Traffic & Transportation

The Impacts of Sectional Speed Control and Dynamic Speed Management on Traffic Safety on Motorways – The Evidence Across the EU and the Impact Estimation for Slovenia

Marina ZANNE[1], Adam TÖRÖK[2]

Original Scientific Paper
Submitted: 17 June 2025
Accepted: 15 Dec 2025
Published: 28 Apr 2026

[1] marina.zanne@fpp.uni-lj.si, Faculty of Maritime Studies and Transport, University of Ljubljana, Portorož, Slovenia
[2] torok.adam@kjk.bme.hu, Faculty of Transportation Engineering and Vehicle Engineering, Budapest University of Technology and Economics, Budapest, Hungary

Publisher:
Faculty of Transport and Traffic Sciences, University of Zagreb

ABSTRACT
Road safety remains a pressing issue worldwide. In Europe, many countries are following the "Vision Zero" strategy, a concept developed in Sweden in the early 1990s, based on the conviction that road deaths can be systematically prevented. Speed is still one of the main causes of traffic accidents. Studies show that the risk of a fatal accident doubles with an increase in speed of just 15 km/h, which has led to numerous measures to reduce speed in various road categories. This article examines the effects of sectional speed control and dynamic speed management on road safety on motorways. Sectional speed control calculates the average speed of a vehicle over a given distance, while dynamic speed management adapts speed limits to traffic and environmental conditions in real time. Although these methods have been implemented successfully in several countries, Slovenia plans to introduce them in the second half of 2025. Based on a review of the relevant literature and existing case studies, this paper assesses the expected benefits for traffic safety on Slovenian motorways. Slovenia's unique context, characterised by its transit location and significant daily interregional migration, results in strong and heterogeneous traffic flows on its motorways and deteriorated traffic safety on these roads.

KEYWORDS
traffic safety; sectional speed control; dynamic speed management.

1. INTRODUCTION

One of the basic qualities describing the performance of a transport system is (road) traffic safety. Traffic safety is commonly measured in terms of the number of accidents and the severity of their consequences. Road traffic injuries are estimated to be a leading cause of death for children and young adults, while they are the eighth leading cause of death in general [1]. Apart from the human suffering caused by traffic injuries, the socio-economic costs of traffic accidents are estimated at around 3% of GDP in most countries [2]. It is thus not surprising that a lot of effort is put into the improvement of traffic safety records.

Many European Union (EU) countries follow the "Vision Zero" strategy, a concept developed in Sweden in the early 1990s. Vision Zero is based on the idea that road deaths can be systematically prevented. The EU is a leader in reducing road traffic deaths and serious injuries; in fact, between 2010 and 2020, the number of road traffic fatalities dropped by 36% [3], while between 2001 and 2020, the target of a 75% reduction in road traffic fatalities was almost reached [4, 5].

Countries confront the issue of road traffic safety in different ways, usually depending on the transport demand, general development of the national transport system and obtainable financial resources [6]. The availability of adequate road infrastructure deeply influences traffic safety records, with motorways being considered the safest roads, although not equally safe around the EU [7, 8]. However, re-engineering the road network to improve safety is a long-term process involving significant human and financial resources [9]. On the other hand, intelligent transport system (ITS) projects can yield high impacts in the relatively short term. ITS includes the application of electronic, computer and communication technology to vehicles and roadways, not only to increase safety, but also to reduce congestion and enhance travel experience, as well as to increase energy efficiency and minimise environmental impact [10].

Speed is the most critical risk factor in road crashes [11, 12]; in around 30% of fatal accidents in the EU, speed is an essential contributory factor [13]. The relation of inverse proportionality between speed and traffic safety holds for all speeds and all roads [14], but the rate of increase in accident risk varies with initial speed level and road type; nevertheless, in general, it holds that every 1% of increase in mean speed produces a 4% increase in the fatal crash risk and a 3% increase in the serious crash risk [2]. On the other hand, congestion can lead to inadequate distance and an increased number of rear-end collisions, resulting in decreased traffic safety, but even more in decreased traffic efficiency. These findings led to the implementation of various measures to reduce speed and increase traffic flow, among others, with sectional speed control and dynamic speed management, which are the focus of this paper. This study investigates how the implementation of sectional speed control and dynamic traffic management impacts the external costs of traffic safety on Slovenian motorways.

