A Digital Twin Simulation Framework to Assess the Impact of Street Experiments: Transforming Urban Mobility in Acireale (Italy)

Vincenza Torrisi[1(✉)], Silvia Rossetti[2(✉)], Antonio Barbagallo[3], Pierfrancesco Leonardi[3], and Matteo Ignaccolo[3]

[1] Department of Electric, Electronic and Computer Engineering, University of Catania, Viale Andrea Doria, 6, 95125, 95100 Catania, Italy
vincenza.torrisi@unict.it

[2] Department of Engineering and Architecture, University of Parma, 43124 Parma, Italy
silvia.rossetti@unipr.it

[3] Department of Civil Engineering and Architecture, University of Catania, Viale Andrea Doria, 6, 95125 Catania, Italy

Abstract. Urban mobility policies focus on several strategies and actions towards sustainability, among them the implementation of street experiments schemes to discourage high-polluting vehicles entering in urban areas. The increase in vehicular traffic generates numerous externalities, including high congestion levels, polluting emissions and a worsening of the quality of life, especially in urban centers. To reduce these critical issues, one can refer to experimental Low Speed Zones (LSZs) or Limited Traffic Zones (ZTLs). These vehicular traffic restrictions can be of several types: spatial (i.e. territorial extension), permanent or temporary (i.e. variation in duration over time); partial or total (i.e. reserved only for specific categories of vehicles).

This work presents a methodology to evaluate the impact of traffic restriction configurations through a digital twin implementation based on microsimulation models to perform scenario analyzes and evaluate quantitative variables (e.g. service levels, queue lengths, delay times). Different scenarios have been simulated and assessed within the municipality of Acireale (Italy): (i) permanent ZTL with limited extension to the central area of the historic centre; (ii) temporary restricted traffic zone extended to the entire historic center; (iii) permanent ZTL extended to the entire historic center (assuming a modal shift in travel demand); (iv) 30 km zone extended to the entire historic centre.

The obtained results, associated with the northern area of the city at the entrance to the historic centre, show that the spatial extension and temporal duration of these street experiments can generate critical issues on alternative roads. Future research developments will include the integration of emission models to assess the environmental impacts deriving from the proposed sustainable mobility actions.

Keywords: Sustainable Mobility · Transport modelling · microsimulation · Low Speed Zones (LSZs) · Limited Traffic Zones (ZTLs) · urban regeneration

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1 Introduction

Vehicle congestion in cities causes several disruptions compromise the livability of urban areas [1]. The impact of pollutants generated by vehicles in cities is significant [2]. In 2021, 24% of total greenhouse gas emissions were caused by transport sector, whereby road mobility is the main driver, accounting for approximately 92.9% [3]. The emissions are primarily carbon dioxide (99.0% in 2021), a gas determined by fuel consumption, which has significant direct health impacts, contributing to respiratory illnesses, cardiovascular diseases, and other ailments, ultimately resulting in premature deaths [4]. The effects of vehicle congestion are remarkable not only in large cities, but also in small and medium-sized cities, especially those with a historic urban fabric, because they are characterised by a road network with reduced capacity and narrow cross-sections [5]. Therefore, to face these issues it is essential to identify and adopt strategies and actions promoting sustainable mobility within urban areas and assess their impacts [6–10]. The need to make sustainable cities [11], emphasizes the role of planning for accessibility that is at the core of all sustainable urban planning policies [12, 13]. In this regard, a strategic European legal tool is the Sustainable Urban Mobility Plan (SUMP), introduced in Italy as "Piani Urbani della Mobilità Sostenibile" (PUMS) by Ministry of Infrastructure and Transport Decree No. 397 of 4th August 2017 [14]. Among its contents, it foresees actions and strategies to achieve the objectives that each municipality must pursue to promote the sustainable mobility for citizens [15, 16]. To foster a holistic and comprehensive vision of the PUMS, also in coherence with European guidelines, four of its areas of interest and related mandatory minimum macro-objectives to achieve balanced and sustainable development are the following: 1. Effectiveness and efficiency of the mobility system; 2. Energy and environmental sustainability; 3. Road mobility safety; 4. Socio-economic sustainability [17]. Among the strategies and actions envisaged by this planning tool there is the possibility of introducing limitations to vehicular circulation as street experiments [18, 19], to encourage active mobility as the main means to access services within a neighbourhood [7]. Specifically, there are several types of vehicular traffic restrictions, including Limited Traffic Zones (LTZs), linked to the type of vehicle, and Low Speed Zones (LSZs), linked to travel speed.

