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A methodology for setting credible speed limits based on numerical analyses and driving simulator experiments

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ABSTRACT

Speed management is an integral part of the Safe System approach and tackling unsafe speeds is the first action to fix a transport system that fails to protect people. There is a consensus that where traffic speeds are a safety issue, lowering the speed limit is considered "reasonable and safe" for conditions. Nevertheless, not only should a speed limit be reasonable and safe, but it should also be credible. Otherwise, that posted speed limit is likely to be ignored. In many instances, speed limits are not credible and highway agencies still need guidance on appropriate procedures to set credible speed limits. The main objective of this study is to propose and test a novel methodology to set credible speed limits, based on the integration of the results achieved by numerical analyses and driving simulator experiments. The proposed methodology is innovative since it takes into consideration both the design characteristics of the road infrastructure according to a specific procedure as well as the drivers' operating speeds, which are evaluated using the results of both speed prediction models and driving simulator experiments. The methodology was tested to set new speed limits on the A16 Naples–Canosa motorway, section Baiano–Candela, in southern Italy, where a posted speed limit of 80 km/h is installed in both travel directions and a new speed limit of 100 km/h is proposed, based on the results of the experiments developed within the methodology. Since the speed limit selection is associated with the expected crash frequency, the final selection of the speed limit should take into account also a safety impact assessment, considering both the expected change in the speed distribution as well as the effects of the safety countermeasures implemented in association to the speed limit change. In this study, the proposed safety countermeasures are the activation of four sections with point-to-point speed control and targeted measures at 45 curves, consisting of (1) high friction surface treatments, (2) correction of superelevation deficiencies, (3) installation of curve warning signs, chevrons, and sequential flashing beacons, and (4) shoulder rumble strips. The safety impact assessment shows that the increase in the speed limit combined with the implementation of the proposed safety countermeasures allows a crash reduction of 23%. The estimated benefit/cost ratio of the safety countermeasures is 4.66.

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1. Introduction

Since speeding is a primary contributor in approximately one-quarter of all road deaths (National Academies of Sciences, Engineering, and Medicine, 2021), the speed management as well as the application of appropriate speed limits are core components of the Safe System approach (FHWA, 2021a; ITF, 2022). The speed limits are used to improve road safety, while maintaining the efficiency of the road network and the preservation of amenity (European Commission, 2018; Ward et al., 2019). Due to roadway conditions or temporary situations at specific locations along the road which may contribute to the crash occurrence or severity (e.g., curves with small radii and poor visibility), highway agencies often consider the establishment of lower speed limits as the primary means to address the safety issues. However, the change in the posted speed limit sign may be not sufficient to also change the user's feeling of speeding and their operating speeds. Such a consequence is the result of speed limits that are "not credible" (PIARC, 2019). This means that the existing roadway geometric features and other factors may result in a prevailing speed (the speed that most people are driving at) higher than the speed indicated by the posted speed limit sign. Hence, the presence of speed limits that demand lower speed values should meet the drivers' acceptance and expectations and reflect a speed that they feel more reasonable to comply with. Speed limits appropriate for the road environment, cognisant of the road function, as well as credible and consistent with driver expectations, should be established based on an engineering study to be performed in accordance with traffic engineering practices. The engineering study should further include an analysis of the current speed distribution of free-flowing vehicles (FHWA, 2022).

Given that, in many instances, speed limits are not credible and highway agencies still need guidance on appropriate procedures to set credible speed limits, in this study a new methodology for setting credible speed limits based on numerical analyses and driving simulator experiments is proposed. This research aims to assist highway agencies in maintaining a safe and efficient transportation network providing them with a procedure whose evaluations are based on inputs like operating speeds and roadway characteristics. The observation of the speeds adopted by the road users allows the procedure to suggest new speed limits that have a significant potential of being considered reasonable. In those sections where safety treatments are needed to support the new speed limits, a set of countermeasures has been suggested. Moreover, the proposed procedure considers a safety impact assessment as a key component of the speed limit selection. The methodology was tested to set new speed limits on the A16 Naples–Canosa motorway, section Baiano–Candela, in southern Italy.

2. Literature review

To move close to zero fatalities and serious injuries on roads by 2050, the European Commission has proposed ambitious interim targets of reducing the deaths and serious injuries due to road crashes by 50% between 2021 and 2030 (European Commission, 2019a). To monitor the progress towards these targets, the European Commission has elaborated a set of Key Performance Indicators (KPIs) related to main road safety challenges to be tackled and underpinned at the European, national, regional, and local levels. Speeding, i.e., exceeding speed limits or traveling too fast for conditions (Montella et al. 2013), is among the challenges to face and is included in the safe road use KPIs. For the measurement of speed there exist various indicators that complement each other (Van den Broek et al., 2023). The principal indicator, named KPI speed in the EU Road Safety Policy Framework 2021–2030 (European Commission, 2019a), is the percentage of vehicles travelling within the speed limit. Other indicators are the average speed and the 85th percentile of speed (V_{85}), i.e., the speed below which 85% of vehicles are driving.

Speed management is an integral part of the Safe System approach (FHWA, 2021a; ITF, 2022), and tackling unsafe speeds is the first action to fix a transport system that fails to protect people. Therefore, setting safe speed limits is a priority to achieve safety improvements. A speed limit that is safe reflects the speed that drivers consider safe under typical road conditions. The most used factor to set speed limits is the 85th percentile speed of free-flowing traffic (AASHTO, 2018; National Academies of Sciences, Engineering, and Medicine, 2021; Italian Ministry of Infrastructures and Transports, 2006; Montella et al., 2015a) that represents reasonable and prudent drivers, excluding the fastest 15%, and representative of the operating speed. In Texas, the Department of Transportation (Rawson, 2015) requires that speed limits on roadways be set at the maximum unless traffic and engineering studies show a need to alter a speed limit for safety reasons. Despite the speed limits should be close to the 85th percentile speed, some modifications for crash rates, traffic volumes, land use, and alignment are allowed. Nevertheless, the major beneficial effects of posting speed limits within 5 mph of the 85th percentile speed were observed in providing improved driver compliance and reducing total crashes whereas a greater risk of non-compliance is provided with setting limits more than 5 mph below the 85th percentile speed (Parker, 1992).

With the premise that the majority of drivers choose reasonable speeds and accommodating such speeds is the primary step to reduce crashes, the NCHRP Research Report 966 (National Academies of Sciences, Engineering, and Medicine, 2021) further provides a procedure for setting speed limits based on a set of decision rules that considers both driver speed choice and safety associated with the roadway to determine the suggested speed limit for a specific roadway segment. Identifying the roadway segment context and type as well as considering the drivers' speed distribution on that segment is crucial to minimize the standard deviation or maximize the pace speed (largest percent of vehicles within a 10 mph range).

Speed limits may be statutory speeds or posted speeds (Neuman et al., 2009). Statutory speed limit, set by national or local government with jurisdiction over roads, is the general limit that applies to a given type of road. The posted speed is the maximum lawful vehicle speed for a particular location as displayed on a regulatory sign (Donnell et al., 2009). In many cases, the statutory speed limit is the most appropriate speed limit, but in some situations, the statutory limit may not be ideal, and a posted speed limit is applied.

Worldwide, each country adopts different statutory speed limits on their roads. New Zealand, Norway, and Japan have motorway limits of 100 km/h. In Australia, Canada, Korea, Russia, Sweden, the UK, and most states of the USA, on access-controlled freeways, the maximum speed limit is equal to 110 km/h. In many parts of Europe, statutory speed limits of 120 km/h (i.e., Finland, Ireland) or 130 km/h (i.e., Austria, Belgium, France, Greece, Italy, Poland) are used. In some countries (i.e., Canada, Italy, USA), in addition to maximum speed limits, there are default minimum speed limits to reduce speed variability in the traffic stream. Laws prohibiting so low speeds are also applied as they are considered dangerous over than impede the normal and reasonable traffic flow. Germany is the only country where some motorways do not have a maximum speed limit.

In Italy, the guidelines of the Italian Ministry of Infrastructures and Transports (2006) specify that a speed limit lower than the statutory speed limit should be considered exceptional and require that a speed limit be only posted in the presence of a real danger.

In New Zealand, when the safe operating speeds are below the statutory speed limit due to the road geometry, the speed limit guidelines (Waka Kotahi NZ Transport Agency, 2022) discourage the installation of a lower speed limit whereas suggest that drivers should be made aware of the need to reduce their speed using warning signs and delineation. In any case, a threshold treatment may be necessary to reinforce a change in the speed limit where there is no obvious change in the road environment meaning that appropriate safety countermeasures are often necessary to enhance speed compliance.

