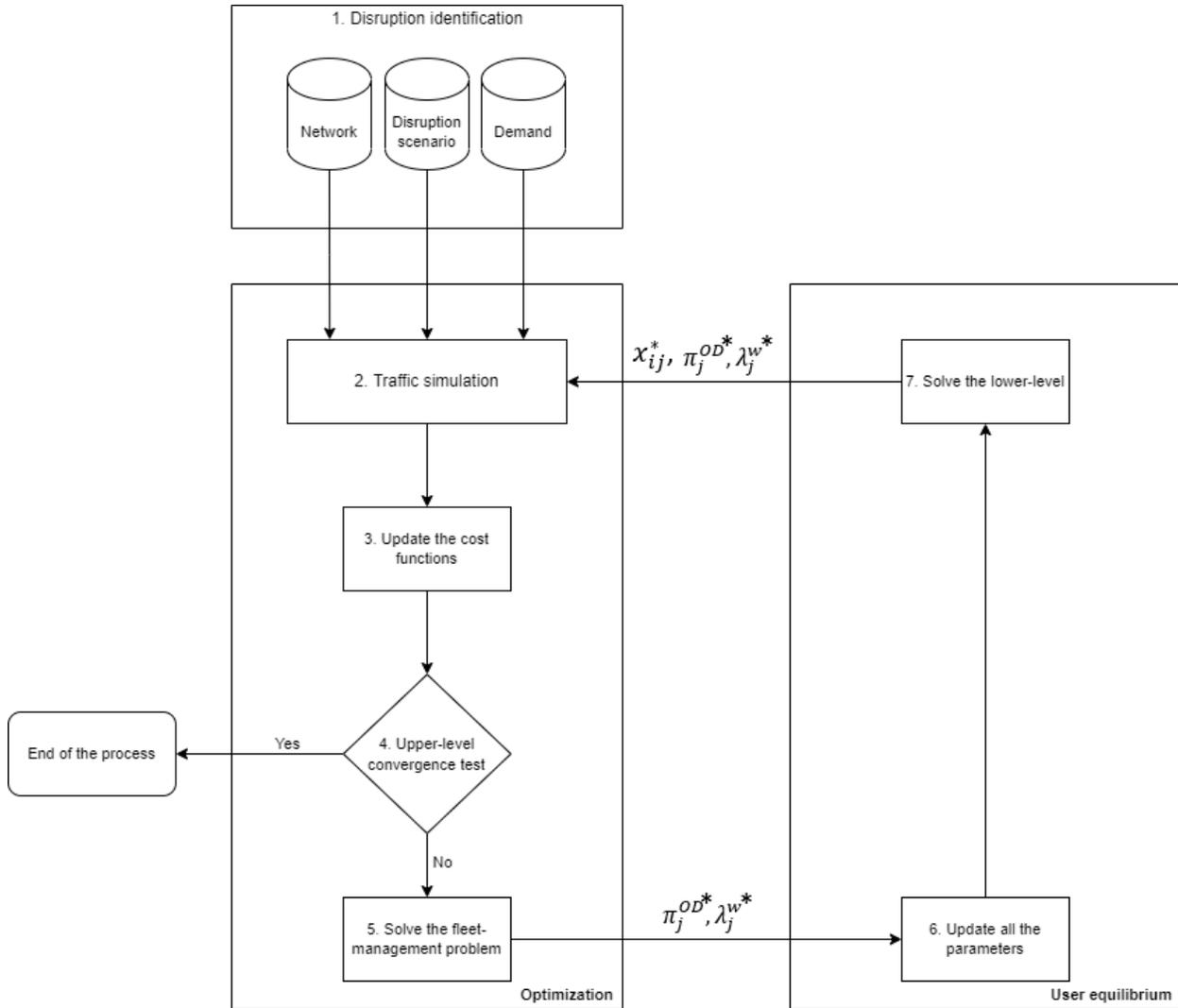


FIGURE 2: Flowchart of the simulation-based framework.