LTZs are areas in which restrictions are enforced on motorized traffic or specific types of vehicles, including 'traffic calming' infrastructural measures [20]. In Italy, LTZs are called "Zone a Traffico Limitato" (ZTL) and they are regulated by the "Linee Guida sulla regolamentazione della circolazione stradale e segnaletica nelle zone a traffico limitato" of 28/06/2019 [21] according to Presidential Decree No. 250/99 [22]. Within LTZs, restrictions may be of different types: spatial (i.e. territorial extension), permanent or temporary (i.e. inter- or intra-day variations); total or partial (i.e. concerning only certain categories of vehicles).

Whereas LTZs are areas or roads where strict speed limits are imposed on motorized vehicles, either through the placement of appropriate prescription signs, or through proper infrastructural interventions for speed moderation (i.e. punctual, along the road axis or coordinated interventions) [23].

The impact of these strategies does not only concern the intervention areas but also the surrounding neighborhoods. In fact, it is quite recorded a decay in level of services

within the areas immediately adjacent to the traffic calming intervention, due to the re-routing of vehicles which generate an increase in vehicle traffic considered (i.e. parasite traffic) [24, 25].

In this regard, there are different methodologies for assessing the impacts of LTZs and LSZs. Some studies focus on pre- and post-intervention speed and volume assessment using measures of central tendency and dispersion, [26]; other studies focus on analyzing the effects of LTZs on air quality and the environment [27]. However, these approaches require the intervention implementation and then measuring the impact.

The impact of a traffic closing should be assessed before implementing temporary or permanent interventions; this can be done through simulations that could provide a detailed representation of the system, i.e. digital twins [28], a set of virtual information constructs that fully describe a potential or actual physical system [29]. This allows to suggest the implementation of traffic restrictions that are more suitable for existing traffic conditions, thus increasing the likelihood of their being maintained over time.

Based on this premise, this work applies a methodological approach described in Sect. 3, for evaluating the impact of different traffic restricted zones, through the implementation of microsimulation models to perform scenario analysis and evaluate several variables (i.e. service levels; queue formation; time loss) [30]. Before, Sect. 2 describes the case study where this methodology has been applied, i.e. to the case study of the city of Acireale (Italy), characterised by a poor public transport supply and a high motorisation rate. The effects of four different vehicle traffic restriction scenarios have been evaluated: (o) Current status; (i) permanent LTZ with reduced extension; (ii) temporary and extended LTZ; (iii) permanent and extended LTZ with modal shift; (iv) 30-km and extended LSZ and the results are discussed in Sect. 4. Finally, Sect. 5 concludes the paper by presenting future developments of the research.

2 Case Study

2.1 Territorial Framework

The examined case study in this work is the city of Acireale, a municipality of approximately 50,000 inhabitants located in the metropolitan city of Catania (Sicily), located in the east of the island, north of the capital of the metropolitan city (Fig. 1).

Acireale is, after the capital city, the most populous municipality in the metropolitan area of Catania [32]. Its relations with Catania are very straitened, characterised by complementarity in terms of tourism and commuting for university studies and work. For these reasons, streets are often characterized by congestion phenomena. Acireale is known for its narrow streets, winding alleys and crowded squares, which make vehicular circulation often tricky and potentially hazardous for pedestrians. In fact, within the historic center of Acireale, the interaction between vehicles and pedestrians presents several critical issues related to the urban characteristics and traffic dynamics, as shown in Fig. 2.

