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Impact Mitigation of Tunnels Maintenance Works on Highway Performance

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Abstract

Major maintenance interventions on highways (e.g., for the safety improvement of tunnels and viaducts) involve the presence of work zones for extended periods of time and along wide sections of the infrastructure. These interventions lead to supply changes, especially a reduction in capacity, causing a decrease in the performance of the transportation system, which users experience with increased traffic congestion and economic losses in terms of productivity. This paper aims to demonstrate that proper traffic management and work zone planning allow for a significant reduction of such impacts. In relation to traffic management, possible solutions consist of diverting traffic flows onto alternative routes (if possible, using primary roads) or keeping them in the remaining lanes along the work zone. In terms of work zone planning, leverage can be applied, on the one hand, through the design of the work zone layout and maintenance scheme and, on the other, through the duration and scheduling of the interventions. The methodology proposed in this paper is based on traffic simulation models in order to assess different maintenance scenarios under varying demand levels (i.e., during the rush hour and off-peak hours, weekdays and weekends, summer and winter months) and vehicular compositions (i.e., percentage of heavy vehicles), with the goal of identifying the scenario that minimizes the impacts on users. Modelling evidence on a real case study of tunnel maintenance interventions on an Italian highway is reported, discussing the policy implications on the basis of quantitative indicators, such as level of service, duration of delays, length of queues, and economic impacts.

Keywords: highway maintenance; scheduling; planning; assessment; simulation models

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1. Introduction

Europe, due to its orographic characteristics, has a substantial development of kilometers of tunnels. In Italy, there are approximately 7,341 kilometers of highways, with 1,474 kilometers of bridges/viaducts (equivalent to 20.1% of the total, and a number of 8,199 bridges/viaducts) and 1,051 kilometers of tunnels (representing 14.3% of the total, and a number of 2,179 tunnels) (ANSFISA, 2022). It is noticeable that more than half of the Trans-European Transport Network (TEN-T) road tunnels are in Italy. Most of these infrastructures have been operating for over 30 years and, as a result, are quite outdated and need for extraordinary maintenance plan and upgrades to meet the latest safety standards required by law. The Italian regulation (Legislative Decree No. 264 of October 5, 2006 derived from the EU Directive 2004/54/EC) (European Parliament, 2004; Italian Parliament, 2006) aims at ensuring a minimum level of safety for road users in TEN-T tunnels over five hundred meters (whether already in operation, in construction, or in the planning phase). This is achieved by designing and implementing preventive measures to reduce critical situations that could endanger human life, the environment, and tunnel facilities. Implementing these preventive measures (e.g., excavation of pedestrian escape routes linking adjacent arcs, construction of tunnel drainage systems, and the installation of fire suppression and liquid collection system) requires the establishment of work zones for long periods of time and along large sections of the highway infrastructure. These interventions cause changes in supply (in particular, a capacity reduction), and affect the performance of the overall transportation system. End users (both passengers and freight vehicles) generally experience this as increased traffic congestion and economic losses in terms of productivity. To comply with regulations within the time limits established by law, in recent years motorway operators have had to resort to widespread work zones on the highway network. It should also be noted that the tunnel adaptation is not the only maintenance intervention planned for the motorway sections. In addition to routine maintenance, there are also other significant works to be carried out (e.g., the replacement and modernization of safety barriers and the adaptation of bridges and viaducts), increasing the number of work zones simultaneously present on a single highway section. These include maintenance works such as the replacement and modernization of safety barriers and the adaptation of bridges and viaducts. In this context, planning and traffic management are essential to minimize the impacts of work zones on the performance of the highway network.

This research proposes a methodology to assess the impacts of works zones using as indicators the congestion levels, queue formation and travel time. Thus, the aim of this research consists in supporting public administration and operators organizing an optimal maintenance program. A case study is analyzed to test the effectiveness of the proposed methodological approach.

Following this brief introduction, the rest of the paper is structured as follows: in Section 2, a literature review on the topic is outlined; in Section 3, the methodological approach based on traffic simulation models for impact assessment is presented; in Section 4, the methodology is applied to the Italian real case study of the A10 Savona-Ventimiglia highway managed by Autostrade dei Fiori SpA, and the results of the analysis scenario simulations are discussed; finally, in Section 5, the research conclusions are drawn.