First, the review of the impact of the installation of sectional speed control and dynamic speed management in various EU countries is done, and then the assessment of the potential of these two systems in Slovenia is provided.

The paper is structured in seven parts. After the introductory section, the methodology of the paper is described. The IT systems impacting traffic safety and congestion are described in section three. The core sections provide the situation on traffic flows and traffic safety on Slovenian motorways, reveal plans for the sectional speed control and dynamic speed management implementation in Slovenia, and finally, the expected improvement analysis after the implementation. The last section is dedicated to discussion and conclusions.

2. METHODOLOGY

First, we did the literature review to gain insights into the impacts of the two safety systems, namely the sectional speed control and dynamic speed management in EU countries. The core of the paper is the estimation of the potential benefits of the introduction of such systems on Slovenian motorways.

The data on road accidents for the period 2014 to 2023 were retrieved from the Slovenian police website [15]. For each road accident, the police compile a total of 36 variables to describe the accident (e.g. accident classification, date and time of the accident, detailed description of the accident location, cause of the accident, type of accident, weather conditions and condition of the carriageway and type of carriageway and condition of traffic) and people involved in the accident (role in the accident, gender, age, place of residence, injury to the party involved, type of party involved, previous convictions for drivers and drunkenness). The data were processed, given unique codes for accidents and road users, and collated in a single database. Data on traffic accidents were used to determine the most dangerous sections of Slovenian motorways and to deeply examine sections where the two systems will be installed.

Data on traffic volumes were obtained from Odprti podatki Slovenije [16, 17], where they were posted by the Ministry of Infrastructure, Directorate of the Republic of Slovenia for Infrastructure. These data were analysed and correlated with the data on traffic safety on Slovenian motorways.

All analyses were carried out using IBM SPSS 28 software.

The external costs of transport due to road accidents include human costs, lost human capital, medical costs and administrative costs resulting from medical treatment, lost work capacity, death and other consequences of accidents (18).

External costs of traffic accidents are estimated for three types of accident consequences, namely minor injuries, severe injuries and fatal injuries, for Slovenian motorways as a whole and for sections of Slovenian motorways where average speed control and dynamic speed management will be installed.

The cost estimation for different types of injury accidents is provided in *Table 1*. The values were retrieved from the European Commission's manual and are given for 2016. The values were adjusted according to the inflation rates for the period 2014 to 2023 from the *inflation.eu* website and tested for the year 2021 (as exact external cost values for 2021 were published in [18]).

Table 1 – External costs of road accidents in Slovenia for 2016 as indicated in the European Commission's manual; Source: [18]

	Minor injury [in EUR]	**Serious injury [in EUR]**	**Fatal injury [in EUR]**
Human costs	25,941	337,228	2,127,862
Lost human capital	1,196	19,549	293,677
Medical costs	586	6,811	2,212
Administrative costs	459	1,067	1,551
Total costs	28,182	364,655	2,425,302

Furthermore, we estimated the potential traffic safety improvement in relation to speed change. Nilsson has developed six power models to predict the number of serious and fatal as well as all injury accidents and adequately injured people based on speed changes [19], however, we opted for an exponential model developed by Elvik [20] that determined the coefficients for various types of accidents and their consequences directly. While Nilsson's model requires combining two separate estimations, the one on fatalities and the other on serious injuries, to approximate the number of slightly injured individuals, Elvik's exponential model allows for a direct and independent estimation of each injury category. Although road characteristics can vary across regions and seasons, leading to slight variations in the coefficients derived by Elvik, his exponential model is generally regarded as an enhancement over Nilsson's power model. The key improvement lies in its ability to reflect the non-linear sensitivity of speed more accurately in relation to traffic fatalities and injuries; for example, a 10% change in speed does not produce uniform effects across different speed levels. Nilsson's model, with its fixed exponents, tends to overestimate the impact at lower speeds and underestimate it at higher speeds, whereas Elvik's model adjusts dynamically based on the initial speed, offering a more realistic representation of risk.