This case study has been proposed as the city of Acireale has been subjected to a spatial planning and management tool to regulate its transport mobility. Specifically, the Municipality of Acireale has a General Urban Traffic Plan (in Italian “Piano Generale del Traffico Urbano” – PGTU) [34] as regulated for municipalities with a population of

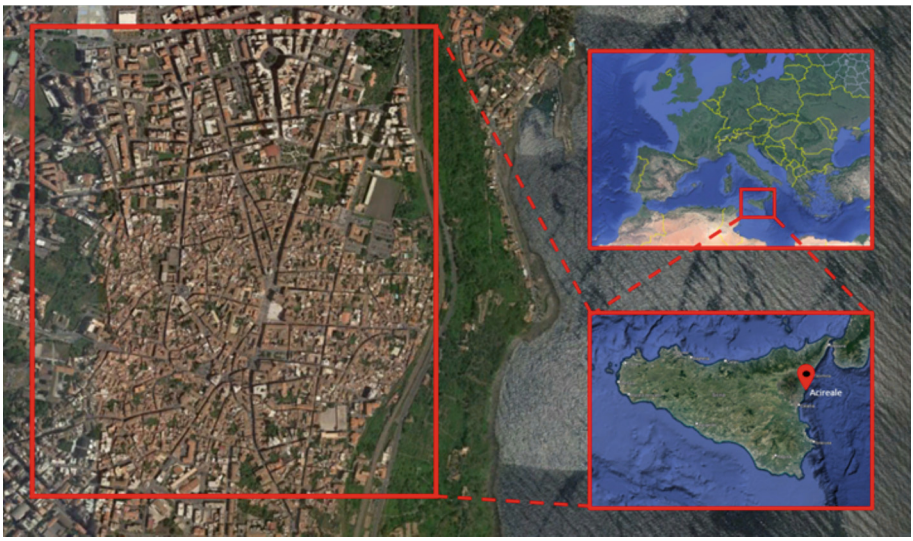

Fig. 1. Study area. Source: Author elaboration [31]



Fig. 2. Interaction between pedestrians and vehicles within the historic center of Acireale. [33]

more than 30,000 inhabitants. It is an urban planning legal tool that defines the guidelines for the territorial development of the city and defines targeted interventions on traffic and mobility to improve the safety, environmental and efficiency conditions of the urban

system, addressing issues related to the territory, the transport supply, the demand for mobility and their interaction. One of the main aims of this plan is to promote widespread and sustainable urban accessibility, referring to the three dimensions of sustainability: environmental, economic and social.

The PGTU revealed the need to limit motorized vehicle traffic and travel speeds in certain areas of the city center (i.e. the historic center) through the implementation of measures to improve the quality of cycling and walking and thus raise the livability indexes of the urban context, i.e., through the spatial and temporal definition of the LTZs and the identification of traffic calming areas (i.e. LSZs).

For the PGTU the temporal implementation of traffic restriction interventions is envisaged in the following four phases:

- phase 1: LTZ with minimum spatial extension (ZTL - 1st step) and 30-km Zone with minimum spatial extension (Zone 30 - 1st step);
- phase 2: LTZ with minimum spatial extension (ZTL - 1st step) and 30-km Zone with maximum spatial extension (Zone 30 - 2nd step);
- phase 3: LTZ with minimum spatial extent (ZTL - 1st step), 30-km Zone with maximum spatial extent (Zone 30 - 2nd step) and access regulation of the most polluting vehicles ("Zona 30 Ambientale");
- step 4: LTZ with maximum spatial extent (ZTL - 2nd step), 30-km Zone with maximum spatial extent (Zone 30 - 2nd step) and access regulation of the most polluting vehicles ("Zona 30 Ambientale").

The objectives to be pursued through the above-mentioned phases (temporally sequential) are mainly:

- to permanently eliminate motorized vehicular traffic in specific areas, subject to special exceptions (i.e. mainly related to residents);
- to reduce pollutant emissions in the central areas of the city;
- to make the historic center more livable;
- and to minimize the number and severity of traffic accidents.

LTZs, like other initiatives involving the temporary transformation of public spaces, e.g. streets or squares, to test new solutions or improvements in the urban environment, can have several impacts on the urban environment, the local economy and the quality of life of residents. The need arises to evaluate the effects of implementing these initiatives impacts on urban traffic.

The application of traffic micro-simulation to model at different level these vehicular restrictions may be an effective approach to evaluate their impact and optimize traffic management for different scenarios (Fig. 3).