Most drivers do not adjust their speeds to the posted speed limits but to their perception of the physical limitations of the highway (Yao et al., 2019). Aarts et al. (2011) and Ambros et al. (2021) found that the credibility of the speed limit is strongly influenced by road design and environmental features as well as by their combination. Where a reason for limiting speed is obvious, drivers are more prone to accept lower speeds. Where drivers don't perceive the reasons for the speed limit, that posted speed limit is likely to be ignored (National Academies of Sciences, Engineering, and Medicine, 2021). Prior research shows that inappropriately high or low speed limits will result in greater speed variation, and this could also result in increased crash frequency and severity (Aarts and van Schagen, 2006; Yu and Abdel-Aty, 2014), creating more conflicts and favouring inappropriate passing manoeuvres (Srinivasan et al., 2006). Moreover, in conditions where there is a large disparity between the operating speed and the posted speed limit, drivers tend to disregard the speed limit and make their own judgments (Gayah et al., 2018; Lee et al., 2017; PIARC, 2019).

There is a consensus that where traffic speeds are a safety issue, lowering the speed limit is considered "reasonable and safe" for conditions (Hu, 2016, Retting and Teoh, 2008). Nevertheless, reducing a speed limit does not necessarily lead to an equivalent drop in the actual vehicle speeds. Furthermore, there is evidence from recent studies that a debate is still open on where, when, and by how much speed limits may or may not be reduced or increased on existing facilities and newly constructed roads (National Academies of Sciences, Engineering, and Medicine, 2022a; 2022b). Xavier et al. (2017) evaluated the safety effects of increasing the speed limits and indirect safety implications that may result from changes in speed limits in Texas. On rural freeways, for instance, a before-after analysis depicted an increase in total crashes and fatal and serious crashes following a change in the maximum speed limit from 70 mph to 75 mph. A considerable increase in rural freeway crashes was observed for night-time crashes, fixed-object crashes, and overturn crashes with increases of 23%, 27%, and 3%, respectively. An analysis carried out for Kansas freeways provided mixed results (Shirazinejad, 2018). After an increase in crashes by approximately 16%, a year-by-year statistical comparison did not provide any evidence of an increase in the mean number of crashes due to the increased speed limit, suggesting that any observed variations can be accounted for by unobserved heterogeneity in the data. Thus, the speed limit change in Kansas had minimal influence on the number of crashes and appeared to be overshadowed by other factors that influenced the number of crashes. In several instances, instead, it was also found that raising the existing speed limits was the appropriate solution (FHWA, 2020) because the solution advocated that the new speed limits better reflect the true nature of the segment. Thus, the new speed limits are more likely to be respected as a reasonable and safe maximum.

Recently, Eustace et al. (2022) have estimated the impacts of raising speed limits on traffic safety on rural freeways in Ohio (from 65 mi/h to 70 mi/h), using available crash, roadway, and traffic data. The Empirical Bayes before-after study showed that total crashes decreased by 24.6% and fatal and injury crashes decreased by 8.8% for the two years after the speed limit was changed.

Hence, achieving drivers' compliance with the speed limit is a crucial issue, and encouraging compliance with posted speed limits is an ongoing challenge in the highway sector. The use of only site observations does not allow to achieve in-depth investigations of human factors as those related to drivers' perceptions and decisions. Emerging technologies make it possible to evaluate the interactions between the driver, the vehicle and the road environment through an interdisciplinary approach based on driving simulations. The driving simulator is a very useful tool, capable of investigating how different factors, both external and internal to the driver, may affect the perception of driving risk and road safety. The use of a driving simulator has several benefits, as the costs are considerably lower than in field studies and the tests are reproducible for all the sample of drivers with the same simulated events and in a controlled environment. The reliability of the tool has been fully validated in previous studies, typically on rural roads and motorways, for speed and trajectory measures (Calvi, 2018; Calvi et al., 2020). Driving simulators enable to investigate the variability of driver performance under different conditions and offer a promising perspective for road safety design and management. At this aim, a driving simulator has been used for the experimental tests, capable of promoting an interdisciplinary approach to evaluate the interactions between the driver, the vehicle, and the road environment. In fact, it is well acknowledged that the driving simulator is a powerful and useful tool for studying how drivers behave on different types of roads and in different situations. Indeed, the driving simulator is a very useful tool, capable of investigating how different factors, both external and internal to the driver, may affect the perception of driving risk and road safety. The use of a driving simulator has several benefits, as the costs are considerably lower than in field studies and the tests are reproducible for all the sample of drivers with the same simulated events and in a controlled environment.

3. Objectives

The main objective of this study is to propose and test a novel methodology to set credible speed limits, based on the integration of the results achieved by numerical analyses and driving simulator experiments. The methodology takes into consideration not only the design characteristics of the road infrastructure but also the drivers' operating speeds, evaluated using both speed prediction models and driving simulator tests, to propose credible speed limits that meet the drivers' expectations; accordingly, it is expected that drivers are more inclined to comply with them.

The proposed methodology is applicable both to new designs where new speed limits must be selected as well as for existing roads when speed limits are inconsistent with drivers' expectations. Finally, a set of countermeasures is proposed in such cases where the new credible speed limits require safety improvements, and a safety impact assessment is carried out to provide all relevant information for an evaluation of the revised speed limits.

4. Methodology

To reflect mobility needs and, at the same time, to ensure safe driving, the proposed methodology combines the concepts of inferred design speed and operating speed, defining the speed limit as a weighted average value of both speeds. In Fig. 1 a step-by-step diagram is provided to offer an easier-to-understand flowchart of the methodology proposed to set credible speed limits.

4.1. Inferred design speed

The inferred design speed is assumed to be the minimum speed between the speed determined on the basis of the vehicle stability on curves (Eq. (1) and the speed consistent with the available stopping sight distance.

The inferred design speed based on the vehicle stability concerning skidding depends on the horizontal curvature according to the mass-point equation:

$$e + f = \frac{V^2}{(127 \times R)} \tag{1}$$

where

e = curve superelevation (m/m);
f = side friction factor;
V = design speed (km/h);
R = curve radius (m).

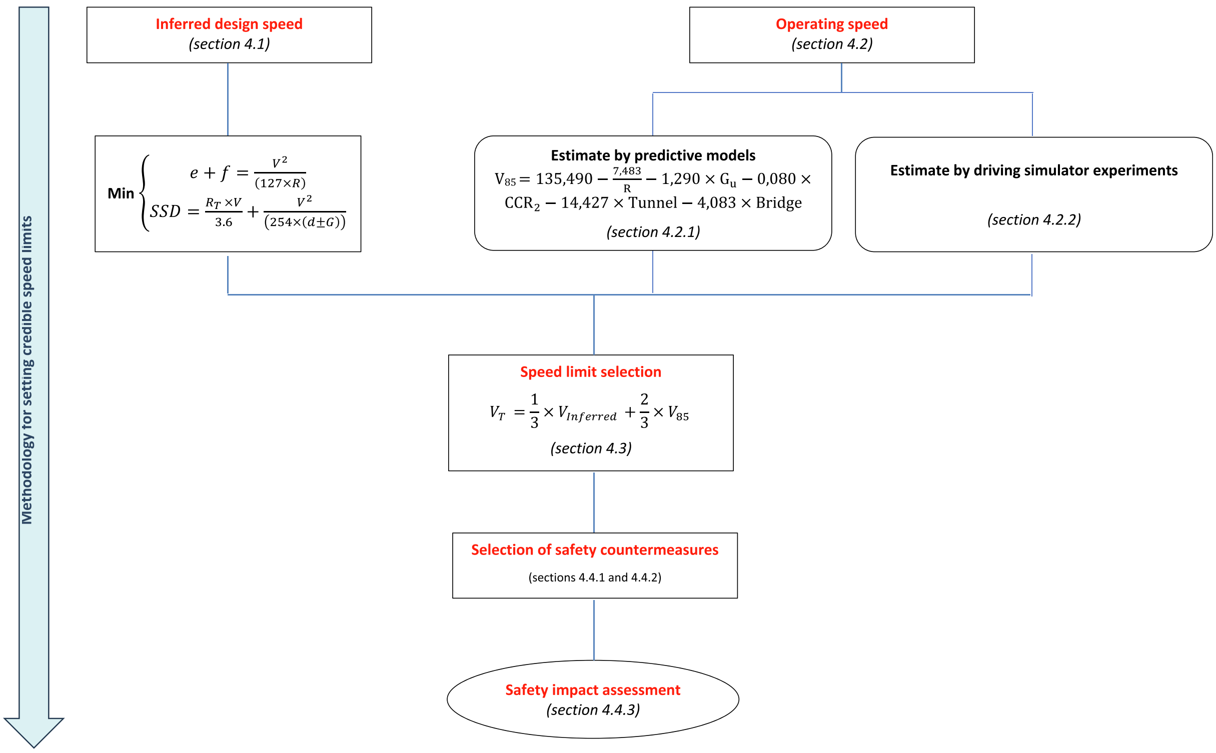

Fig. 1. Flowchart of the methodology.

