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THE DESIGN OF ADDITIONAL PUBLIC TRANSPORT SERVICES TO INCREASE THE RESILIENCE OF ROAD NETWORKS

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Abstract. Some events (as, for instance, a bridge collapse, an underpass closure or a road maintenance intervention) may generate the total or partial unavailability of some elements of urban road networks. Hence, some users have to redirect their paths generating an increase in congestion on the remaining part of the network. In this context, this paper proposes the design of additional public transport services to increase the resilience of road urban networks by affecting the user modal choices to reduce road flows and bring congestion levels as close as possible to the initial equilibrium conditions. Finally, to verify the usefulness and feasibility of the proposed methodology, it has been applied in the case of the road network of Fuorigrotta, a district of the city of Naples, in southern Italy.

Keywords: urban transport management, public transport services, network resilience, multimodal network design, user equilibrium.

JEL Classification: C61, L92, O18, O21, R41, R42.

Introduction

According to the Cambridge Business English Dictionary (2023), the term resilience means "*the quality of being able to return quickly to a previous good condition after problems*". In this context, the resilience of a transport system (as, for instance, a road network) can be considered as the ability to react to external events (such as disruptions, breakdowns, etc.) returning to the unperturbed initial conditions.

Balakrishnan and Cassottana (2022) propose a simulation platform which analyses jointly power, water and transport networks to verify disaster effects in terms of infrastructure failures and determine subsequent post-disaster restoration. Likewise, Besinovic et al. (2022) propose a passenger-centred resilience assessment for analysing disruption scenarios in railway contexts. In particular, they identify two classes of disruptions: short-duration disruptions (about 1–2 hours) and long-duration disruptions (multiple days or weeks). Moreover, Guo et al. (2021) identify the optimal location of emergency rescue facilities to improve resilience on multimodal transport networks; while Liu et al. (2022) propose to act modifying access flows to railway stations to increase the resilience of multimode public transit networks. Finally, Potter et al. (2022) apply the resilience concept to the rail freight context.

Since a transport system represents an object that is designed (or in some cases redesigned), in terms of resilience, it is possible to identify 3 feasible conditions: (1) the design of a transport system with pre-established resilience values; (2) the analysis of an (existing) transport system to determine its resilience values; (3) the modification/redesign of a transport system to vary its resilience values.

Whatever the condition to be analysed, it is necessary to have 2 classes of models: (a) design models, to define the values of decision variables (design parameters) to achieve a prefixed objective; (b) simulation models, to define the values of descriptive variables (flow parameters) to describe the performance of a transportation system in the case of a prefixed configuration.

Both classes of models have been extensively analysed in the literature. Indeed, design models have been examined in the case of private road systems (Magnanti & Wong, 1984; Meng & Yang, 2002; Mahmoudi et al., 2019; Shanmugasumdaram et al., 2019), public transport systems (LeBlanc, 1988; Cipriani et al., 2012; Yao et al., 2014; Bin et al., 2015; Szeto et al., 2015; Owais & Osman, 2018) and multimodal transport systems (D'Acierno et al., 2011; Gallo et al., 2011; Miandoabchi et al., 2012; Huang et al., 2018;

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Pinto et al., 2020). Likewise, simulation models have been examined in the case of private road systems (Daganzo & Sheffi, 1977; Sheffi & Powell, 1981; Yildirimoglu et al., 2018; Salman & Alaswad, 2018), public transport systems (Fernandez et al., 1994; Wu et al., 1994; Nguyen et al., 1998; Nuzzolo et al., 2012; Narayan et al., 2020) and multimodal transport systems (Cantarella, 1997; D'Acierno et al., 2002; Zhang et al., 2020; Jiang & Nielsen, 2022).

In this context, the paper aims to increase the resilience of the road transport network by providing additional public transport services. Indeed, in the analysis of urban context, it is necessary to adopt multimodal approaches since: (a) users generally have at least 2 available transport systems: the private road and the public transport systems. A variation in the performance of one of them can produce a variation in user modal choices and, therefore, a different use degree for each of them; (b) congestion of the private road system affects the performance (i.e., travel times) of buses in shared lanes and service frequencies of buses in share lanes affect congestion of the private road system.