2. Literature review

Maintenance of the highways (e.g., pavements, tunnels, guardrails) is a topic addressed in the literature from different points of view. Dai et al. (2023) proposed a method to evaluate the service reliability of the tunnels and defined some different safety grades. Poister et al. (2002) reported the case of a maintenance management procedure based on the participation of the road users: each year, the data collected from users feedback are used to plan the interventions on highway. Zhang & Zhang (2023) identified in the bad maintenance management a cause of tunnel defects, and provided some considerations to improve such an aspect (both in economic and technological terms). Tong et al. (2022) proposed two strategies to model the maintenance scheduling of a highway, the first aimed to minimize the traffic delay, while the second considers as objective the minimization of the makespan. Chien et al. (2002) developed a method to optimize work-zone scheduling and the traffic control when a lane of the highway is closed for maintenance, the aim is the minimization of the total cost. Sarasua et al. (2004) investigated the factors affecting the highway capacity by analyzing the flow characteristics in presence of a work zone, the approach is based on microsimulation. Ramadan & Sisiopiku (2018) proposed a microsimulation approach to simulate operations in a work zone under different traffic flow levels obtaining a set of performance indicators (e.g., level of service, environmental impacts). Jacob et al. (2006) proposed an approach to provide real time information to the drivers when approaching to a work zone, the objective is to optimize the use of alternative routes.

Ge et al. (2020) examined the highway maintenance procedures from the point of view of the driver's safety near the work zone area, the aim is the reduction of the traffic accidents. Li & Bai (2009) identified the risk factors affecting the accidents near a work zone and quantify their impact on accident severity. Waleczek et al. (2016) discussed the impacts (in terms of road safety and traffic delay) of reversing the lanes of a highway when maintenance work is in progress. Li & Zhang (2017) studied the safety characteristics of the lane changing near the work area by analyzing the merging decisions of the drivers. Ravani & Wang (2018) studied the road accidents near a work zone in a highway and proposed measures (e.g., police presence) to limit them. Liang et al. (2014) assessed the safety of the work zones by analyzing the lane change maneuver and proposed a method to classify the safety of work zones. Noel et al. (1988) proposed the implementation and the assessment of some procedures to reduce the impacts of the speed in the work zones safety. Chammout et al. (2024) provided a cluster analysis to evaluate such a combination of factor to increase road safety in the proximity of the working areas.

Maintenance or construction work on a road section could affect environmental impacts (Ma et al., 2023). Vyas & Varia (2023) studied the impacts of work zones on traffic congestions and related externalities (e.g., pollution). Mehrabani et al. (2021) used some approaches to evaluate vehicle emissions within the limits of a work zone. Sun et al. (2022) proposed a bilevel approach to minimize the drivers travel time and the pollutant emissions, by optimizing the use of the available lanes. Liu et al. (2022) proposed a framework to correlate the traffic delay to the pollutant emissions caused by highway maintenance with the aim to individuate a work zone management strategy able to minimize the emissions. Ranawaka & Pasindu (2020) proposed a method to evaluate the emission from traffic flow due to the presence of a work zone in an urban highway arc.

3. Methodology

The impact assessment of road traffic is carried out using a mesoscopic simulation model based on a dynamic traffic flow assignment model that simulates the interactions between transport supply and demand. This approach allows analysts to simulate, over the time period of activity of the working zones, queue phenomena taking into account the impedance related to the arcs (homogeneous highway sections) and the nodes (ramp deviations to/from highway entrance/exit) of the transportation network. This simulation approach evaluates the evolution over time of demand (individual vehicles) in relation to supply (infrastructure characteristics). Meanwhile, vehicle interactions are modeled by using car following and lane change models. The assignment of traffic demand to the network is performed through an iterative process that includes the search for the best route for each vehicle, flow balancing (i.e., the distribution of demand among the routes), and network loading. These steps are repeated iteratively until the system converges. Convergence criteria can be either reaching a maximum number of iterations or achieving a threshold difference value between the flows or the costs in two consecutive iterations. Specifically, for volume balancing, the method of successive averages (MSA) is employed to solve an equilibrium optimization problem.