Elvik's exponential model describing changes in traffic safety in relation to changes in speed is defined by the following equation:

$$A_2 = A_1 e^{\beta(v_2 - v_1)} \quad (1)$$

where A_2 denotes the number of crashes or injured people after the speed change, A_1 denotes the number of crashes or injured people before the speed change, v_1 and v_2 are the average speeds before and after. The coefficient β for different injuries is indicated in *Table 2*.

Table 2 – Coefficient β for different injuries in road accidents for rural roads and motorways with speed from 80 to 130 km/h; Source: [20]

	Best estimate [%]	**95% confidence interval [%]**
Fatal injury	4.6	4.0-5.2
Serious injury	3.5	0.5-5.5
Minor injury	1.4	0.5-2.3

Plans for the implementation of the sectional speed measurement and dynamic speed management system have been obtained from DARS through the semi-structured interview. DARS is the company that is building, managing, and maintaining the motorways and expressways of Slovenia.

3. SPEED CONTROL AND SPEED MANAGEMENT

Speeding is a major problem on European roads; among the countries monitoring speed on motorways, between 23% and 59% of observed vehicle speeds were higher than the speed limit [21]. Traffic monitoring cameras are essential tools for speed limit enforcement. Spot speed enforcement using fixed speed cameras was introduced in Norway in 1988 [22]. Today, Italy is the EU member state with the most fixed speed cameras installed, more than 11,000 [23]. The effects of speed cameras are visible only in their immediate proximity; they varied between 5% to 69% for the number of accidents, 12% to 65% for the number of injured people, and 17% to 71% for road deaths [24, 25]. However, conventional fixed speed cameras bear certain problems, namely braking just before the camera and subsequent acceleration [22], therefore more advanced systems have been developed.

3.1 Sectional speed control

Sectional speed control or average speed control is an upgrade of fixed speed cameras. This system measures the time it takes a vehicle to travel over a given stretch of road, usually 2 to 5 kilometres, to calculate the average speed. Section speed control relies on two technologies, namely Automatic Number Plate Recognition (ANPR) and Global Positioning System (GPS). All vehicles are subject to speed control, and vehicles that pass the stretch too quickly are fined. The purpose of installing sectional speed control systems is twofold: to maintain a high effect on the entire stretch of road between two camera boxes, and to reduce braking and acceleration at the actual camera box [22].

Section speed controls are a well-known way of regulating traffic across Europe. In fact, studies from various European countries confirm that section speed cameras contribute notably to improving road safety [26]. The before-and-after study by Høye [27] indicated a considerable reduction in serious and fatal injuries (49%) and a minor change in all injury accidents (12%) in Norway on all road sections equipped with average speed control. A similar study by Vadeby & Howard [28] showed even better results: the implementation of section speed cameras reduced the total number of accidents by around 30% and the number of fatal and serious injury accidents by 56%. It has also been found that drivers drive more steadily during monitored sections, without frequent braking and acceleration, which further contributes to safety.

In the Netherlands, the implementation of sectional speed measurement dates to the late 1990s. On one of the motorway sections in the Netherlands, only 0.5% of vehicles were detected speeding after section speed control was put in use in 2002, resulting in the reduction of the total number of collisions by 47% [29].

A section speed control system called Tutor was introduced on the Italian motorway network in December 2005 [20]. The Tutor system has been installed along routes with above-average mortality rates; currently, it is positioned on more than 2,500 km of Italian motorways, where a significant reduction in the average speed (- 15%) and peak speed (-25%) has been recorded. This resulted in a decrease in the number of accidents and in the consequences for people; in the first year, the mortality rate fell by 56% on the routes along which Tutor had been installed, and by now, a reduction of around 81.5% was recorded [30]. Borsati et al. [31] determined that a 10% increase in the Tutor system coverage reduced total accidents by around 4%.

On one of the tunnels in Austria, the installation of section control reduced all injury accidents by a third and almost halved the number of deaths and serious injuries compared to the three years prior [29]. On the other hand, Sándor and Monostori [32] found that a significant part of the drivers on Hungarian motorways do not obey the 130 km/h speed limit; the share ranges from 38 to 50% depending on the sections, although a large part of the road traffic accidents in Hungary arise from speeding. Sándor [33] estimated that the implementation of sectional speed control would yield social cost savings from EUR 4 million to EUR 7.937 million, considering exchange rates of May 2025.