The close dependence between the 2 transport systems in urban areas can be exploited to mitigate the effect of feasible disruptions and/or breakdowns on a system by improving the other transport system.

The paper is organised as follows: Section 2 provides a methodology based on a multimodal approach for analysing the resilience of transportation systems and suggesting optimal mitigative interventions; Section 3 applies the proposed methodology in a real case study; finally, conclusions and research prospects are synthesised in Section 4.

1. The resilience analysis of a multimodal transportation network

As described in the introduction, the analysis of an urban transport system requires a multimodal approach to take into account the users' choices (the users' modal choices are a function of the performances of all transport systems in the area) and the reciprocal influences of the networks (the number of vehicles travelling on a network may affect the performance of other networks).

Therefore, a *Resilience Analysis Model* (*RAM*) may be formulated as a multidimensional constrained optimisation problem based on a multimodal network design problem framework (Montella et al., 2000), that is:

$$\hat{\boldsymbol{y}} = \underset{\boldsymbol{y} \in \boldsymbol{S_y}}{\arg\min}\ Z\left(\boldsymbol{y}, \boldsymbol{f_c^*}, \boldsymbol{f_b^*}\right) \tag{1}$$

subject to:

$$\left[\boldsymbol{f_c^*}, \boldsymbol{f_b^*}\right] = \boldsymbol{\Lambda}\left(\boldsymbol{y}, \boldsymbol{f_c^*}, \boldsymbol{f_b^*}\right); \tag{2}$$

$$\mathrm{B}\left(\boldsymbol{y}, \boldsymbol{f_c^*}, \boldsymbol{f_b^*}\right) \le \mathrm{B}^*, \tag{3}$$

where $\boldsymbol{y}$ is the decisional variable vector to be optimised; $\hat{\boldsymbol{y}}$ is the optimal value of $\boldsymbol{y}$; $\boldsymbol{S_y}$ is the feasibility set of variable $\boldsymbol{y}$; Z is the objective function to be minimised; $\boldsymbol{f_c^*}$ is the equilibrium flow vector associated with the private road system; $\boldsymbol{f_b^*}$ is the equilibrium flow vector associated with the public transport system; $\boldsymbol{\Lambda}$ is the assignment function; B is the budget function and B^* is the budget threshold.

Equation (1) expresses the optimisation problem which consists in determining the optimal value of variable $\boldsymbol{y}$, indicated as $\hat{\mathbf{y}}$, which belongs to the feasibility set $\boldsymbol{S_y}$ and minimises objective function Z, depending on decisional variable $\boldsymbol{y}$ and equilibrium flows ($\boldsymbol{f_c^*}$ and $\boldsymbol{f_b^*}$).

Constraint (2) is the multimodal assignment constraint which provides equilibrium flows of each transportation system consistent with themselves. Details on the formulation of the multimodal assignment problem and related solution algorithms can be found in Cantarella (1997) and D'Acierno et al. (2002). To further clarify this aspect, it has been detailed in Section 2.1.

Constraint (3) is the budget constraint which provides the budget value associated with each value of decisional variable $\boldsymbol{y}$ and corresponding equilibrium flows ($\boldsymbol{f_c^*}$ and $\boldsymbol{f_b^*}$) which has to be not higher than budget threshold B^*.

Hence, the resilience analysis consists in determining: (a) the disruption scenarios in terms of event/events, the duration of the event/events, and the implications in terms of transport networks; (b) the variables to be designed/improved to compensate for the negative effects induced by the hypothesised disruption scenarios; (c) the evaluation of network performance variations among the different scenarios: initial condition, disruption scenarios without interventions and disruption scenarios with interventions.

1.1. The bimodal assignment model

In transportation networks, users make travel choices (such as mode choices and/or path choices) as a function of network performance but network performance depends on the number of users that share the same element of the network. Hence, it is necessary to identify a user flow configuration which provides network performance which affects user choices so as to generate user flows equal to the initial flow configuration. With the assumption of stochastic choice models, the definition of coherent user flows may be formulated as a fixed-point problem.