The input data that enable the simulations include the following:

- **Road Network – Base Scenario**. The road network is defined by all the arcs and the nodes of the highway to be simulated.
- **Maintenance Scenarios.** Analysis scenarios can be identified based on the work zone layouts that the highway operator intends to implement, specific to each section. For tunnel maintenance, it is commonly assumed that works are carried out in one direction of travel, closing one carriageway, and diverting traffic to one lane of the opposite carriageway, according to the bypass locations along the highway. In such a case, on both carriageways there is a capacity reduction for certain sections due to the closure of the overpassing lane/right lane, depending on the direction of the closed tunnel.
- **Traffic Demand.** Hourly origin-destination matrices (from toll booth to toll booth) are obtained from a daily matrix, disaggregated by travel direction and vehicle category (light and heavy), taking into account hourly traffic flow profiles differentiated by types of day (e.g., working days and holidays) and vehicle category. Heavy vehicle flows can be converted to equivalent light vehicle flows using a conversion factor of 2.5.

- **Car-Following Model Parameters.** The car-following model simulates interactions between vehicles on the network. The model distinguishes two motion states for a vehicle: the state in which the vehicle travels along the road segment at the maximum speed allowed for that type of segment and the state in which the vehicle maintains a constant time gap from the vehicle in front. This time gap corresponds to the sum of the vehicle's reaction time and braking time. The following parameter values are generally used for the car-following model: reaction time, which represents the temporal safety gap between two consecutive vehicles, is set to 1.50 seconds for both light and heavy vehicles; effective length, which represents the sum of the vehicle's length and the distance it maintains from the vehicle in front when stopped in a queue, is set to 6.00 meters for light vehicles and 12.00 meters for heavy vehicles.

4. Application

The case study relies on the A10 highway, considering the segment from Savona and Ventimiglia (on the border with France) in the Liguria region (north Italy). The highway stretch is 112 kilometers long and contains 18 tunnels (in Fig. 1 the three main tunnels considered in the study are reported). The SS1 road has been considered as an alternative route solution to divert a certain percentage of cars flows.

For each tunnel, it is assumed that the works will be carried out in one direction of travel, thus closing a direction and diverting traffic onto a lane in the opposite direction. As a result, bypass points along the network have been located, which allow diversions of vehicular traffic, to define the segments subject to work zones. In both directions there is, for some links, a reduction in capacity as a result of the presence of the working zone, this impact on congestion and delays.

Fig. 1 – Location of the A10 Savona-Ventimiglia highway case study

4.1. Scenarios identification

Two different scenarios have been identified: the first under the hypothesis of completing maintenance operations by the end of 2025 (scenario 1), the second by considering an extension for maintenance operations up to the end of 2028 (scenario 2). The schedule for scenario 1 includes interventions on 18 tunnels along 12 sections (from toll booth to toll booth) of the A10 Savona-Ventimiglia highway. Fig. 2 shows, for scenario 1, the maintenance scheduling by quarter for each tunnel subject to maintenance.

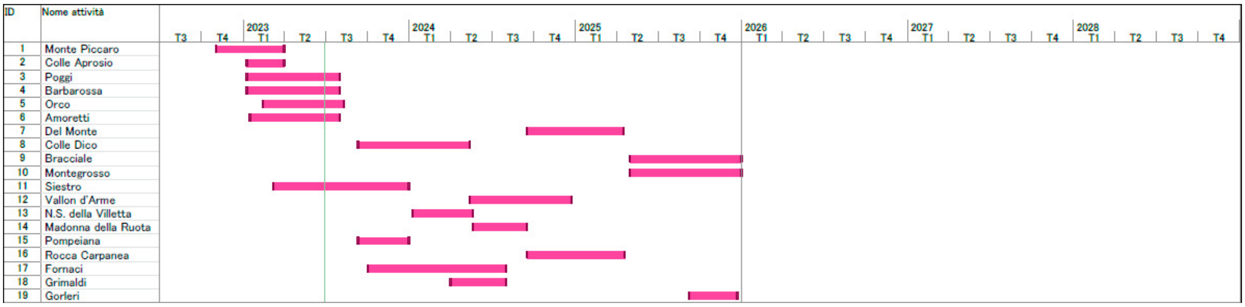

Fig. 2 - Maintenance schedule in the scenario 1 (work completion by 2025)