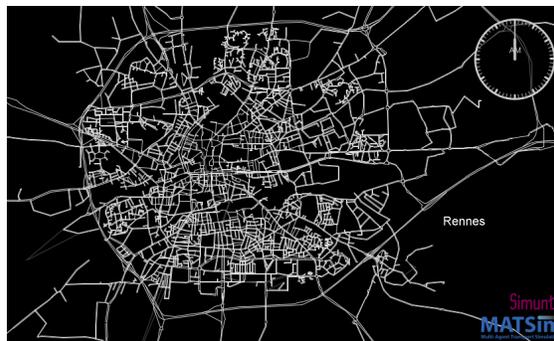
1 and the transit schedule file and vehicles file needed to integrate the public transport mode in the
2 simulation.

3 **The application Scenario**

4 The scenario consists of simulating the traffic of Rennes and its surroundings in different circum-
5 stances, i.e., normal traffic and disrupted traffic. The disruption event is a fleet failure mainly
6 applied to the bus line that connects Chantepie (a suburb of Rennes) to Rennes' downtown. It
7 means that the passengers in Chantepie will not be able to go directly to Rennes. We are using a
8 subpopulation of almost 1% to simulate the traffic between Chantepie and Rennes. The bus capac-
9 ities are respected, and there is no traffic congestion in the simulated network. This simplification
10 makes it easier to study the impact of the fleet failure disruption event on the passengers and the
11 operators as well. We apply the RaaS methodology to this disruption case and solve the bi-level
12 optimization problem. Note that we do not consider any extra or reserved fleet available in the
13 period of disruption. Therefore the RaaS provider needs to reallocate the resources used by other



(a) Rennes mapping data ©Google 2022

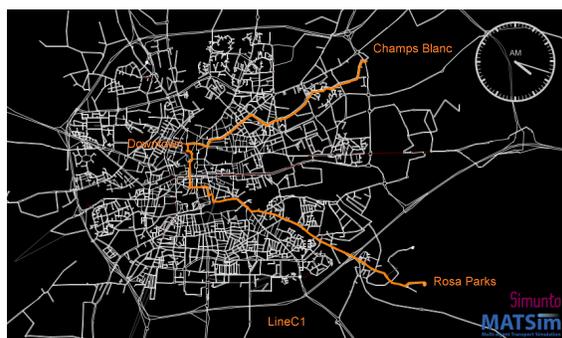


(b) MATSim city network

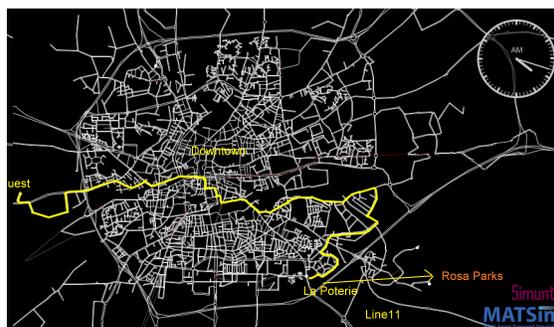
FIGURE 3: Network map of Rennes city

1 services. Thus, we expect that the model, based on the number of passengers in the disrupted line,
 2 suggests sending one or more busses from other lines to disrupted travelers. The sent busses should
 3 be coming from the nearest bus station, in which the passengers will wait for the next bus to begin
 4 their trip.

5 Figure 4a displays in orange an example of LineC1 that goes from Rosa Parks in Chantepie
 6 to Champs Blanc in Cesson Sévigné via Rennes' downtown. It travels 13.692 kilometers and serves
 7 39 stops. When LineC1 is disrupted, our methodology proposes to reallocate a bus from Line11.
 8 In other words, Line11 is passing by the nearest stop (called Forum) to rescue LineC1. Line11 is
 9 shown in yellow in Figure 4b. It goes from La Poterie in Rennes to ZI Ouest in Vesin-Le-Coquet
 10 via Rennes' downtown, making a traveling distance of 15.889 kilometers and serving 41 stops. The
 11 taken bus will make the route from the terminus of Line11 (La Poterie) to the terminus of LineC1
 12 (Rosa Parks) to rescue the passengers, making an additional distance of 6.845 kilometers and an
 13 additional travel time of 23 minutes 23 seconds. This additional travel time made by Line11 from
 14 La Poterie (Line11 terminus) to Rosa Parks (LineC1 terminus) will cause an additional waiting
 15 time for passengers using LineC1 at Rosa Parks.