The inferred design speed based on the stopping sight distance (Eq. (2) is the maximum speed consistent with the available sight distance, formulated according to the equation:

$$SSD = \frac{R_T \times V}{3.6} + \frac{V^2}{(254 \times (d \pm G))} \tag{2}$$

where

SSD = stopping sight distance (m);
R_T = perception-reaction time (s);
V = vehicle speed (km/h);
d = deceleration (m/s^2);
G = percent of grade divided by 100.

Different values of R_T and d are recommended by the geometric design standards. The available stopping sight distance is assessed assuming the position of the driver to be on the axis of all the lanes with the eye placed 1.10 m (1.05 m in the UK, 1.0 m in Germany) above the roadway surface and the height of the obstacles equal to 1.0 m (FGSV, 2008, 2012), 0.60 m (AASHTO, 2018; République Francaise, 2021; TAC, 2017), 0.26 m (Highways England, 2020), 0.20 m (Austroads, 2021a), or 0.10 m (Italian Ministry of Infrastructures and Transports, 2001).

4.2. Operating speed

The operating speed is the speed at which drivers are observed operating their vehicles during free-flow conditions, unimpeded by traffic control devices or by other vehicles in the traffic stream. Because only a small percentage of drivers travel at extremely high speeds, the 85th percentile of the distribution of the observed speeds (V_{85}) is the most frequently used measure of the operating speed (AASHTO, 2018).

On the existing highways, agencies usually collect speed measures. However, these measures are collected only on some sections of the highways and don't provide continuous speed profiles whereas operating speed predictive models allow the estimation of continuous speed profiles (Montella et al., 2015b).

4.2.1. Estimating operating speed by predictive models

Many predictive models have been developed to estimate the operating speeds as a function of horizontal alignment, vertical grade, cross-sectional dimensions, and roadside features (TRB, 2011). The form of the models and the number of variables used in each model can vary considerably (Montella et al., 2015b). Most of these models are based on speed data collected by measuring the individual speeds of a sample of the vehicles passing a given spot calculating the operating speeds assuming constant speed on curves and, therefore, deceleration and acceleration that occur entirely on the approach tangent and the departure tangent. In recent years, continuous speed profiles have been developed through instrumented vehicles (Lv et al., 2019; Malaghan et al., 2021; Montella et al., 2014; Wang et al., 2020), floating car data (Farah et al, 2019; Vos et al., 2021), and driving simulators (Bobermin et al., 2021; Calvi, 2015a; Calvi et al., 2023; Choudhari and Maji, 2022) showing potential for a more accurate investigation of drivers' behaviour. Overall, it is important to apply models calibrated in conditions like the ones of the speed limit evaluation.

4.2.2. Estimating operating speed by driving simulator experiments

Driving simulators allow experiments to be conducted in controlled conditions, to collect reliable data, and to better understand interactions between drivers and roadway surroundings (Galante et al., 2022; Calvi, 2015b). The use of driving simulators has some possible shortcomings, including physical limitations and realism, simulator sickness, and most importantly validity (Bella and Calvi, 2013; Bella et al., 2014). The issue of validation must be addressed before the experimental results can be applied to real life situations, thus only a validated simulator can be considered as a useful research tool. Fortunately, validation of using driving simulators in highway research can be achieved (Calvi, 2018; Calvi et al., 2020; Galante et al. 2010), and the benefits have been demonstrated by the fact that several full-scale research driving simulators exist worldwide, owned and operated by academic institutions, government research establishments and vehicle manufacturers.

Several validation studies have been worldwide developed over the years for validating driving simulators specifically for speed research. As an example, Godley et al. (2002) performed a behavioural validation of an advanced driving simulator for its use in evaluating speeding countermeasures (rumble strips). They found that participants reacted to the rumble strips, in relation to their deceleration pattern on the control road, in very similar ways in both the instrumented car and simulator experiments, establishing the relative validities.

More specifically, the reliability of the driving simulator used in this study (Roma Tre driving simulator) has been fully validated (Bella, 2007; Calvi, 2018) allowing for use it for the evaluation of the driving performance in terms of speed, acceleration and trajectory under different driving conditions and road environments (Calvi, 2015a; Calvi, 2015b; Cafiso, Calvi et al., 2021, Cafiso, Montella et al., 2021). Indeed, Bella (2007) recorded speeds at eleven measurement sites with different alignment configurations on a two-lane rural road, in both the real and simulated environment. The overall findings, based on comparative and statistical analysis, established the relative validity in all the measurement sites and also revealed that absolute validity was obtained in nine out of the eleven measurement sites. Another validation study of the driving simulator used for this research was developed by Calvi (2018) by comparing the speeds measured on-site with the speeds recorded during the simulations tests along a rural road reproduced in the scenario. A bilateral Z-test for non-matched samples was used and it was found that the differences in average speeds between the two samples were not statistically significant. Calvi et al. (2020) also validated the driving simulator for use by designers in adopting the best solution for speed change lanes on motorways. Specifically, driving performance along exit and entry manoeuvres, from the motorway to service areas and vice versa, was recorded in real and simulated scenarios using an instrumented vehicle and a driving simulator, where an exact representation of the existing roadway was reproduced. Validation of the driving simulator was performed by comparing field and simulation data in terms of driving speeds and trajectories of two driver samples. The main results demonstrated the relative and absolute validity of the simulator for deceleration and acceleration lanes to/from service areas. Finally, Bella (2005) reproduced in the driving simulation environment a segment of an Italian motorway, like the case study of the research here presented and collected speeds both on the field (using a laser speed meter) and during the driving simulation tests. Again, the statistical analysis revealed that differences between the speeds observed in the real situation and those measured with the simulator were not statistically significant.

4.3. Speed limit selection

In each curve, the theoretical speed limit is evaluated by combining the inferred design speed and the operating speed as a weighted average:

$$V_T = \frac{1}{3}\times V_{Inferred} + \frac{2}{3}\times V_{85} \tag{3}$$

where

V_T = theoretical speed limit (km/h);
$V_{Inferred}$ = inferred design speed (km/h);
V_{85} = operating speed (km/h).

The theoretical speed limit needs engineering adjustment. Indeed, to improve operating speed consistency, it is recommended to select constant speed limits for significant sections of the route, thus reducing the speed limit changes as much as possible.

4.4. Safety impact assessment

Since the speed limit selection is associated with the expected crash frequency, the final selection of the speed limit should also include a safety impact assessment, considering both the safety effects of the expected change in the speed distribution as well as the effects of the safety countermeasures implemented in association to the speed limit change.

4.4.1. Safety effects of the speed limit change

First step is the estimation of the speed distribution based on the different speed limits alternatives. The crash modification factor of a speed limit change may be estimated as (Austroads, 2012):

$$CMF_{speed} = \left(\frac{Speedafter}{Speedbefore}\right)^2 \tag{4}$$

where

CMF_{speed} = crash modification factor of a speed distribution change;
Speed after = estimated average speed after the speed limit change (km/h);
Speed before = estimated average speed before the speed limit change (km/h).

4.4.2. Safety effects of the countermeasures

Agencies can use speed safety cameras (SSCs) as an effective and reliable technology to supplement more traditional methods of enforcement, engineering measures, and education to alter the social norms of speeding (FHWA, 2021b). SSCs can be deployed as: fixed units – a single, stationary camera targeting one location; point-to-point (P2P) units – multiple cameras to capture average speed over a certain distance; and mobile units – a portable camera, generally in a vehicle or trailer. It is strongly recommended to use point-to-point (P2P) speed enforcement, also named average speed enforcement or section speed enforcement (Lynch et al., 2011; Montella et al., 2012, 2015a, 2015c; Soole et al., 2013), which is a relatively new technological approach to traffic law enforcement that has increased in use in several highly motorized countries. Point-to-point enforcement involves the installation of a series of cameras at multiple locations along a road section. The average speed is calculated by dividing the distance between two camera sites by the time taken for the vehicle to travel between those two sites. If the corresponding average speed of a vehicle exceeds the posted speed limit for that road section, image and offence data are transmitted to a central processing unit from the local processor via a communication network and a sanction is imposed only for an average speed exceeding the posted speed between the cameras. The installation of P2P systems in Italy showed a decrease in speed variability and a reduction in excessive speeding behaviour (Montella et al., 2015a, 2015c). The decrease in the standard deviation of speed was 26% while the proportion of light and heavy vehicles exceeding the speed limits of more than 20 km/h was reduced respectively by 84% and 77%. In Belgium, considerable decreases were found by 5.8 km/h in the average speed, 74% in the odds of drivers exceeding the speed limit and 86% in the odds of drivers exceeding the speed limit by more than 10% (De Pauw et al., 2014). Moreover, in Italy, the P2P system yielded a reduction in the total crashes equal to 31% in rural motorways (Montella et al., 2012) and equal to 32% in urban motorways (Montella et al., 2015c). On Korean expressways, the P2P system yielded a reduction in total crashes equal to 43% (Shim et al., 2020). In Norway, Høye (2015) found a 49% reduction in crashes with fatal and severe injuries after P2P installation in 14 sites.