Scenario 2 (work completion by 2028, Fig. 3) was developed with the dual objective of, on one hand, ensuring the completion within the deadline set by Legislative Decree 264/06 (i.e., December 31, 2025) for the majority of tunnels and, on the other hand, minimizing the impact of work zones on traffic, both on the highway network and secondary roads. This plan consists in removing all tunnel work zones on the section between Savona and Albenga during the holiday periods, such as Easter, April 25th, May 1st, August, and during the Christmas holidays. As for the remaining tunnels that fall within the Albenga - Ventimiglia section characterized by significantly lower traffic volumes, the only fallback period will last until the end of August. This scheduling allows to complete the maintenance operation for 15 out of 18 tunnels in accordance with the prescriptions contained in the Legislative Decree 264/06. The only exceptions will be the Fornaci and Rocca Carpanea tunnels, within the critical section, and the Grimaldi tunnel near the national border, where temporary measures will be maintained to ensure adequate levels of road safety levels.

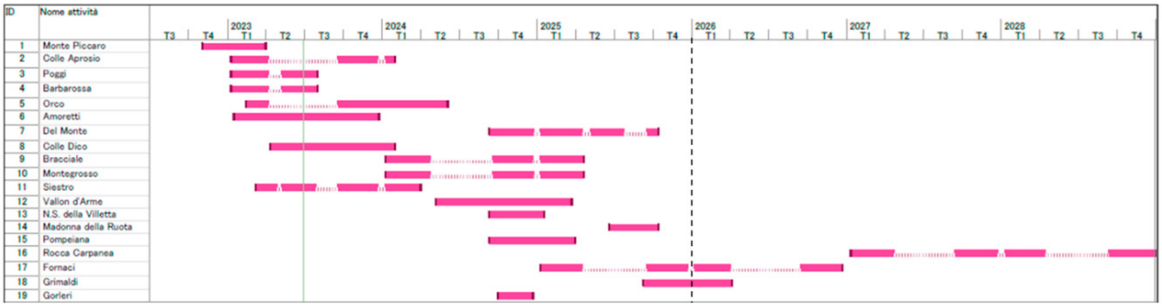

Fig. 3 - Maintenance schedule in the scenario 2 (work completion by 2028)

This schedule aims to limit the impact of highway work zones on the Ligurian highway and road network, which has been a concern for local authorities as well as industrial and consumer associations. They have repeatedly called for limiting the presence of work zones to only those that are strictly urgent and indispensable for public safety. Indeed, the presence of maintenance activities on the highway infrastructure during periods of high traffic volume results in a decrease in the overall level of service of both the highway and road network, consequently leading to negative impacts on the local economy, primarily based on tourism.

The only alternative is the SS1 "Aurelia," a primary road that links several urban areas displaced along the Ligurian coasts. This road is often characterized by chronic congestion phenomena, especially during peak periods such as summer tourism period and holidays.

4.2. Impacts on traffic flow

Mesoscopic dynamic traffic simulation models were employed to assess the potential impacts of congestion-related delays on the highway network (Cascetta, 2009; Di Gangi et al., 2016). Simulations take into account, on the supply side, the infrastructure capacity and, on the demand side, the average vehicular traffic in the individual tunnel sections under examination. The analyzes are differentiated for four typical days: summer weekdays, summer holidays, winter weekdays, and winter holidays.

The total number of working days increases from 3,171 for the 2025 maintenance schedule to 3,834 (+17%) for the 2028 maintenance schedule, after rescheduling of workdays to mitigate the impact of work zones on traffic flow conditions, especially on congested summer days. The overall economic costs are used as an indicator to assess the two scenarios. Starting from delays obtained by simulation, the cost evaluation is based on the average value of time (VOT) of the users, distinguished for light and heavy vehicles (Ministero delle Infrastrutture e dei Trasporti, 2022).