Analytically, the path choice model, which allows to calculate user path choices depending on network performance, may be formulated as:

$$\boldsymbol{F_m} = \boldsymbol{P_m^{path}}\left(\boldsymbol{C_m}\right) \cdot \boldsymbol{d_m} \quad \forall m \in \{c, b\}, \tag{4}$$

where $\boldsymbol{F_m}$ is the path flow vector associated with the generic mode m; $\boldsymbol{P_m^{path}}(\cdot)$ is the path choice matrix associated with generic mode m; $\boldsymbol{C_m}$ is the path cost vector associated with generic mode m; $\boldsymbol{d_m}$ is the travel demand vector associated with generic mode m; the generic mode m may be equal to c in the case of the private car system and equal to b in the case of the public transport system.

Likewise, the mode choice model, which allows to calculate user mode choices depending on network performance, may be formulated as:

$$\boldsymbol{d_m} = \boldsymbol{P_m^{mode}}\left(\boldsymbol{C_c}, \boldsymbol{C_b}\right) \cdot \boldsymbol{d} \qquad \forall m \in \{c,b\}, \tag{5}$$

where $\boldsymbol{P_m^{mode}}(\cdot)$ is the modal choice vector associated with generic model m; $\boldsymbol{d}$ is the all-modes travel demand model.

The flow propagation model, which allows to calculate user link flows depending on user path flows, may be formulated as:

$$\boldsymbol{f_m^{pax}} = \boldsymbol{A_m} \cdot \boldsymbol{F_m} \quad \forall m \in \{c,b\}, \tag{6}$$

where $\boldsymbol{f_m^{pax}}$ is the user link flow vector associated with generic mode m; $\boldsymbol{A_m}$ is the link-path incidence matrix associated with generic mode m, where the generic element $a_{i,j}^m$ is equal to 1 if i-th link belongs to j-th path, 0 otherwise.

The congestion model, which allows to calculate network performance depending on vehicular link flows, may be formulated as follows:

$$\boldsymbol{C_m} = \boldsymbol{C_m}\left(\boldsymbol{f_c^{veh}}, \boldsymbol{f_b^{veh}}\right) \quad \forall m \in \{c,b\}, \tag{7}$$

where $\boldsymbol{f_c^{veh}}$ is the vehicular link flow associated with the private road system; $\boldsymbol{f_b^{veh}}$ is the vehicular link flow associated with the public transport system.

It is worth noting that in the private road system, there is a direct proportionality between user and vehicular flows through the average occupancy coefficient, while in the public transport systems, the vehicular flows are fixed, independent from user flows and equal to the service frequencies $\boldsymbol{\phi_b}$. Hence, Eq. (7) may be reformulated as:

$$\boldsymbol{C_m} = \boldsymbol{C_m}\left(\boldsymbol{f_c^{pax}}, \boldsymbol{\phi_b}\right) \quad \forall m \in \{c,b\}. \tag{8}$$

By combining Eqs (4)–(6) and (8), we obtain the following relation:

$$\begin{cases} \boldsymbol{f_c^{pax}} = \boldsymbol{A_c} \cdot \boldsymbol{P_c^{path}}\left(\boldsymbol{C_c}\left(\boldsymbol{f_c^{pax}}, \boldsymbol{\phi_b}\right)\right) \cdot \\ \cdot \boldsymbol{P_c^{mode}}\left(\boldsymbol{C_c}\left(\boldsymbol{f_c^{pax}}, \phi_b\right), \boldsymbol{C_b}\left(\boldsymbol{f_c^{pax}}, \boldsymbol{\phi_b}\right)\right) \cdot \boldsymbol{d} \\ \\ \boldsymbol{f_b^{pax}} = \boldsymbol{A_b} \cdot \boldsymbol{P_b^{path}}\left(\boldsymbol{C_b}\left(\boldsymbol{f_c^{pax}}, \boldsymbol{\phi_b}\right)\right) \cdot \\ \cdot \boldsymbol{P_b^{mode}}\left(\boldsymbol{C_c}\left(\boldsymbol{f_c^{pax}}, \phi_b\right), \boldsymbol{C_b}\left(\boldsymbol{f_c^{pax}}, \boldsymbol{\phi_b}\right)\right) \cdot \boldsymbol{d} \end{cases}, \tag{9}$$