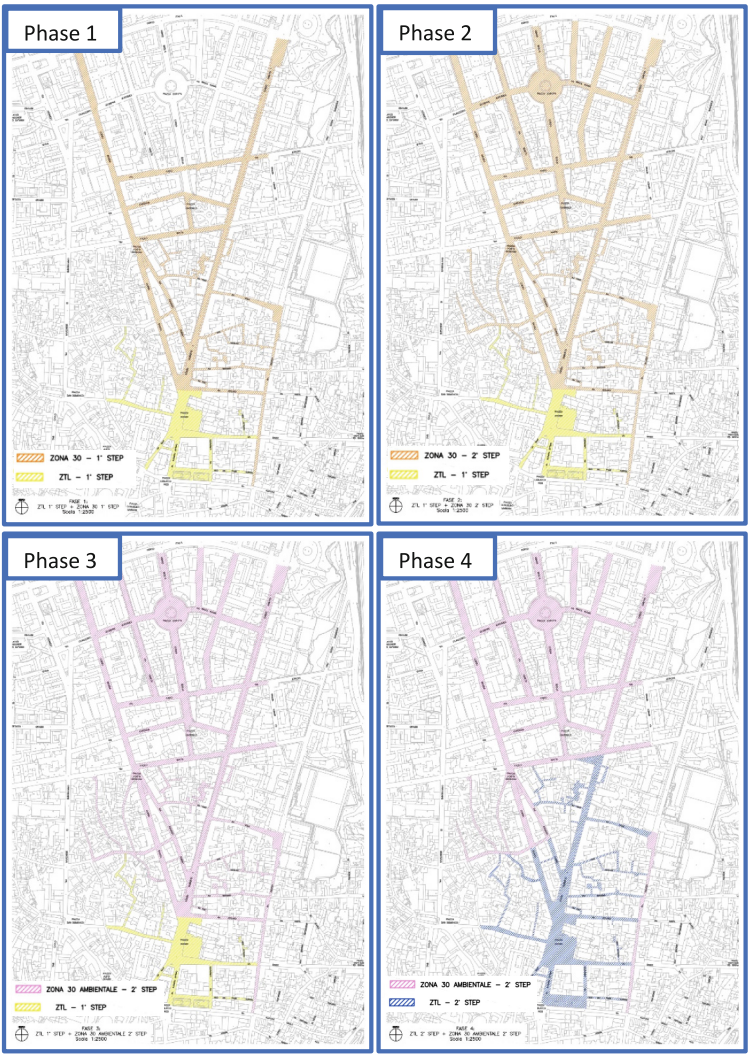

Fig. 3. Phases of traffic limitation interventions [34]

2.2 Traffic Survey Campaign and Scenario Analysis

Analyzed scenarios have been hypothesized and modelled through microsimulation software (i.e. PTV Vissim) to assess the impact that these interventions would have in the northern part of the city, with traffic flows entering the historic center.

It has been first necessary to determine the mobility demand through proper traffic survey campaigns. Traffic surveys were carried out at specific time slots of the day to record critical flows affecting the study area. The duration of each individual survey time slot was 15 min and was recorded during the following peak hours: morning (8:05–8:20 a.m.), midday (12:55–1:10 p.m.), and evening (5:35–5:50 p.m.).

In this work, in addition to the current scenario, four alternative scenarios have been considered:

- (o) current status at the time of traffic surveys; an assessment of this scenario is made in order to compare the indicators calculated for other scenarios;
- (i) permanent LTZ with reduced extension to the central area of the historic center, with closure of the road from Duomo Square to Porta Gusmana Square;
- (ii) temporary LTZ extended to the entire historical center: the hypothesis is made of extending the LTZ up to Savoia Road;
- (iii) permanent LTZ extended to the entire historical center (assuming a modal shift in the travel demand); following the total closure of the historic center, a reduction in the vehicular flow is assumed;
- (iv) 30-km zone (i.e. LSZ) extended to the entire historical center. This alternative is considered for a short time.

These scenarios have been identified based on the various vehicular restrictions phases in the PGTU with a view to intervening in the entire historic center and making it a permanent LTZ. Thus, the choice of scenarios is geared toward maximizing the long-term benefits of the extended LTZ, while attempting to mitigate any transitional problems through temporary measures such as 30-km Zone.