The increase in the overall economic costs related to delays along the A10 section between the national border and Savona, rise from €427.6 million for the scenario 1 to €483.8 million for the scenario 2, this is due to the overall increase in working days, reflecting a broader timeframe of analysis. However, the redistribution of working days in the 2028 maintenance schedule is helpful for preventing the more significant congestion phenomena that might occur during summer days, thus reducing the global economic impact on users (see Tab. 1). The accumulated user delays due to network congestion decrease from €77.9 million for the 2025 maintenance schedule to €71.9 million for the 2028 maintenance schedule (-8%). Therefore, regarding the impacts on user delays along the A10 between the national border and Savona, the results of the 2028 maintenance schedule are more economically advantageous than those of the 2025 maintenance schedule. This rescheduling helps avoid spikes in travel time increases. Compared to the data obtained for the scenario 1, where delays exceeded 160 minutes, the scenario 2 ensures that delays are at most 60 minutes in the worst cases. This approach can also reduce the repercussions on secondary roads, preventing a portion of the highway traffic from diverting to the road SS1 "Aurelia" and thereby minimizing local increases in congestion and incidents.

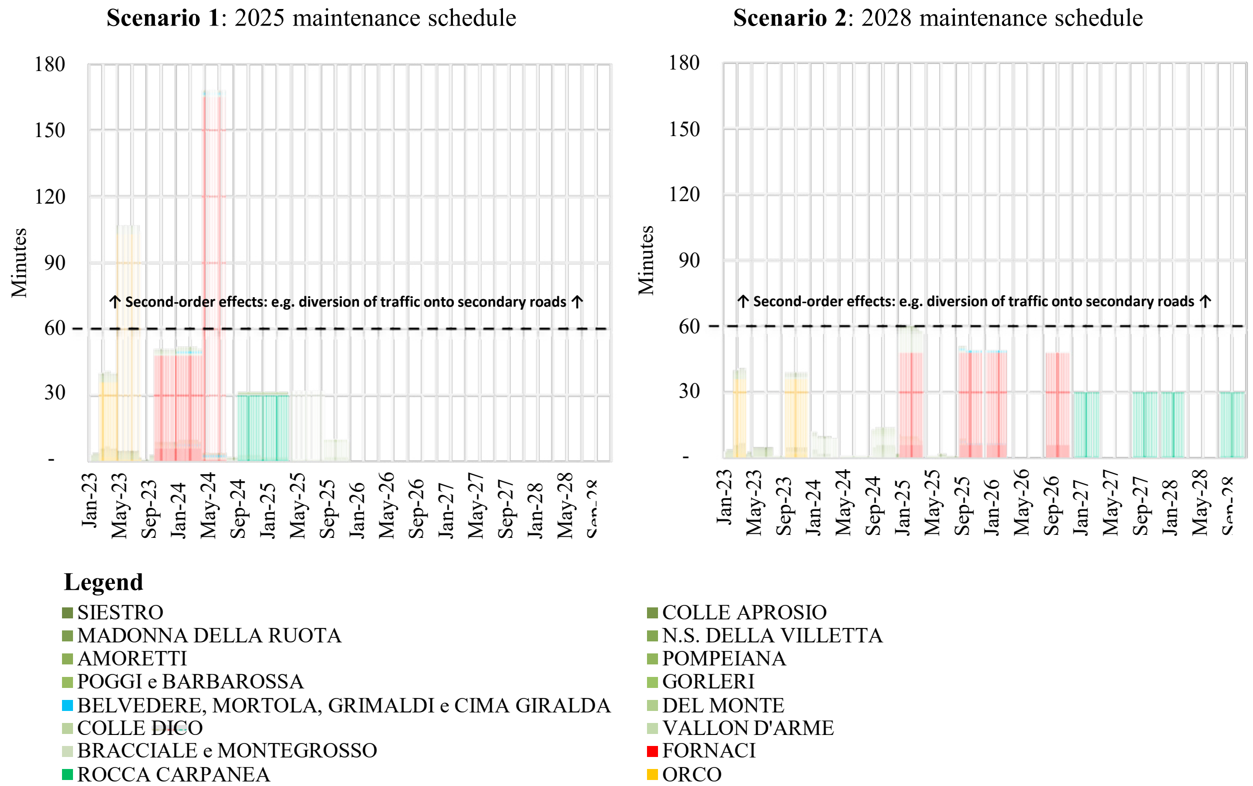

Fig. 4 - Comparison of the maximum user delays experienced between the 2025 and 2028 maintenance schedules

In previous paragraphs, it emerged that there are some days (in particular, 64 days) in which the delay for drivers traveling on A10 is greater than 60 minutes. In this case, drivers may reduce the time loss undertaking a different route on the secondary road SS1. This paragraph reports an analysis of the costs, in terms of travel times and monetary costs, if the 20% of flow cars diverges from the highway A10 to the road SS1. It is assumed that the traffic subject to the route change consists of cars only. The assumption on cars route change is consistent with two aspects: 1) the transit of heavy vehicles on SS1 is not currently permitted by law, and 2) from surveys emerged that this percentage is the number of vehicles using highway for travels within the study area. Thus, car drivers leave the motorway to avoid maintenance sites and re-enter the A10 once it has passed the tunnel in question. Considering the percentage of traffic that changes route, the increase in travel time and therefore in the monetary cost is evaluated compared to the current situation.

Since the threshold value for the travel time is set to 60 minutes, there will be no consequences for the 2028 scenario, while the flow diversion on SS1 will be necessary for 64 days for the 2025 scenario. In this case, the increase in the overall economic costs related to delays along the interstate SS1, between the national border and Savona, rises from about €23 million in the current scenario to about €80 million for the scenario 1. The assumptions for scenario 2 allow us to avoid the diversion of the flow and, consequently, avoid the congestion on the SS1 interstate (see Tab. 1).