Germany introduced sectional speed control later than several other EU countries, due to concerns about data protection. The first such system was implemented in 2014. During the test period, a significant local reduction in the mean speeds by approximately 2 km/h to 5 km/h was recorded for both lanes over the entire road section under observation. After the test period, soon into the beginning of the real exploration period, the speed reductions were even higher, ranging from approximately 2 km/h to 10 km/h, relative to the values of the pre-period. In addition, record on time headway in time to collision improved [34].

In Luxembourg, they installed their first fixed cameras only in 2016 and tested sectional speed control on a 1.5-kilometre stretch of road in 2021. In the first three months, around 1,500 drivers exceeded the average speed [35].

Furthermore, Ragnøy [22] demonstrated that connected sequential speed cameras yield significantly better outcomes than non-connected ones. The influence on vehicle speed, accident frequency and accident-related costs is approximately 2.5 times greater when using a skeletal (connected) speed camera system compared to unlinked cameras.

3.2 Dynamic speed management

Dynamic speed management, also known as dynamic speed limits or variable speed limits, is a system of speed limits that change according to real-time traffic, road or weather conditions. Such a system keeps traffic moving by controlling the flow of vehicles in relation to changing conditions and operational requirements. It relies on traffic flow sensors or speed cameras, weather stations, and variable speed signs through which road users are informed about speed limit changes.

Speed limits can be adapted remotely, either automatically by an algorithm or manually by an operator [36]. The algorithms can be safety-oriented, efficiency-oriented or pollution-oriented [37]. Dynamic speed management systems are introduced to achieve homogeneity of driving speed, which is often considered to improve traffic flow (throughput) and traffic safety [38], as there are usually fewer rear-end collisions, near-miss crashes and intensive braking manoeuvres [39]. The study by Lee et al. [40] indicated that variable speed limits could reduce crash potential by 5 to 17% by temporarily decreasing speed limits. In a before-and-after study, De Pauw et al. [41] showed a 18% decrease in the number of injury crashes after the introduction of the system.

In addition, the implementation of dynamic speed management helps increase the credibility and acceptance of the speed limit system, as the general speed limits do not correspond to the appropriate speed on all roads at all times due to constantly changing conditions [42]. The limits that dynamic speed management systems indicate are not the advisory speeds, but the legal maximum speeds [39].

With dynamic speed management, individual lanes can have different speeds (*Figure 1*). In the Netherlands, a camera is installed at each gantry, and drivers who exceed the speed limit are fined because their actions disrupt the ideal traffic flow, which can lead to danger [43].

Figure 1 – Dynamic lane control in the Netherlands; Source: [43]

4. TRAFFIC FLOWS AND TRAFFIC SAFETY ON SLOVENIAN MOTORWAYS

Slovenia is a small country at the crossing of important transport corridors, which influences the amount of traffic on Slovenian roads, especially motorways. In the 10-year period from 2014 to 2023, the traffic volume on Slovenian motorways recorded a compound annual growth rate (CAGR) of 3.1% to reach more than 7.5 billion kilometres (a total increase of 31% in the ten-year period). In 2023, 48% of all kilometres travelled in Slovenia were on motorways, compared to 45% in 2014. During the period under review, the share of heavy goods vehicles on motorways has increased only slightly (1.5%), but the volume of traffic by these vehicles has increased by 40%. Trucks now cover almost a quarter of all kilometres on Slovenian motorways, or nearly 1.85 billion kilometres. The dynamics of traffic volumes on Slovenian motorways are presented in *Figure 2*.

The research on traffic flows on Slovenian motorways that was conducted in March and April 2014 yielded the following results [44]:

— Higher density of vehicles on the fast lane than on the regular lane: in 15.0% of measurements on motorways in total, and 26.5% on A1 motorways.
— Inadequate time heading: in 24.3% of cases, when there is more traffic on the fast lane than on the regular lane, the time heading is less than 2 seconds.
— High difference between the average speed on fast and regular lanes: 26 km/h (25 km/h on A1) when traffic density is higher on the fast lane than on the regular lane.