3 Methodological Approach

The procedural steps of the proposed methodological approach are described as follows (Fig. 4):

- Definition of the study area;
- Implementation of the transport demand, both vehicular and pedestrian;
- Node evaluation and calculation of the level of service of the current scenario.

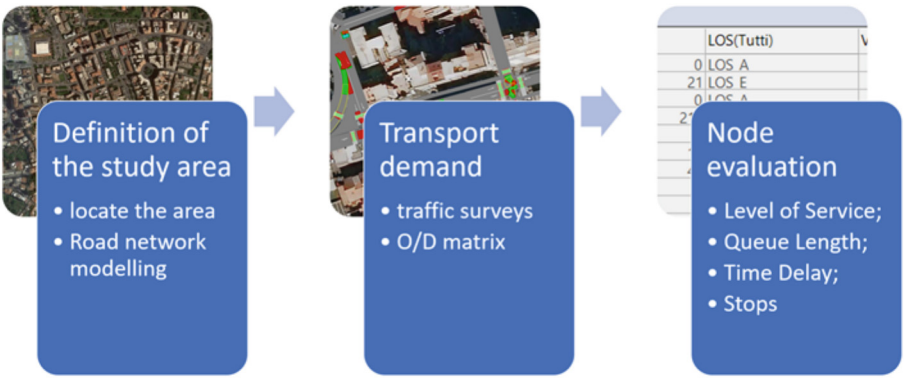

Fig. 4. Methodological framework. Source: Authors elaboration.

For the first phase, the study area has been identified, coinciding with the area in which the LTZ is planned and where data are collected, e.g. topography, existing road network,

priority and access rules to the LTZ, travel speeds, crossing times at intersections and other factors influencing the movement of vehicles. This network has been modelled through the design of links with the corresponding lanes and priority rules.

For the second phase, the characterization of transport demand has been carried out by means of special fixed operator traffic surveys carried out at specific times of the day, to record the critical flows that affect the areas under study, specifying the vehicular composition (consisting of cars, motorbikes, heavy vehicles and buses). From these measurements, an O/D matrix was drawn up with reference to the critical flow of the morning time slot, which was used during the assignment procedure to distribute transport demand through flows and routes within the simulated model. The vehicular flows were assigned to the incoming connected network link so that the vehicles in the network were in operation at the beginning of the simulation. Once the flows were assigned, the vehicular routes were defined, of static type, specifying for each of them the origin and destination arc, assigning to each of them the corresponding flow and considering some maneuvers not performed by certain categories of vehicles.

In the third phase, a node evaluation of the network's level of service and other calculated quantities has been carried out for several alternative scenarios.

The Level of Service (LOS) of a road section is a measure of the quality of vehicular flow on that section. These levels are distinguished by six letters, i.e. from A to F, in descending order of traffic flow quality. In general, for roads with uninterrupted flow, the vehicle running conditions at the various LOS can be defined as follows:

- A: free circulation, i.e. each vehicle moves without any constraints and in absolute freedom to maneuver within the current: maximum comfort, stable flow;
- B: circulation can still be considered free but there is a modest reduction in speed and manoeuvres begin to be affected by the presence of other users: acceptable comfort, stable flow;
- C: the presence of other vehicles causes increasing constraints in maintaining the desired speed and freedom to maneuver comfort is reduced while the flow remains stable;
- D: the range of speed choice and freedom to maneuver is restricted; there is high density and disturbance problems arise: comfort is lowered and the flow may become unstable;
- E: flow approaches the limit of compatible capacity and speed and freedom to maneuver are reduced: flow becomes unstable as even moderate disturbances can cause congestion;
- F: Forced flow: the disposable vehicular volume decreases along with the ve-location; unstable flow conditions easily occur up to the onset of severe queuing phenomena.

Other important performance measures that have been evaluated are queue length, number of stops and vehicle delay:

- Queue length: in each time step the queue length is measured and then the mathematical average is calculated for each time interval;
- Stops: number of vehicles stops linked to interference experienced on their journey;
- Vehicle delay: the time delay of a vehicle is obtained by subtracting the ideal travel time from the real one. The ideal one is what would be obtained under free flow conditions.