In the sites where the inferred design speed is lower than the speed limit, the critical condition is the low friction in wet pavement which is associated with longer stopping sight distances and lower vehicle stability on curves. In these sites, the installation of High Friction Surface Treatments (HFSTs) is recommended since pavement friction improvement helps to keep vehicles on the road when brakes are applied and when navigating curves or steering aggressively, especially in wet weather (Elvik et al., 2009; Intini et al., 2020) when even a thin film of water on the surface of the pavement can reduce contact between the tire and pavement surface, the level of pavement friction is reduced, and this may lead to skidding or hydroplaning. HFST involves the application of very high-quality aggregate to the pavement using a polymer binder. Results of the installation of HFSTs in the US (Lyon et al., 2020) showed impressive statistically significant crash reductions at curve sites. There was a reduction of 84%, 73%, and 57% for wet-road crashes, run-off-road crashes, and total crashes, respectively. Geedipally et al. (2017) developed safety performance functions to describe the relationship between crash frequency and traffic, geometric, and pavement variables for horizontal curves in a southern state of the United States. According to their models, an increase in the Skid Number from 25 to 65 on rural two-lane highways results in a 61% decrease in wet-weather run-off-the-road crashes. In Italy, Cafiso, Calvi et al. (2021), Cafiso, Montella et al. (2021) developed crash modification functions for the Grip Number showing that an increase in the Grip Number from 25 to 65 results in a 75% decrease in wet-road crashes and a 58% decrease in total crashes.

Usually, curves with inferred design speed lower than the speed limit require high-performance markings and supplemental delineation, such as combined installation of chevrons and sequential flashing beacons, which are light emitting diodes (LED) lights within each chevron sign to provide sequential lighted guidance through the curve. In Italy, the combined installation of curve warning signs, chevrons, and sequential flashing beacons produced a reduction of 77% in night-time crashes and 48% in total crashes (Montella, 2009). In the US, Hallmark et al. (2020) found a total crash reduction of 66% after the installation of chevrons and sequential flashing beacons. In these sites, a further low-cost recommended safety countermeasure is the installation of shoulder rumble strips to enhance the curve delineation and alert drivers with an audible, visual, and haptic cue when they are leaving the travel lane producing noise and vibration. Their use produced a 79% reduction in single-vehicle run-off-the-road crashes (SVROR) on freeways (AASHTO, 2010).

4.4.3. Benefit/cost analysis

The purpose of the benefit/cost analysis is to determine the economic feasibility of implementing the safety countermeasures. The benefit-cost ratio is assessed as the ratio between the annual benefits and the annual costs of the safety countermeasures.

Safety benefits are measured in terms of reduction in crash costs. Costs of road crashes have been studied since several decades (Wijnen et al., 2017). Recently, the European Commission (2019b) has published estimates of crash cost components per casualty. Similarly, estimates of crash costs in the US are published in the Highway Safety Manual (AASHTO, 2010), estimates of crash costs in Australasia are published in the Austroads (2021b) Guide to Road Safety, and estimates of crash costs in Great Britain (Department for Transport, 2022) are published on annual basis. Annual safety benefits can be estimated as:

$$\mathrm{B} = \Delta CF \times C = \sum_{i=1}^{n} \Delta CF_i \times C_i \tag{5}$$

where

B = annual safety benefit;
ΔCF = reduction in annual number of total crashes;
ΔCF_i = reduction in annual number of crashes with severity level equal to i;
C = crash cost (all severity levels);
C_i = cost of a crash with severity level equal to i;
N = number of severity levels used in the analysis.

Crash reduction can be estimated as:

$$\Delta CF = CF_{before} - CF_{after} = CF_{before} - CF_{before} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_n) \tag{6}$$

where

CF_{before} = expected annual number of crashes that would have occurred in the after period without safety countermeasures;
CF_{after} = expected annual number of crashes in the after period with implementation of the safety countermeasures;
CMF_j = crash modification factor of the safety countermeasure $j = 1 + (CMF_{jra} - 1) \times p_{jra}$;
CMF_{jra} = CMF of the crash types affected by the countermeasure j;

P_{jra} = proportion of the crash types affected by the countermeasure j (1 if the countermeasure affects all crash types).

Costs of the countermeasures are converted into an annualized value using the capital recovery factor:

$$CRF = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{7}$$

where

CRF = capital recovery factor;
i = discount rate;
n = service life (years).

5. Case study

5.1. General characteristics of the study site

The study site is the section Baiano–Candela of the A16 Naples–Canosa motorway (L = 202.0 km, i.e., 101.0 km per carriageway), in southern Italy. A16 is a divided motorway with two lanes for each direction (lane width = 3.75 m, right shoulder width = 0.50–3.50 m, median width = 2.00 m), access control, and interchanges. The motorway has a bending alignment, with several low radius curves, many design inconsistencies, and sections with high longitudinal grades (Montella and Imbriani, 2015; Montella et al., 2021). The study section is on mountainous terrain with 11 tunnels (L = 4.03 km) and 38 bridges (L = 8.11 km). The radius of the horizontal curves varies between 250 m and 4,000 m. Spiral transitions are not present. The deflection angle varies between 5 gon and 109 gon. The superelevation mean is equal to 3.25%. The maximum longitudinal grade is equal to 5.00%. The roadway geometric features and the pavement surface condition data were extracted using the database provided by ASPI (Autostrade per l'Italia), the concessionary company that manages the biggest motorway network in Italy. The database is named AGE (Autostrade Google Earth), is georeferenced (Fig. 2) and contains both videos collected by the Automatic Road Analyzer (ARAN) as well as pavement surface data collected every six months by the ARAN and the SUMMS equipment, geometric data and detailed data on several assets such as road restraint systems, noise barriers, markings, signs, roadworks, walls, tunnels, and bridges.

In Italy, the statutory speed limit on motorways is equal to 130 km/h. Nevertheless, in the study site, posted speed limits equal to 80 km/h are installed in both travel directions (L = 101 km in the east carriageway, L = 101 km in the west carriageway). In the sections of the motorway outside the study site, the speed limit is equal to 130 km/h. Given that the 80 km/h speed limit is 50 km/h lower than the speed limit of the other sections and is applied to very long segments, it is perceived by most drivers as unrealistic. In November 2021 the Italian Ministry of Interior – Department of Public Safety wrote a formal note to ASPI asking for a revision of the speed limit. Then, ASPI asked for scientific support for the revision of the speed limit at the Universities of Naples Federico II and Roma Tre.

Fig. 2. Example of the AGE database.

5.2. Numerical analyses

5.2.1. Inferred design speed

The inferred design speed, i.e. the minimum speed between the speed determined on the basis of the vehicle stability on curves (Eq. (1) and the speed consistent with the available stopping sight distance (Eq. (2), was evaluated according to the Italian geometric design standard criteria (Italian Ministry of Infrastructures and Transports, 2001). The inferred design speed ranges between 62 km/h and 140 km/h and has a mean value of 96 km/h (see Table 1).

5.2.2. Operating speed

The operating speed was assessed using the model previously developed on the same motorway (Eq. 8) by Montella et al. (2014). In the study, an instrumented vehicle with GPS continuous speed tracking was used to analyse driver behaviour in terms of speed choice and deceleration and acceleration performances and to develop operating speed prediction models. The model assessed the operating speeds on curves as follows:

$V_{85} = 135,490 - \frac{7,483}{R} - 1,290 \times G_u - 0,080 \times CCR_2 - 14,427 \times \text{Tunnel} - 4,083 \times \text{Bridge}$ (8).where

V_{85} = 85th percentile of operating speed on curves (km/h);
R = curve radius (m);
G_u = equivalent upgrade (%);
CCR_2 = curvature change ratio of the 2 km preceding the curve (gon/km);
Tunnel = binary variable, equal to 1 if the segment is on a tunnel;
Bridge = binary variable, equal to 1 if the segment is on a bridge.

The operating speed ranges between 90 km/h and 132 km/h and has a mean value of 116 km/h (see Table 1).

5.2.3. Theoretical speed limit

The theoretical speed limit was evaluated by combining the inferred design speed and the operating speed as a weighted average according to Eq. (3). In the 294 horizontal curves of the study site, the theoretical speed limit ranges between 84 km/h and 135 km/h and has a mean value of 109 km/h (see Table 1).