(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

16 In order to evaluate the effectiveness of the RaaS strategy, we need to compare the scenario
 17 of disruption with and without the RaaS solution. In addition, we need to consider the normal

TABLE 3: 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

1 scenario (no disruption) as the reference/baseline scenario to measure the cost and benefits of
 2 RaaS. Thus, the analysis should be carried out for the three following cases:

- 3 1. Simulate public transport demand in a normal situation.
- 4 2. Simulate the public transport demand in a disruption situation.
- 5 3. Simulate public transport demand in a rescue situation.

6 **Results**

7 By simulating the three cases, the analysis of different output attributes can lead us to calculate
 8 the travel time, the waiting time, and the traveled distance for each passenger and vehicle in the
 9 simulation in three different situations. Table 3 summarizes the simulation results for the bus
 10 LineC1 in a normal situation, during the disruption, and with the help of bus Line11. For Line11,
 11 the results are collected in only two cases: the normal situation and during the disruption of LineC1
 12 while passengers of Line11 wait for the next bus.

13 Simulating the upper-level of the RaaS decision model, in order to minimize the impact
 14 of the disruption while using the minimum resource, Line11, the nearest is interrupted and sent to
 15 help the LineC1 for the total Origin-Destination demand. This RaaS intervention, reduced by more
 16 than 50 minutes the travel time of passengers of LineC1 (from 1:35:16 in the disruption situation
 17 to 45:12 seconds when the line C1 is rescued after the disruption). The traveled distance is also
 18 decreased from 8775 meters to 7106 meters which is exactly the traveled distance in the normal
 19 situation because it eliminates the walking distance done by passengers in the disruption situation
 20 to reach the nearest bus station. In the absence of RaaS, the delay in the average travel time would
 21 be 56 minutes. When we apply RaaS, the delay is 6 minutes for LineC1 and 11 minutes for Line11,
 22 which gives a total delay of 17 minutes. consequently, the average travel time of all users would be
 23 reduced by 69%. While we have an important gain in rescuing LineC1 by Line11, there is a cost
 24 to be paid by Line11, however, it is negligible compared to the time saved for line C1.