In the results of implementing microsimulation model, at the node level, indicators can also be displayed that measure exhaust gas emissions, referring to a typical North American vehicle fleet their node rating is used to compare the emissions of different scenarios. These indicators are:

- Emissions CO: Quantity of carbon monoxide [grams];
- Emissions NOx: Quantity of nitrogen oxides [grams];
- Emissions VOC: Quantity of volatile organic compounds [grams];

By evaluating these indicators for different traffic micro-simulation scenarios, it has been possible to gain an in-depth understanding of the effects of changes in traffic conditions, enabling informed decisions to be made to improve the efficiency and safety of the road system. In this work, these indicators have been calculated for the existing state scenario and for the 4 redevelopment scenarios.

The adopted methodology stands out for its replicability and innovation. Using models based on users' behavior, it enables accurate reproduction of road conditions and traffic flow in virtual scenarios. Its replicability derives by clear processes and algorithms used, that can be implemented at different levels. At the same time, the innovative approach is evident in the use of advanced data analysis and predictive modeling techniques to simulate traffic dynamics in complex contexts, thus providing valuable insights for improving urban planning and road infrastructure management.

4 Application and Results

Regarding the application of the methodology to the study area, i.e. the historic center of the municipality of Acireale, the area north of the historic center has been considered to carry out the simulation analysis.

Information have been collected on the network geometry, i.e. number of lanes characterizing each road, width, traffic flows, traffic directions, parking, presence of priority and stop rules, horizontal and vertical signs, etc. This analysis was used to implement the modelling on Vissim microsimulation software of the entire area under study.

As a first modelling phase of the road network, the individual lanes have been modelled using the link command, characterised by information regarding the geometry and relative connections, taking care to calibrate the conflict areas generated by the intersections between various links. This calibration has been carried out respecting the priority rules that regulate the road network in the study area.

The mobility demand has been reconstructed by means of traffic surveys as described in the previous section. This mobility demand was modeled through the inclusion of vehicular flows and routes.

For the evaluation of the level of service it has been necessary to insert a node enclosing the area under study as shown in figure (see Fig. 5).

The indicators have been calculated using a special command, the time of each simulation is 3600 s, for a total of 5 different simulations. Table 1 shows the simulation results in terms of vehicle parameters (i.e. Level of Service, Queue Length, Time Delay and Stop) and environmental parameters (i.e. CO, Nox and VOC emissions).

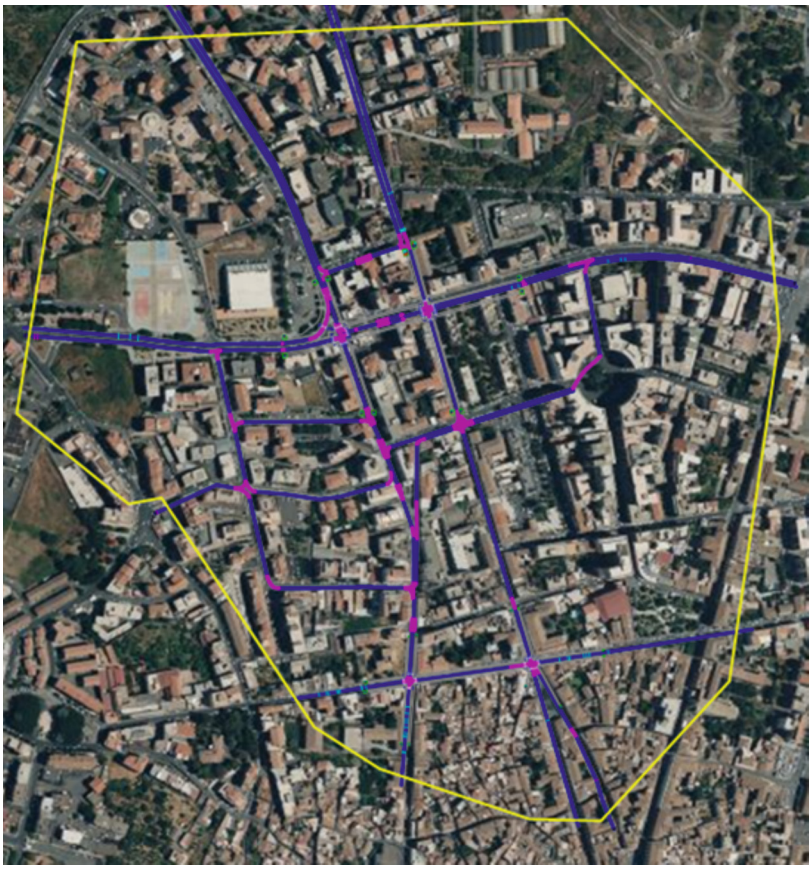

Fig. 5. Network of arcs and connections made in the model and node for evaluating the service level. Source: Elaboration on PTV Vissim