which extensively expresses the multimodal assignment constraint (2). Indeed, by replacing passenger flows (i.e. $\boldsymbol{f_c^{pax}}$ and $\boldsymbol{f_b^{pax}}$) with equilibrium flows (i.e. $\boldsymbol{f_c^*}$ and $\boldsymbol{f_b^*}$) in Eq. (9), we obtain Eq. (2).

2. Application to a real case study

To show the utility and the feasibility of the resilience analysis for transport networks in urban areas through a multimodal approach, it has been applied in the case study of the Fuorigrotta district of the city of Naples, in southern Italy.

This district is characterised by mobility consisting of about 18,000 vehicles travelling in the morning rush hour and about 4,400 people travelling on public transport. Public transport consists of 3 rail/metro lines and 6 bus lines. Details of the road and public transport network can be found in Figure 1.

The disruption scenario considered to evaluate the resilience improvement strategies was the following: the closure of one of the two underpass tunnels that pass under the "Diego Armando Maradona" football stadium was assumed. The closure of a main road link has produced a reallocation of flows on the road network, generating an increase in congestion (and related travel times) both on the private transport network and on the public transport (bus) network.

The intervention strategy proposed to mitigate the negative effects of the disruption consisted in identifying

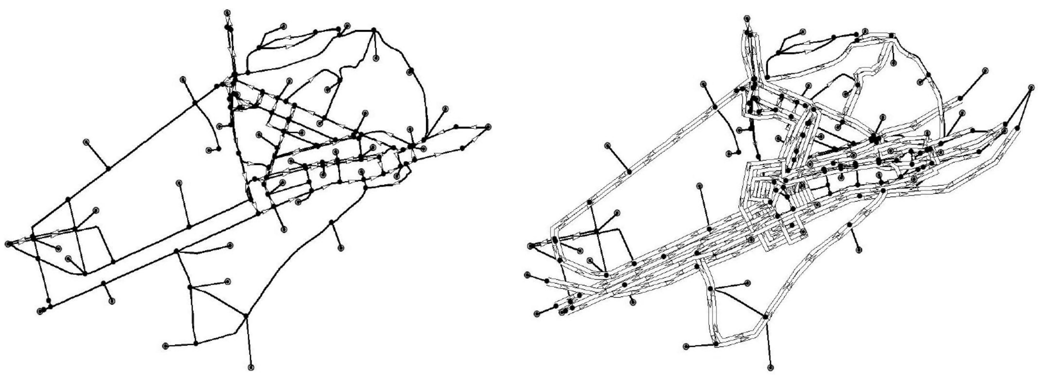

Figure 1. Private road network (left) and public transport network (right) in the case of Fuorigrotta district (Naples, Italy)

the bus lines serving the origin-destination pairs which in the initial (non-intervention) scenario used mainly the underpass with the private road system and in proposing an increase in service frequencies for these bus lines. The lines identified with this approach are line 2 and line 5.

Hence, the analysed scenarios are:

- Scenario 0: The non-intervention scenario where all road links are considered;
- Scenario 1: The disruption scenario where one of the two underpass tunnels is closed but public transport frequencies are unchanged compared to scenario 0 (non-intervention scenario). This scenario corresponds to the state of the system in the case that the underpass is closed and no mitigating action is undertaken;
- Scenario 2: The scenario where the underpass is closed and the frequencies of line 2 and line 5 are doubled compared to scenario 0 (or scenario 1);
- Scenario 3: The scenario where the underpass is closed and the frequencies of line 2 and line 5 are tripled compared to scenario 0 (or scenario 1).