Annual average daily traffic (AADT) on Slovenian motorways reached almost 38 thousand vehicles in 2023, up from 29.5 thousand in 2014 (CAGR = 2.8%). With increased traffic volumes and a relatively stable traffic structure on limited transport infrastructure (the length of motorways increased by barely 2%, while the traffic volume increased by 31% in the ten-year period) (*Figure 2*), traffic flow patterns are showing increasingly concerning trends. These include phantom jams, often triggered by drivers maintaining insufficient safety distances, braking too late when approaching slower vehicles, and frequent lane changes.

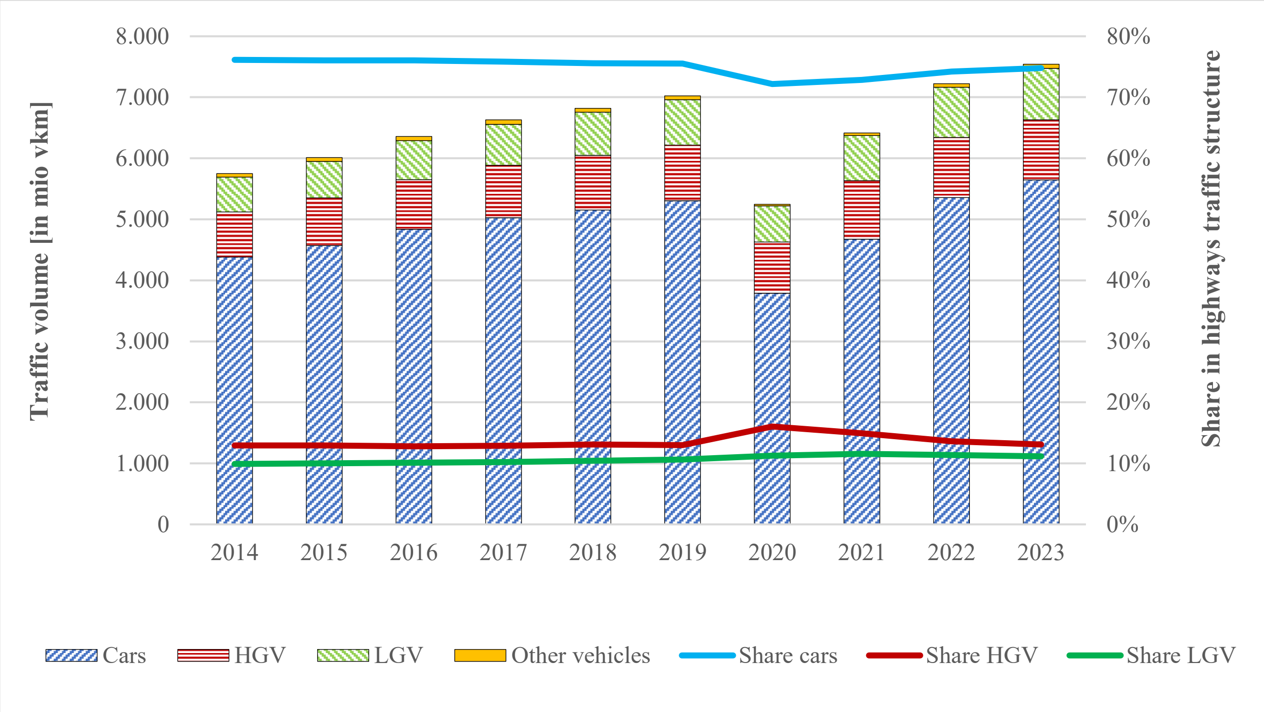

Figure 2 – Traffic volume on Slovenian motorways; Source: authors based on [17]

Therefore, the results from *Table 3* are not surprising; traffic volume is moderately correlated with all accident types, but the relationship is strongest with material damage accidents, as more traffic volume on limited infrastructure results in lower speeds of vehicles but more rear-end collisions due to inadequate safety distance (CAGR = 5.0%). Almost 60% of rear-end collisions on Slovenian motorways occur during heavy traffic.