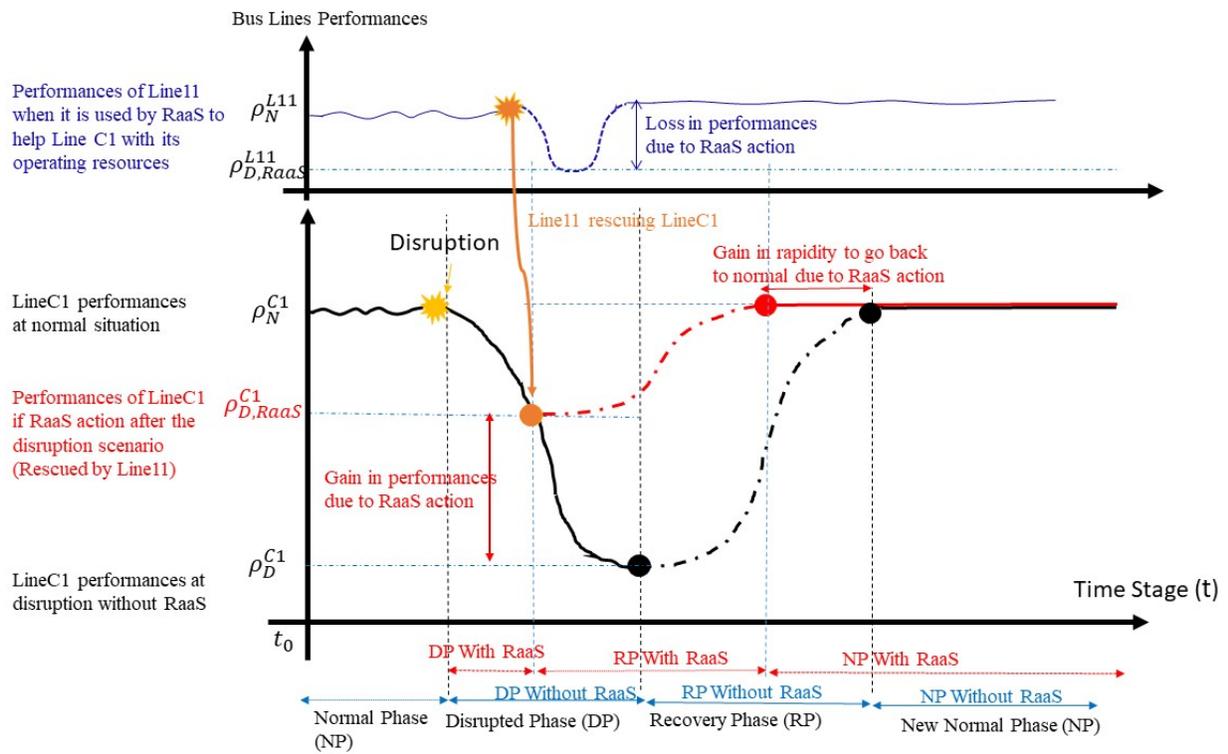


FIGURE 5: The schematic of performances of LineC1 and Line11 with and without RaaS

1 Discussion

2 Figure 5 gives the schematic of the performances of the two bus lines. It is drawn based on the
 3 figure given by (25). The performances (i.g. speed, capacity) with respect to the occurrence time
 4 of the disruptive event can be divided into three stages: pre-disruption, during-disruption, and post-
 5 disruption periods. In the pre-disruption stage, the system operates in a normal state as planned
 6 (ρ_N performances). When a disruptive event occurs, the system performances decline and the
 7 degradation continues. Without any help, the performances drop to the threshold value (ρ_D). when
 8 the negative effects of the disruption are restored, a new cycle of system performance begins. The
 9 new normal phase may be different from the first one. As Shown in Figure 5, at lower part, when
 10 Line11 rescues LineC1 (the RaaS is active), the performance of line C1 doesn't drop until ρ_D^{C1} but
 11 to the better level of ($\rho_{D,RaaS}^{C1}$). As shown in Table 3, average passengers' travel time improved
 12 by more than 50 minutes. Normally LineC1 and Line 11 belong to different bus operators. If
 13 there were a backup fleet in the second company, RaaS would have only benefits. However in our
 14 example, Line11 doesn't serve its passengers to help LineC1, therefore the drawback is a longer
 15 travel time for passengers of Line11 of 10 minutes (Figure 5, upper part). But as one can see, the
 16 global travel time of all passengers improved. The cost for all passengers is of 23 minutes and 23
 17 seconds), and the disturbances are less spread over time (The disrupted phase and Recovery phases
 18 are less important with RaaS than without it).

19 CONCLUSIONS

20 In this paper, we provided a definition of a new paradigm in resilience for transportation systems,
 21 which is called Resilience as a Service (RaaS). The idea behind this concept is to propose a frame-
 22 work that aims to integrate the different forms of resilience services into one single resilience
 23 service. Taking into account the benefits of the transportation systems stakeholders, this frame-
 24 work considers the complex transportation systems in order to have a fast recovery from any kind
 25 of disruptions. In order to elaborate on the concept of RaaS, and the way this management service
 26 works, we provided an example representing one management unit of RaaS in multi-modal urban
 27 transportation systems. To reach this objective, we proposed a bi-level mathematical model. The
 28 upper-level problem fulfills directly the RaaS providers' goals, which are partially aligned with the
 29 benefits of service providers and authorities. The objective of this level is to find the best resource
 30 re-allocation for all mobility services in the case of a disruption. The lower-level model repre-
 31 sents the decision-making process of the traveler, it aims to achieve the user equilibrium. After
 32 formulating the lower level, we extended the bi-level programming model to a simulation-based
 33 framework, in order to address practical test cases, the framework covers the objectives of both
 34 levels, the summary of the proposed framework is shown in the Figure 2.

35 In order to examine the feasibility and the effectiveness of our solution method, we de-
 36 ployed an agent-based simulator and conducted a case study on the city of Rennes. One of the
 37 key findings of this study is that by disrupting a mobility service that operates at the nominal level,
 38 we might use some new resources to help another fully disrupted mobility service. Our test case
 39 demonstrates that the benefits of this method are about 70%.

40 This work has several limitations, for example, in order to clearly illustrate and describe the
 41 concept of RaaS, we only take into account a management issue of bus providers for our test case.
 42 Other RaaS units (i.g. re-routing models in case of infrastructure disruption) should be considered.
 43 Also, including all the transportation services in the urban area (e.g., shared vehicle services, taxis,
 44 trains, etc.) will be more interesting for the RaaS service, and challenging as it will extend our

1 model to other modes. It will increase the computation time and complicate the simulation-based
2 framework.

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

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