This application requires the use of a suitable multimodal assignment model as described in Section 2.1, whose schematization is summarised in Figure 2.

Tables 1–4 provide the numerical results of the applications. In particular, the main consequences of the underpass closure are: (a) an increase in travel times on the private road system because some vehicles have to change their paths, increasing congestion on the rest of the network; (b) an increase in travel times (onboard times) on the public transport system because buses travel in shared lanes.

Hence, Scenario 1 provides an increase in travel times for each user of the network.

The adoption of intervention strategies (i.e., Scenario 2 and Scenario 3), based on the increase in service frequencies for some bus lines, provides the following effects: (1) a primary effect, consisting in reducing waiting times (and therefore total travel time) of passengers of the public transport system; (2) a secondary effect, consisting in modifying the modal choice of users in favour of public transport, thus generating a reduction in vehicle flows with the consequent reduction in travel times on the private road system and onboard times of the public transport system.

Therefore, Scenarios 2 and 3 produce a reduction in travel times for each transport system, compared to the non-intervention scenario (i.e. Scenario 1). Indeed, the underpass closure provides an increase in congestion on both transportation systems (the total user generalised cost increases from 516,288 min-pax to 527,785 min-pax). The implementation of the mitigation strategies reduces these increases, providing an increase reduction of up to

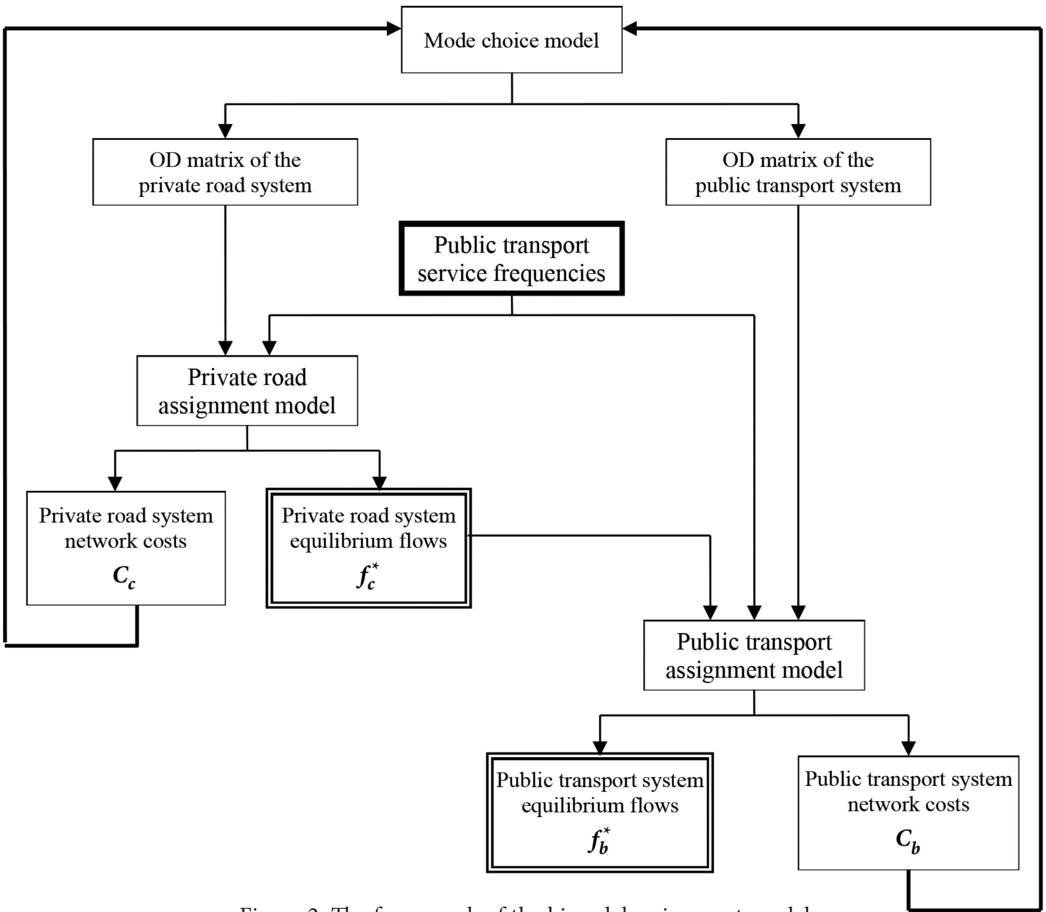

Figure 2. The framework of the bimodal assignment model

Table 1. User Generalised Cost (UGC) for each analysed scenario, expressed in terms of minutes per user