Table 3 – Correlation between traffic volume and accidents' occurrence on Slovenian motorways in the period from 2014 to 2023 (n=10)

	Accidents	Injury acc.	Material damage	Traffic volume
Accidents	1	.822**	.977**	.708*
Injury acc.	.822**	1	.680*	0.522
Material damage	.977**	.680*	1	.714*
Traffic volume	.708*	0.522	.714*	1

*** Correlation is significant at the 0.01 level (2-tailed)*
** Correlation is significant at the 0.05level (2-tailed)*

On average, 8% of all road deaths in the EU occur on motorways (ETSC, 2019); in Slovenia, an average of 15.4% of traffic deaths happened on the motorways in the period from 2014 to 2023. The largest share was in 2022 with 24.4%, and the lowest was in the COVID year 2020 (6.8%), as can be seen from *Figure 3*.

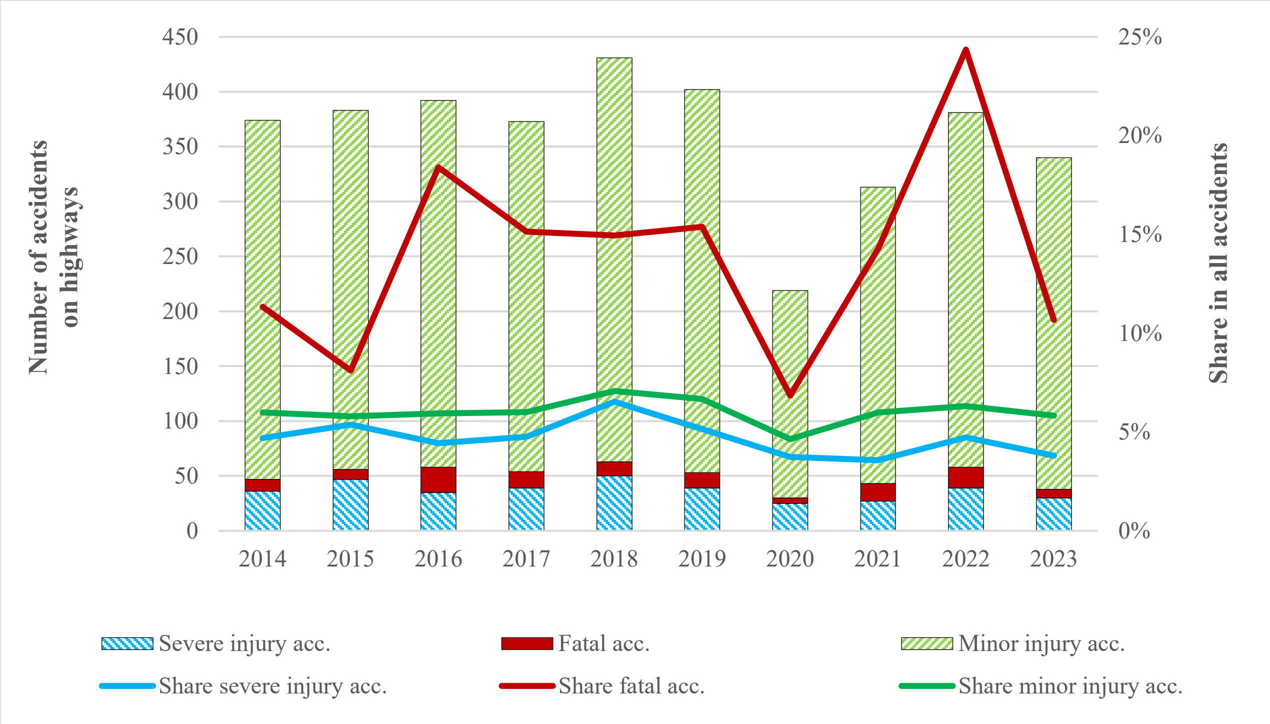

Figure 3 – Traffic safety on Slovenian motorways; Source: authors based on [15]

A total of 156 people died, and 465 remained seriously injured in accidents on Slovenian motorways during the ten-year period from 2014 to 2023, mainly because of speeding. In fact, 52.3% of serious injury accidents and 41.4% of fatal accidents happened due to excessive speed. Although there is a slight decline observable (but without a constant trend), speeding remains the key contributing factor to the accidents on Slovenian motorways in general. The average share for accidents caused by speeding was 27.1% for the observed period (2014: 32.6%, 2023: 25.6%).