Tab. 1 - Monetized impacts of traffic congestion due to the presence of work zones (additional to the congestion costs of the baseline scenario)

Traffic congestion	**Scenario 1 (completion of works by 2025)** [million €]	**Scenario 2 (completion of works by 2028)** [million €]
Highway	77.90	71.90
Secondary roads	56.90	0.00
Total monetized impacts	**134.80**	**71.90**

5. Conclusion

Maintenance of highway tunnels and viaducts is crucial for the safety of drivers. However, it may imply a loss of travel time for users. Consequently, operations must be planned to ensure the maintenance of the tunnels and reduce the inconvenience (wasted time) for drivers.

For this reason, in this work a methodology for assessing the impact of work zones on traffic congestion has been proposed and tested in a real case. Considering as study case a section of the highway A10 in the northern Italy, subject to maintenance works on 18 tunnels, the system has been simulated in order to evaluate the monetary costs due to the loss of time. Two scenarios have been considered: the scenario 1 with the work completion by 2025, and the scenario 2 with the work completion by 2028. Scenario 1 allows for full compliance of maintenance of all tunnels within legal deadlines through a tightly scheduled working plan; however, it entails unavoidable negative effects on both the highway and secondary road network with respect to incidents and traffic. Scenario 2, through a more phased scheduling, significantly mitigates the negative impacts on the community but inevitably requires a postponement of the completion of some tunnel works.

The application demonstrated how the proposed methodology allows for a quantitative assessment of the impacts of work zones, providing easily interpretable evidence for stakeholders, even in the case of a complex issue such as the scheduling of extraordinary maintenance interventions.

Among the limitations of this study, it is worth mentioning that other wider economic impacts should have been evaluated in the application such as: level of road safety, both for highway A10 and road SS1, due to the presence of work zones along the highway infrastructure, pollution (noise and emissions) in residential areas, loss of tourism interchange between Italy and France/Spain, loss of commercial exchanges in the north-western area (where over 50% of freight interchange relies on the Ventimiglia junction). However all these impacts are expected to be greater in the scenario with work completion by 2025 due to the higher estimated congestion levels.

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