5.3. Driving simulator experiments

5.3.1. Driving simulator

The study was conducted in the fixed-based medium-fidelity driving simulator (STISIM M300; Systems Technology Incorporated) of the Department of Civil, Computer Science and Aeronautical Technologies Engineering at Roma Tre University (Fig. 3). The laboratory is equipped with a full-cab Toyota Auris. The simulator has a force-feedback steering wheel, brake and accelerator pedals, and a performance measurement system. Three overhead projectors with a resolution of 1920 × 1200 pixels each and a frame rate of 60 Hz project the driving environment on a curved projection screen that provides a 180° horizontal field of view.

5.3.2. Scenario design

Two segments of the A16 motorway were selected and reproduced in the driving simulator in two different configurations, meaning with and without the actual posted speed limits. Fig. 4 provides a comparison between the real-environment setting (on the left) and the virtual driving simulator scenario (on the right) in some locations of the two tested segments. The first segment, from Monteforte to Baiano, has a length of 9.5 km. Initially, the section is a divided three-lane motorway. The cross-section is equal to 10.5 m (a passing lane, a conventional lane, and a climbing lane placed on the right-hand side of the motorway, without the shoulders; the width of each lane is equal to 3.5 m). Then, the section reduces to two lanes plus the right shoulder, except in some locations, i.e. in presence of bridges, where there is no right shoulder. The longitudinal grade ranges between 2.2% and 5.8%. In this segment, the radii of the curves range between 300 m and 1400 m. Operational concerns are for the two consecutive curves (C_6 and C_7 in Table 2) with a radius equal to 300 m, as they are located on a downgrade equal to 5.0% and after a large curve (C_8) with a radius equal to 1400 m. There are 13 tangent–curve configurations along the segment. The length of tangents and radius of curves ranges between 162 m and 686 m and between 300 m and 1400 m, respectively. The first three columns of Table 2 show the overall features of the horizontal alignment of the first segment.

Table 1
Summary statistics of numerical analyses (294 horizontal curves).

Parameter	Mean	Standard deviation	Minimum	Maximum
Design speed (km/h)	114	18	80	140
Sight distance speed (km/h)	96	18	62	140
Inferred design speed (km/h)	96	18	62	140
Operating speed (km/h)	116	8	90	132
Theoretical speed limit (km/h)	109	10	84	135

Fig. 3. Roma Tre driving simulator.

The second selected segment, from Scampitella to Lacedonia, has a length of 10.0 km. The section is a divided two-lane motorway. The cross-section is equal to 9.5 m (a passing lane and a conventional lane of width equal to 3.5 m and a right shoulder of 2.5 m). A longitudinal upgrade equal to 5.0% is followed by downgrades ranging between 1.5% and 4.0%. There are 10 tangent–curve configurations along the segment. The length of tangents and radius of curves ranges between 80 m and 844 m and between 300 m and 2000 m, respectively. The first three columns of Table 3 show the overall features of the horizontal alignment of the second segment.

5.3.3. Participants

A total of 31 participants (volunteers), 12 women and 19 men, took part in the driving simulator study. Three participants were excluded due to technical errors in data acquisition or simulator sickness. Thus, the final sample consisted of 28 subjects (11 women and 17 men), with a mean age of 37.6 years (range between 24 and 64 years, s.d. = 10.9 years). The participants were recruited among students and staff of the Department of Civil, Computer Science and Aeronautical Technologies Engineering at Roma Tre University, held a valid driver's license, and had not yet participated in previous driving simulator studies.

In this study, a homogeneous sample of subjects was selected, and the same standard simulation protocol was run to avoid bias in the results due to drivers' attitudes, driving experience, age, stress level, emotional state, neuro-cognitive state, or other factors. The authors' choice of sample homogeneity is based on the fact that many studies have shown that driving performance is primarily affected by age (Domeyer et al., 2013) and driving experience (Dixit et al., 2014). In the present study, with the overall objective of determining the operating speeds and the speed profiles of the drivers along the segments of the A16 motorway, the authors recruited a homogeneous sample of subjects so that any bias due to sample heterogeneity would be reasonably negligible or severely limited.

5.3.4. Procedure

First, the participants were introduced to the overall objective and research procedure of the study (without revealing the exact purpose and details to avoid biased results). They were then asked to fill out a short questionnaire with their gender, birth date, driver's license date, assessment of their driving ability and frequency of driving. To get confident and familiarize themselves with the driving simulator, participants were requested to complete a training scenario for about 10 min, before starting the actual simulation tests. The participants were asked to drive as they would normally do and as they considered appropriate for the road situation and environment. Finally, each participant performed the four drives (two for each motorway's segment, with and without the posted speed limits) on two different days (two drives per day) in daylight with dry pavement and clear weather conditions. The sequence of drives was random to avoid any influences due to repetition of the same order in the experimental conditions and to disable drivers from memorizing the scenarios.

Following each driving test, a post-driving questionnaire, on the type and extent of any perceived discomfort while driving (nausea, dizziness, fatigue, etc.), was completed by the driver.

5.3.5. Data analysis

Drivers' speeds were collected on the two segments in the configurations with and without the posted speed limits. Based on the collected speed data it was possible to obtain the speed profile of each driver along the four drives (Fig. 4 and Fig. 5) and to determine the mean speed of each driver in each geometric feature of the segments. In detail, in each tangent and each curve, the mean speed (V_{mean}), the standard deviation of speed (s.d.), the operating speed (V_{85}), the minimum (V_{min}) and the maximum (V_{max}) speeds of the sample of drivers were calculated (Table 2 and Table 3).

Fig. 4. Comparison between the real-environment setting (on the left) and the virtual scenario (on the right).

5.3.6. Results

5.3.6.1. Segment 1. Fig. 5 shows the speed profiles along the first segment. Specifically, the mean speed profile and the operating speed profile are reported in the two configurations with and without the posted speed limits. Table 2 summarizes the speed data. The speed data collected on the first segment in the configuration with the actual posted speed limits show that the mean speed of the drivers' sample ranged between 85.2 km/h and 94.3 km/h, while the operating speed ranged between 88.1 km/h and 100.0 km/h. The minimum speed recorded was equal to 77.6 km/h, whereas the maximum speed exceeded 100 km/h. Along the entire segment 1, the mean speed was 91.1 km/h (s.d. ranged between 3.1 km/h and 5.8 km/h), demonstrating very low speed dispersion. The operating speeds exceed the mean speeds from 2.4 km/h to 8.1 km/h. The difference between the maximum and the minimum speeds was equal to 18.0 km/h on average (ranging between 11.8 km/h and 23.3 km/h).

In the absence of the posted speed limits, drivers showed a more heterogeneous behaviour resulting in a greater speed variance. The mean speeds ranged between 101.1 km/h and 118.9 km/h. The lowest speeds were recorded on the smallest curves (those with a

Table 2
Mean speed (V_{mean}), operating speed (V_{85}), minimum (V_{min}) and maximum (V_{max}) speeds on the first motorway's segment.