The external costs of road accidents on Slovenian motorways in the period under review were EUR 731 million, which is around 9.3% of all external costs attributable to injury traffic accidents in Slovenia (*Table 4*) or around 0.15% of Slovenian GDP. The consequences of speeding on motorways are estimated at EUR 315.2 million, and the consequences of inadequate distance (clearance) are at EUR 60.4 million.

Table 4 – External costs of road accidents on Slovenian motorways [in EUR];
Source: authors based on [15, 18, 24]

Year	All roads	Share of GDP [%]	Motorways (MW)	Speeding on MW	Inadequate distance on MW
2014	772.631.735	2,1%	72.949.088	18.838.912	5.603.262
2015	850.644.620	2,2%	67.129.319	37.108.241	3.744.248
2016	843.112.497	2,1%	88.056.176	39.067.292	5.317.843
2017	777.252.209	1,8%	71.036.112	27.347.678	6.687.093
2018	739.193.875	1,6%	74.214.618	35.577.867	6.185.719
2019	775.268.765	1,6%	72.942.398	44.896.350	6.020.538
2020	617.143.060	1,3%	33.883.674	10.538.902	2.746.531
2021	777.597.718	1,5%	70.820.842	33.297.485	4.698.020
2022	823.025.472	1,4%	107.983.582	33.230.950	12.280.702
2023	856.107.457	1,3%	72.431.630	35.344.063	7.075.316
	7.831.977.408	**1,7%**	**731.447.440**	**315.247.741**	**60.359.273**

5. THE SPEED CONTROL AND SPEED MANAGEMENT PLANS FOR SLOVENIAN MOTORWAYS

When selecting road sections for section speed control, DARS and the Police considered several key factors: the frequency and severity of traffic accidents, the characteristics of the road infrastructure, levels of traffic congestion, and data from existing speed monitoring systems embedded in the infrastructure (interview).

Initially, the idea was to install section radars at nine locations at a total estimated cost of EUR 1.8 million, excluding VAT. Ultimately, they selected four locations: on the Štajerska motorway from Blagovica to Vransko (Trojane tunnels) heading toward Maribor, on the Gorenjska motorway between Ljubljana Brod and Vodice (2 sections) in the direction of Kranj, on the Primorska motorway between Logatec and Vrhnika heading toward Ljubljana, and on the Dolenjska motorway near Grosuplje to Ivančna Gorica (Višnja Gora hill) in the direction of Novo mesto (*Figure 4*). The maximum allowable bid amount is EUR 835,000, excluding VAT (interview). Two of these sections were identified as prone to speeding accidents, also in our analysis.

Figure 4 – Sectional speed control on Slovenian motorways; Source: DARS

On certain parts of Slovenian motorways, AADT, mainly on the entrances to Ljubljana, reaches more than 60 thousand vehicles per day. On the Ljubljana ring, even more than 80 thousand, according to available data, which results in heavy congestion and significantly decreased speed in peak hours, as can be seen in *Figure 5*.