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
User generalised costs of the private road system [min-pax]	260,243	270,528 (+3.95%)	270,251 (+3.85%)	270,196 (+3.82%)
User generalised costs of the public transport system [min-pax]	256,045	257,257 (+0.47%)	254,270 (–0.69%)	252,460 (–1.40%)
Total user generalised costs [min-pax]	516,288	527,785 (+2.23%)	524,521 (+1.59%)	522,656 (+1.23%)

Table 2. Average user generalised cost for each analysed scenario

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Average user generalised cost on the private road system [min/pax]	11.86	12.33 (+3.98%)	12.32 (+3.89%)	12.32 (+3.88%)
Average user generalised cost on the public transport system [min/pax]	58.19	58.38 (+0.34%)	57.65 (–0.93%)	57.22 (–1.66%)
Average user generalised cost on the network [min/pax]	23.52	24.05 (+2.26%)	23.91 (+1.64%)	23.82 (+1.29%)

Table 3. User costs for each analysed scenario

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
User costs on the private road system [Euro/h]	21,687	22,544 (+857)	22,521 (+834)	22,516 (+829)
User costs on the public transport system [Euro/h]	21,337	21,438 (+101)	21,189 (–148)	21,038 (–299)
Total user costs [Euro/h]	43,024	43,982 (+958)	43,710 (+686)	43,555 (+531)

Table 4. Intervention scenarios analysis

	Scenario 1	Scenario 2	Scenario 3
Variation in total user costs [Euro/h]	0	–272	–427
Implementation costs [Euro/h]	0	104	208
Balance [Euro/h]	0	–168	–219

44.61%. Moreover, in terms of intervention costs, against a cost of 104 euro/h for the strategy of doubling frequencies (i.e. Scenario 2) and 208 euro/h for the strategies of tripling frequencies (i.e. Scenario 3), the reductions in terms of travel costs are respectively equal to 272 euro/h and 427 euro/h, providing an overall savings balance of 168 euros/h in the first case and 219 euros/h in the second case.

Conclusions and research prospects

The current paper has shown how the increase in the financing of public transport can be used to increase the resilience of transport networks. In particular, the numerical applications have shown that for every euro invested in the public transport system, the benefits are propagated both on the public transport and on the private transport systems.

Indeed, the underpass closure has provided an increase in congestion on both transportation systems (+10,285 min-pax in the private road system and +1,212 min-pax in the public transport system). The implementation of the mitigation strategies has provided a reduction in congestion increase in the case of the private road system (–2.69% in the case of Scenario 2 and –3.23% in the case of Scenario 3). Although these values may seem rather negligible, in the case of the public transport system, these reductions have quite other orders of magnitude, bringing the user generalized cost to values lower than the initial unperturbed condition (Scenario 0).

As research prospects, we propose to apply the proposed methodology for evaluating the short-term effects (for example, in the case of disruption with a limited duration over time) on urban networks.

Furthermore, it would be possible to investigate, for example through a combinatorial analysis, the influences of other bus lines on the entire transport system or to apply an optimisation model for the definition of the optimal frequency values.

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Contribution

Supervision: D'Acierno & Strano; Conceptualisation: D'Acierno & Strano; Methodology: D'Acierno; Design of numerical experiments: D'Acierno & De Matteis; Numerical applications: D'Acierno & De Matteis; Data analysis: D'Acierno & De Matteis; Writing, review and editing: D'Acierno, De Matteis & Strano.

Disclosure statement

Authors declare that they don't have any competing financial, professional, or personal interests from other parties.

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