Element	R [m]	L [m]	With speed limits of 80 km/h [Km/h]					Without speed limits [Km/h]					ΔV_{mean} [Km/h]	ΔV_{85} [Km/h]
			V_{mean}	s.d.	V_{85}	V_{min}	V_{max}	V_{mean}	s.d.	V_{85}	V_{min}	V_{max}		
T_1	–	322	85.6	3.7	88.8	77.9	92.4	105.9	4.9	110.2	95.6	115.3	20.3	21.4
C_1	300	171	85.7	3.2	88.1	77.6	94.0	102.3	4.1	106.0	94.1	109.9	16.6	17.9
T_2	–	169	85.2	3.2	88.1	78.2	92.1	103.9	5.2	109.4	94.1	114.1	18.7	21.3
C_2	800	328	86.1	3.1	89.5	80.7	92.5	105.1	6.3	112.0	91.4	119.7	19.0	22.5
T_3	–	686	92.9	4.3	97.4	86.0	100.7	114.3	7.5	121.7	96.5	129.9	21.5	24.3
C_3	450	148	91.0	4.7	96.3	82.1	100.2	111.7	7.6	119.3	95.5	126.8	20.7	23.0
T_4	–	347	91.7	4.7	96.0	83.5	103.5	113.0	7.6	120.7	96.1	129.4	21.3	24.7
C_4	800	203	91.2	4.9	96.1	83.1	101.3	111.6	8.1	118.2	94.5	129.3	20.4	22.1
T_5	–	492	92.9	5.4	97.9	82.3	105.6	114.8	8.9	121.7	98.8	129.9	22.0	23.9
C_5	700	214	92.7	5.0	97.4	83.5	105.4	110.2	9.9	119.5	92.7	129.9	17.5	22.2
T_6	–	537	93.3	4.8	97.3	85.3	104.3	112.9	9.5	122.2	95.3	134.5	19.5	24.9
C_6	300	309	89.5	5.5	94.7	79.4	101.5	102.6	8.6	111.3	88.8	120.6	13.1	16.6
T_7	–	224	89.6	4.5	93.1	82.6	103.8	103.1	8.1	111.0	89.9	117.9	13.6	17.9
C_7	300	514	87.5	4.1	91.2	81.0	97.0	101.1	7.4	108.9	88.1	114.6	13.6	17.7
T_8	–	525	92.1	4.1	96.0	85.4	100.5	110.2	7.4	118.6	97.5	126.2	18.1	22.6
C_8	1400	282	92.9	5.2	99.3	83.4	102.4	113.5	7.2	121.2	101.3	128.6	20.6	21.8
T_9	–	162	92.6	4.6	96.5	85.6	104.6	115.9	6.5	122.1	105.3	131.6	23.3	25.6
C_9	900	343	92.0	4.1	95.3	84.9	100.7	116.2	6.9	122.8	103.2	130.2	24.2	27.5
T_{10}	–	277	92.7	4.2	96.0	85.6	100.7	118.1	7.0	124.6	103.9	130.7	25.3	28.6
C_{10}	900	128	92.9	4.3	97.5	84.1	101.1	118.5	7.4	124.3	103.9	131.4	25.6	26.8
T_{11}	–	532	93.2	4.3	97.4	84.6	101.5	118.9	6.6	124.9	103.0	129.3	25.7	27.5
C_{11}	700	309	93.7	4.8	98.2	84.3	102.8	115.6	6.9	122.0	101.9	125.9	21.9	23.8
T_{12}	–	225	94.3	5.3	99.8	86.6	107.0	115.7	7.7	124.4	101.1	129.3	21.4	24.6
C_{12}	400	179	91.9	5.8	100.0	80.3	101.8	109.5	7.5	114.1	97.8	125.7	17.7	14.1
T_{13}	–	382	92.4	4.7	95.9	83.0	103.2	113.0	6.8	119.0	102.9	125.8	20.6	23.1
C_{13}	800	191	92.1	4.8	96.5	83.8	101.5	111.8	7.2	118.6	100.8	125.4	19.7	22.1

Table 3
Mean speed (V_{mean}), operating speed (V_{85}), minimum (V_{min}) and maximum (V_{max}) speeds on the second motorway's segment.

Element	R [m]	L [m]	With speed limits of 80 km/h [Km/h]					Without speed limits [Km/h]					ΔV_{mean} [Km/h]	ΔV_{85} [Km/h]
			V_{mean}	s.d.	V_{85}	V_{min}	V_{max}	V_{mean}	s.d.	V_{85}	V_{min}	V_{max}		
C_1	700	256	86.9	3.4	89.1	76.6	91.9	104.3	5.5	108.0	94.9	119.0	17.4	18.9
T_1	–	168	87.4	3.0	89.6	80.9	93.6	104.7	5.2	110.8	97.7	115.7	17.3	21.3
C_2	800	764	88.4	2.5	90.5	83.1	94.9	106.3	5.3	112.5	97.4	116.8	17.9	22.0
T_2	–	671	91.4	3.3	94.7	85.0	96.7	114.5	4.1	118.6	108.2	123.0	23.0	23.9
C_3	2000	293	91.5	3.6	95.1	84.4	100.3	114.7	5.4	119.6	105.0	125.4	23.1	24.5
T_3	–	417	91.7	3.7	95.4	84.5	99.6	112.6	5.9	119.2	100.4	123.5	20.9	23.8
C_4	500	134	90.7	4.6	94.8	83.2	101.0	110.8	5.5	116.9	102.9	120.4	20.1	22.1
T_4	–	80	90.2	4.2	94.3	82.1	99.3	109.4	6.1	115.0	99.4	121.8	19.3	20.6
C_5	300	339	90.2	4.3	94.7	81.6	98.6	109.5	6.1	115.5	98.1	120.0	19.3	20.8
T_5	–	362	92.0	3.7	95.5	85.7	100.4	114.0	4.7	119.0	103.1	120.3	22.0	23.5
C_6	1000	484	92.2	3.5	95.6	84.6	97.4	114.3	4.7	118.6	103.2	121.9	22.0	22.9
T_6	–	329	92.4	3.8	96.1	84.1	100.1	114.8	4.5	118.5	106.3	123.2	22.4	22.5
C_7	500	317	91.9	4.3	96.0	84.0	101.3	114.0	4.8	117.5	101.5	122.6	22.1	21.5
T_7	–	722	92.5	3.9	96.1	84.4	101.0	116.6	4.4	121.9	105.6	123.3	24.1	25.8
C_8	800	182	92.3	3.8	95.9	85.2	99.9	115.7	5.0	121.3	105.5	124.3	23.3	25.4
T_8	–	844	93.9	3.7	96.8	84.8	101.2	119.6	4.7	123.8	109.6	130.7	25.7	27.0
C_9	1000	602	93.4	3.8	96.9	85.3	99.2	120.8	3.7	124.4	113.2	128.4	27.3	27.5
T_9	–	392	93.6	3.2	96.0	88.3	101.2	120.6	4.0	124.2	113.4	130.1	27.0	28.2
C_{10}	700	620	92.4	4.0	96.0	81.9	101.7	119.1	4.1	122.7	109.0	126.6	26.6	26.8
T_{10}	–	267	92.8	3.6	95.7	82.5	100.5	119.2	4.5	123.9	108.6	128.9	26.4	28.2
C_{11}	1000	156	92.0	3.1	94.9	84.8	97.8	119.4	4.9	123.9	108.6	132.3	27.4	29.0

radius equal to 300 m) and exceeded 100 km/h (102.6 km/h and 101.1 km/h, respectively for C_6 and C_7); the maximum speeds (up to 120.0 km/h) were reached on tangents. The operating speeds ranged between 106.0 km/h and 124.9 km/h. The large difference between the maximum and the minimum speeds (28.0 km/h on average, ranging between 15.8 km/h and 39.2 km/h) provided evidence of greater speed variability.

As expected, for each road element, the mean speeds as well as the operating speeds in the scenario without the speed limits were greater than the mean speeds and the operating speeds in the scenario with the posted speed limits.

In the configuration with posted speed limits of 80 km/h, the mean and operating speed profiles vary very slightly, between 85 Km/

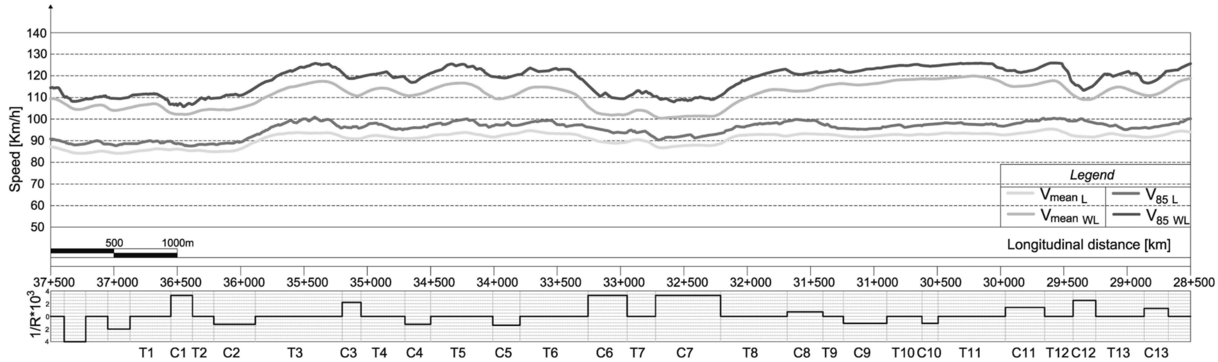

Fig. 5. Mean and operating speed profiles of drivers' sample in configurations with ($V_{mean\ L}$ and $V_{85\ L}$, respectively) and without ($V_{mean\ WL}$ and $V_{85\ WL}$, respectively) posted speed limits on the first motorway's segment.

h and 95 Km/h and between 90 Km/h and 100 Km/h, respectively; the same profiles are more variable in the configuration without speed limits and, as expected, with values approximately 20% higher than those recorded in the configuration with the posted speed limits. Indeed, the mean speed varied between 100 km/h and 120 km/h and the operating speed between 110 Km/h and 125 Km/h. Furthermore, the mean and operating speed profiles in the configuration with posted speed limits are closer to each other, confirming a smaller speed variability.