Table 1. Scenario evaluation Source: Elaboration on PTV Vissim

Scenario	LOS	QLEN [m]	VEHDELAY [s]	STOPS	EMISSIONS CO [g]	EMISSIONS NOX [g]	EMISSIONSVOC [g]
o	B	0,99	13,02	1,05	4677,34	910,04	1084,02
i	D	1,73	28,91	2,04	5593,68	1088,33	1296,39
ii	E	3,38	46,50	3,59	6618,24	1287,67	1533,84
iii	C	0,59	14,97	1,29	3689,87	717,91	855,16
iv	C	1,11	15,27	1,31	4919,06	957,07	1140,04

For the Current State scenario there is a rather good situation with an average service level of B. If street experiments implementation is considered, the results significantly change. From the LTZ relating to the historic center with closure in the section between Piazza Duomo and Piazza Porta Gusmana, the situation worsens (i.e. LOS is equal to

D). If the area is extended in the section between piazza Duomo and Corso Italia, as described in scenario ii, the level of congestion increases further (i.e. LOS equal to E). This worsening of LOS in the areas surrounding the LTZ entails multiple benefits, e.g. improved walkability, decreased accidents, improved local economy, etc.

Considering this, it is assumed that following a permanently extended LTZ in the long term there will be a component of vehicle traffic that will choose other modes of transport to travel to the center. Therefore, a scenario is calculated, where a reduction in vehicle flows of 20 per cent is assumed, resulting in a LOS C. Thus, a long-term extended LTZ has better effects than a LTZ restricted to the city center alone. It is assumed, however, that the transition period between the activation of the extended LTZ beyond the historic center and its full operation is the one that will generate traffic problems. Therefore, a further scenario has been assumed for this phase, namely that of a 30-km Zone in the short term. From the results of this scenario, the impact of a 30-km has on traffic, compared to that of an LTZ reduced to just the historic center, is less, since a LOS C is obtained.

The calculated emissions are related to the service level values, because they have been calculated through an emission model based on vehicular traffic flow. Thus, same consideration can be highlighted: for scenario o, the calculated pollutant emissions are quite significant. With the implementation of vehicular restrictions, there is a significant increase in congestion levels, resulting in a substantial increase in pollutant emissions. In this regard, considering the scenario in which a reduction in vehicular flows is assumed for the long-term scenario, emissions become lower than in the most congested scenarios.

5 Conclusions and Future Research

This study highlighted the central role of some kinds of street experiments, through a synthesis of empirical data and traffic modelling techniques. We evaluated the impacts of implementing different LTZ scenarios (i.e. both temporary and permanent) on traffic flow, air quality and, thus, overall urban livability.

The results underline the potential of traffic experiments as valuable tools for policy makers and urban planners seeking to create sustainable, people-centered cities.

Furthermore, the application of microsimulation allowed for a qualitative and quantitative examination of LTZ interventions, revealing insights into their effectiveness on various spatial and temporal scales. In fact, by entering input data (e.g. number and width of lanes, vehicular and pedestrian flows and routes, etc.), it has been possible, thanks to the simulation process, to measure the changing behaviour of drivers. By simulating different scenarios and assessing their real-world implications through the implementation of a digital twin model, we gained a deeper understanding of the complex interactions within urban environments. The implemented model allowed us to calculate and compare the reference parameters (i.e. LOS, delays, emissions and fuel consumption) for the various alternative scenarios.

Going ahead, this research emphasizes the importance of collaboration between urban and transport planning and decision-making supported by data and models in shaping the future of urban mobility. Future research developments will include the integration of emission models to assess the environmental impacts deriving from the

proposed sustainable mobility actions. It is also intended to implement this methodology on other contexts, which can be a significant step toward more efficient and sustainable urban planning and traffic management.

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