Overall, an upward translation of the speed profiles in the configuration without speed limits is observed. Finally, a paired *t*-test has been carried out on each element (tangent and curve) to verify the statistical significance of the difference between the drivers' speeds with and without the speed limits. The statistical tests have been performed for both the mean and the operating speeds. The t-tests demonstrated a significant effect of the presence of the posted speed limits on drivers' speed choices (p-value < 0.001).

5.3.6.2. Segment 2. Similar results were observed in the second tested segment of the motorway, both in the configuration with posted speed limits and in the configuration without the speed limits (Fig. 6 and Table 3).

In the configuration with posted speed limits, the mean speed ranged between 86.9 km/h and 93.9 km/h, while the operating speed ranged between 89.1 km/h and 96.9 km/h. The minimum speed was equal to 76.6 km/h and the maximum speed was equal to 101.7 km/h. Along segment 2, the mean speed was 91.4 km/h with the standard deviation ranging between 2.5 km/h and 4.6 km/h, confirming very low speed dispersion. The difference between the maximum and the minimum speeds was equal to 15.3 km/h on average (ranging between 11.7 km/h and 19.8 km/h).

In the configuration without posted speed limits, the higher variability in speeds was confirmed. The mean speeds ranged between 104.3 km/h and 120.8 km/h, while the operating speeds varied between 108.0 km/h and 124.4 km/h. The difference between the maximum and the minimum speeds was 19.4 km/h on average, ranging between 14.8 km/h and 24.1 km/h. Also in segment 2, the standard deviation was quite low, ranging between 3.7 km/h and 6.1 km/h.

The statistical tests developed for each element of segment 2 confirmed a significant effect of the presence of posted speed limits on drivers' speed, as revealed for both the mean and operating speeds.

5.4. Comparison between numerical analyses and driving simulator experiments

The operating speeds recorded on the experimental tests carried out in driving simulation at Roma Tre University and the operating

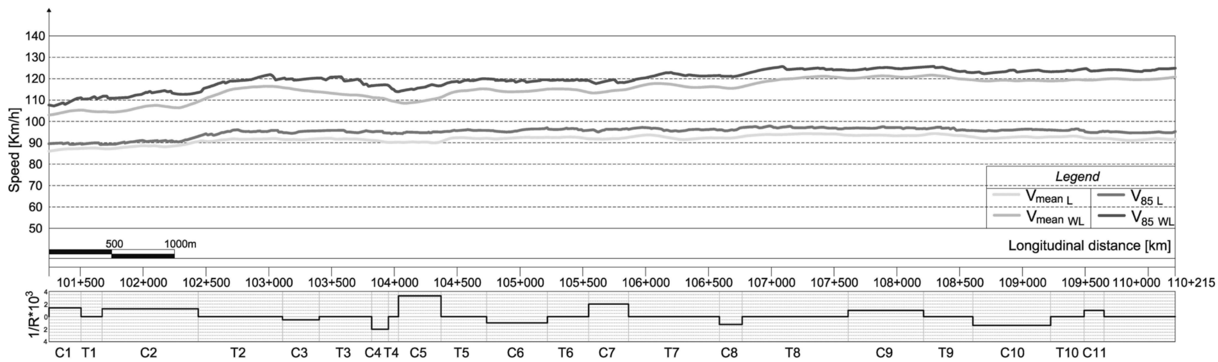

Fig. 6. Mean and operating speed profiles of drivers' sample in configurations with ($V_{mean\ L}$ and $V_{85\ L}$, respectively) and without ($V_{mean\ WL}$ and $V_{85\ WL}$, respectively) posted speed limits on the second motorway's segment.

speeds obtained by the predictive models developed by the University of Naples Federico II (Montella et al., 2014) have been compared. Specifically, the drivers' operating speeds in the configurations without posted speed limits, where the drivers were free to choose and adopt their desired speeds according to the geometric characteristics of the motorway's alignment and environment, as perceived during the driving simulation tests, were compared with the operating speeds obtained by the predictive models developed by the University of Naples Federico II based on an instrumented vehicle experiment previously developed on the A16 motorway. Such comparison allowed to extend the simulation results limited to the geometries of the two segments reconstructed in the virtual environment to all the geometries of the motorway under study. This integration of the results obtained from the experimental tests in simulation, descriptive of the drivers' behaviour, with those recorded in the field tests, has provided a considerable added value to the entire study and, consequently, to the proposal of the new speed limits to be adopted along the motorway.

Table 4 and Table 5 summarize the results of the comparison between the operating speeds recorded in each curve, respectively of the first and second motorway's segment reconstructed in the driving simulator study, as calculated from the simulation outputs (V_{85S} in the configuration without speed limits) and the equation of the predictive model (Eq. (5) for estimating the operating speeds (V_{85M}). The last column of the two tables shows the differences recorded between the two operating speeds on each curve of the segments. As can be seen, the differences in the operating speeds are quite limited, demonstrating the consistency of the results of the two experimental studies and the consequent possibility of using them reciprocally to validate the proposed methods and extend the simulation results related to the speed behaviour of drivers to the entire motorway. As can be seen from the results shown in the tables, the percentage differences between the operating speeds are always lower than 10% (only in one case equal to 10.5%), with an average value among the various curves of the two segments equal to 4.5% (4.2% for the curves of segment 1 and 4.8% for those of segment 2). The differences are also definitely low in absolute terms: an average of 5.3 km/h for all the curves of the two segments, ranging between 0 km/h and 11 km/h. Furthermore, it is important to note that the differences are very low regardless of curve radius, both for curves with a narrow radius and for those with greater radii, very similar values were recorded between the two operating speeds. For this reason, it is reasonably possible to consider that the results of the experiments in driving simulation on the two tested segments can also be valid for those motorway geometries that have not been reconstructed in the simulated environment. Thus, the experimental equation for the operating speeds proposed in the field study well interprets the drivers' behaviour along the entire motorway layout and can be used as a reference for the selection of the speed limits along the entire route.

5.5. Speed limit selection

Both the operating speed model and the speed profiles from the driving simulation experiments show that drivers' speed selection is inconsistent with the speed limit of 80 km/h. According to the model, the operating speed in the 294 curves of the study site ranges between 90 km/h and 132 km/h and has a mean value of 116 km/h. According to the driving simulator experiment, in the test sections including 24 curves, the operating speed ranges between 106 km/h and 124 km/h and has a mean value of 117 km/h. Overall, the average operating speed is almost 40 km/h higher than the speed limit, showing the need for a speed limit increase.

The combined analysis of the operating speed, the speed determined on the basis of the vehicle stability on curves and the speed consistent with the available stopping sight distance suggests theoretical speed limits ranging between 84 km/h and 135 km/h, with a mean value of 109 km/h and a standard deviation of 10 km/h. To provide a clear message to the road users and to foster homogeneous speed along the freeway, ensuring at the same time the mobility needs and safe driving, a constant speed limit equal to 100 km/h was selected in all the study site.

5.6. Safety impact assessment

The final selection of the speed limit has been carried out after a safety impact assessment (see section 4.4), considering both the

Table 4
Comparison between the operating speeds in curves recorded in simulation and obtained by the predictive model on the first segment.

Curve	R [m]	L [m]	V_{85S} [Km/h]	V_{85M} [Km/h]	ΔV_{85} [%] (V_{85M} - V_{85S})
C_1	300	171	106	105	−1.0
C_2	800	328	112	106	−5.7
C_3	450	148	119	120	0.8
C_4	800	203	118	129	8.5
C_5	700	214	120	129	7.0
C_6	300	309	111	115	3.5
C_7	300	514	109	109	0.0
C_8	1400	282	121	126	4.0
C_9	900	343	123	126	2.4
C_{10}	900	128	124	129	3.9
C_{11}	700	309	122	129	5.4
C_{12}	400	179	114	121	5.8
C_{13}	800	191	119	128	7.0

Abbreviations: V_{85S} = Operating speed recorded in simulation, V_{85M} = Operating speed obtained by the predictive model, DV_{85} = Differences recorded between the two operating speeds.

Table 5
Comparison between the operating speeds in curves recorded in simulation and obtained by the predictive model on the second segment.

Curve	R [m]	L [m]	V_{85S} [Km/h]	V_{85M} [Km/h]	ΔV_{85} [%] (V_{85M} - V_{85S})
C_1	700	256	108	99	−9.1
C_2	800	764	112	104	−7.7
C_3	2000	293	120	128	6.3
C_4	500	134	117	118	0.8
C_5	300	339	115	104	−10.6
C_6	1000	484	119	124	4.0
C_7	500	317	117	112	−4.5
C_8	800	182	121	123	1.6
C_9	1000	602	124	122	−1.6
C_{10}	700	620	123	119	−3.4
C_{11}	1000	156	124	120	−3.3

Abbreviations: V_{85S} = Operating speed recorded in simulation, V_{85M} = Operating speed obtained by the predictive model, DV_{85} = Differences recorded between the two operating speeds.

expected change in the speed distribution as well as the effects of the safety countermeasures to be implemented in association with the speed limit change, which is the activation of four sections with P2P speed control and targeted measures at 45 curves. Both the safety impact assessment as well as the report describing the procedure and the analytical results of the numerical analyses and the driving simulator experiments have been discussed with the Italian Ministry of Infrastructures and Transports. The Ministry approved the new speed limit as well as the budget to implement the requested safety countermeasures.

Currently, a P2P speed control system is active on two segments of the motorway, which represent 6% of the study site. To improve the effectiveness of the system and to give the road users the feeling of almost continuous speed control, 4 new sections of P2P will be activated, thus realizing a total extension of the system of 76.56 km, which represents 38% of the study site. Moreover, specific safety countermeasures will be implemented at 45 curves with an inferred design speed lower than the new speed limit. The countermeasures consist of: (1) HFSTs, (2) correction of superelevation deficiencies, (3) installation of curve warning signs, chevrons, and sequential flashing beacons, and (4) shoulder rumble strips.

The safety impact assessment has been carried out separately in the sections where the P2P system is already active (P2P sections) and in the other sections. In the P2P sections, the effect of the speed limit change has been estimated using Equation (4). Currently, the average speed is 80 km/h. After the installation of the new credible speed limit (100 km/h), the average speed has been estimated equal to 90% of the speed limit (i.e., 90 km/h) based on the results of the speed study carried out before and after the installation of the P2P system on the motorway A56 (Montella et al., 2015c). In the P2P sections, safety countermeasures (HFSTs, CMF = 0.43; installation of curve warning signs, chevrons, and sequential flashing beacons, CMF = 0.52; shoulder rumble strips, CMF = 0.75) will be implemented at 5 curves. The CMF of HFSTs has been estimated based on the results of the study carried out in the US by Lyon et al. (2020). The CMF of the installation of curve warning signs, chevrons, and sequential flashing beacons has been estimated based on the results of the analysis carried out in the study site by Montella (2009). The CMF of the shoulder rumble strips has been estimated based on the HSM (AASHTO, 2010), considering that in the study site, SVRORs account for 32% of the total crashes. In the other sections, the average speed is currently about 90 km/h. After the installation of the new credible speed limit, the average speed has been estimated equal to the speed limit (i.e., 100 km/h). The safety effect of the speed increase, without the activation of the P2P system, has been estimated by equation (4). Then, the safety effect of the activation of the 4 new sections of P2P speed control has been estimated considering a spill-over safety effect in all the study site, assuming a CMF equal to 0.69 based on the results of the study carried out by Montella et al. (2012) on the motorway A1. In the other sections, safety countermeasures (HFSTs, CMF = 0.43; correction of super-elevation deficiencies, CMF = 0.69; installation of curve warning signs, chevrons, and sequential flashing beacons, CMF = 0.52; shoulder rumble strips, CMF = 0.75) will be implemented at 40 curves. The CMF of the correction of the superelevation deficiency, which will be implemented in 5 curves, has been estimated based on the results of the study carried out in Italy by Cafiso, Calvi et al. (2021), Cafiso, Montella et al. (2021). Using the procedures described in section 4.4.3, and assuming that there will be not changes in traffic volumes and that the expected annual number of crashes without safety countermeasures and speed limit change would be equal to the average number in the period 2017–2021, it has been estimated that the increase in the speed limit is associated with an increase in total crashes equal to 23%. However, the implementation of the safety countermeasures allows a crash reduction of 37%. Overall, the increase in the speed limit combined with the implementation of the proposed safety countermeasures allows a crash reduction of 23% (Table 6). The average cost per crash has been estimated equal to 60,583 €, based on estimates of the cost per casualty (fatality, serious injury, and slight injury) published by European Commission (2019a, 2019b), the ratio between cost per collision and cost per casualty, and the cost of property damage only crashes of the motorways in Great Britain (Department for Transport, 2022), and the distribution of the crash severity levels of Italian motorways. Estimated annual benefit of the safety countermeasures is equal to 4,543,465 €. Total cost of the safety countermeasures has been estimated equal to 10,159,960 €, corresponding to annual cost of 974,193 €. As a result, the benefit/cost ratio of the safety countermeasures is equal to 4.66.

6. Discussion and conclusions

Setting speed limits that are safe, credible, and compliant with driver expectations remains a key challenge. The linkage between

Table 6
Benefit/cost analysis of the proposed safety countermeasures.

Expected total annual crashes with speed limit of 80 km/h	163.00
Expected total annual crashes with speed limit of 100 km/h	201.29
Expected total annual crashes with speed limit of 100 km/h and safety countermeasures	126.29
Crash cost (all severity levels)	60,583 €
Annual benefit of the safety countermeasures	4,543,465 €
Total cost of the safety countermeasures	10,159,960 €
Annual cost of the safety countermeasures	974,193 €
B/C ratio of the safety countermeasures	4.66

the Safe System approach, road network management, and speed management has generated a need for highway agency managers to be engaged with and cognisant of strategies associated with asset management and road safety principles. This research paved the way for a new methodology for setting credible speed limits based on numerical analyses and driving simulation experiments that can be used to make informed decisions about establishing posted speed limits on motorways. The methodology defines the speed limit as the result of a trade-off between the need for safety and mobility. A weighted average of the inferred design speed, i.e. the minimum speed between the speed determined on the basis of the vehicle stability on curves and the speed consistent with the available stopping sight distance, and the operating speed is assumed as the basis to satisfy these conflicting demands.

The research showed good consistency between the operating speed predicted by a model calibrated based on real-world experiments with instrumented vehicles and the operating speed observed in driving simulation, thus confirming the validity of the driving simulator experiments. The driving simulator experiments have allowed us to analyse continuous speed profiles, which was crucial for the overall objective of the study. Indeed, speed data typically collected by motorway operators are usually limited to spot measurements with no chance to process speed data along the entire motorway. Moreover, speed predictive models, where available and applicable to the specific motorway context and environment due to concerns related to calibration, validation, and generalization of the models themselves, typically provide average or operating speeds along the single geometric element (curve and tangent). Therefore, the driving simulation allowed collecting continuous speed data and overcome such conditions where only spot and local speed data or predictive speed models not validated for the specific road context and environment are available. In this study, by comparing the driving simulator speed results with the speeds calculated using the predictive speed models, calibrated, and validated on the same A16 motorway in previous research, a further validation of both speed models and driving simulator results is obtained, as demonstrated in results summarized in Tables 4 and 5.

Since posting credible speed limits often requires speed limits higher than the inferred design speed, the implementation of targeted safety countermeasures and a safety impact assessment are key elements to provide sound decisions.

The methodology was tested in the section Baiano–Candela of the A16 Naples–Canosa motorway, in southern Italy, where a posted speed limit of 80 km/h is installed in both travel directions and a new credible speed limit of 100 km/h is proposed, based on the results of the experiments developed within the methodology. The selection of the new credible speed limit has been carried out after a safety impact assessment, considering both the expected change in the speed distribution as well as the effects of the safety countermeasures to be implemented in association with the speed limit change. The proposed safety countermeasures are the activation of four sections with point-to-point speed control and targeted measures at 45 curves, consisting of: (1) high friction surface treatments, (2) correction of superelevation deficiencies, (3) installation of curve warning signs, chevrons, and sequential flashing beacons, and (4) shoulder rumble strips. The safety impact assessment shows that the increase in the speed limit combined with the implementation of the proposed safety countermeasures allows a crash reduction of 23%. The estimated benefit/cost ratio of the safety countermeasures is 4.66. Finally, it is worthwhile to mention that the study results and a specific monitoring plan related to crashes, traffic volumes, and speeds have been discussed with the Italian Ministry of Infrastructures and Transports, which approved the new speed limit as well as the budget to implement the requested safety countermeasures and the monitoring plan.

It is further noteworthy to observe that in this study the usual caveats of laboratory research must apply, in particular those relating to driver motivation and the level of perceived risk in a simulated environment when considering the results of the driving simulator study. Furthermore, the participants in the simulator experiments were recruited only from academia and this may potentially cause some bias in the results. Despite these limitations, the drivers' behaviour was generally consistent with previous real-world studies.

CRediT authorship contribution statement

Alfonso Montella: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Alessandro Calvi:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. **Fabrizio D'Amico:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. **Chiara Ferrante:** Formal analysis, Investigation, Software, Validation, Writing – original draft. **Francesco Galante:** Formal analysis, Investigation, Software, Validation. **Filomena Mauriello:** Software, Validation. **Maria Rella Riccardi:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Antonella Scarano:** Formal analysis, Investigation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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