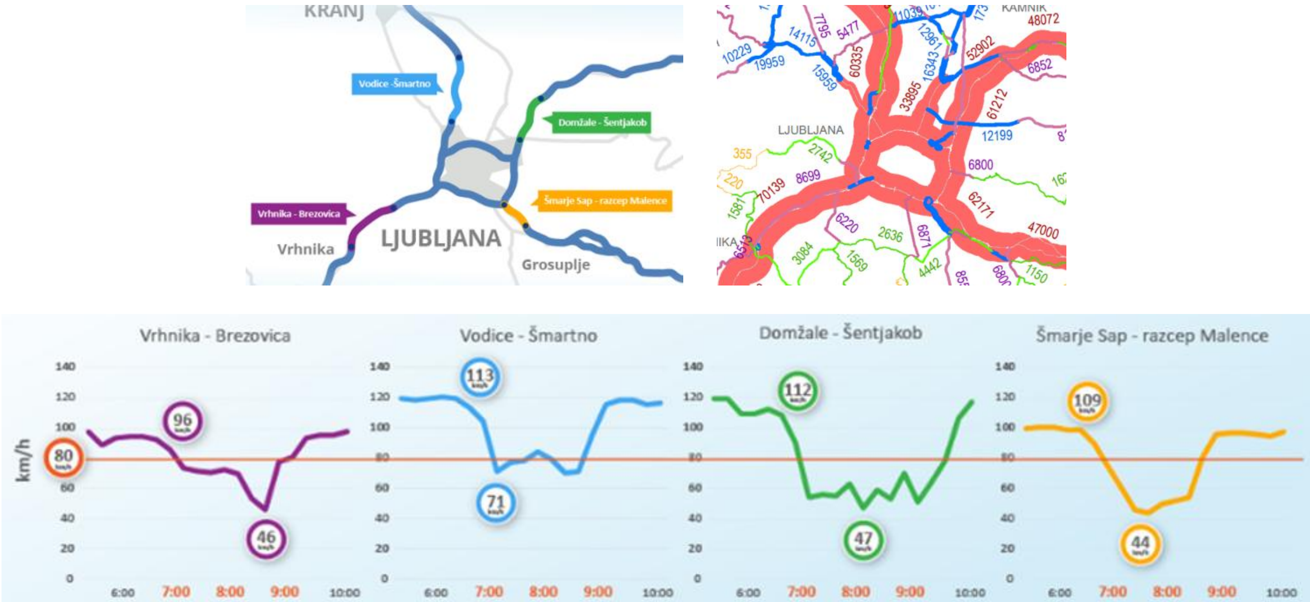

Figure 5 – Traffic characteristics on access roads to Ljubljana ring; Source: DARS

Therefore, the preparations to install a dynamic speed management system are underway. The driving speed will be adjusted according to the flow of vehicles around 20 kilometres before a point of concentrated traffic on the Ljubljana ring. The Ljubljana ring with the access roads is the key transport node in Slovenia, having an AADT of around 80,000 vehicles with 11–13% of heavy goods vehicles. In the event of heavy traffic on the ring road around Ljubljana, the speed limit on the motorway will be automatically lowered, and the change will be displayed on the portals. For this purpose, new panels will be installed at 53 locations, and existing ones will be upgraded. In addition, 117 microwave traffic counting detectors, seven video surveillance cameras, and 65 Bluetooth and Wi-Fi detectors will be installed (interview).

6. THE ANALYSIS OF TRAFFIC SAFETY ON SELECTED SEGMENTS OF SLOVENIAN MOTORWAYS

In terms of external costs of traffic accidents, the two most dangerous motorway sections are the sections from Logatec to Unec and from Unec to Postojna in the direction towards Koper, while speeding causes most external costs on the section Senožeče–Razdrto. None of these sections will have the average speed control implemented in 2025.

Nevertheless, on the six sections on which the average speed control will be implemented, around 43% of the external costs of accidents can be attributed to speeding. Recorded speeds of 105 km/h or 137 km/h are classified as speeding violations on the sections of Slovenian motorways with speed limits of 100 km/h or 130 km/h, respectively. Between 2014 and 2023, three people lost their lives, 15 were seriously injured, and 147 sustained minor injuries due to 384 speeding accidents on these road segments (*Table 5*). When adjusted for inflation, the estimated external costs of these accidents result in a total of EUR 18 million (*Table 6*).

Table 5 – Number of injured people on the motorway sections where the average speed control will be installed; Source: authors based on [15]

Section		Injured people in traffic accidents			Injured people due to speeding		
		Minor i.	Serious i.	Fatal i.	Minor i.	Serious i.	Fatal i.
22	Grosuplje-Ivančna G.*	98	6	2	65	6	2
653	Logatec-Vrhnika	69	11	2	34	6	1
667	Blagovica-Trojane*	39	1	0	12	0	0
643	Trojane-Vransko*	29	2	1	6	1	0
611	LJ Brod-Lj Šmartno	19	1	2	9	0	0
610	Lj Šmartno-Vodice	48	3	2	21	2	0
Total		302	24	9	147	15	3

Table 6 – External costs of all injuries and injuries due to speeding on the motorway sections where the average speed control will be installed [in EUR]; Source: authors based on [15, 18, 45]

Section		External costs due to road accidents [in EUR]				External costs due to speeding [in EUR]			
		Minor i.	Serious i.	Fatal i.	Total	Minor i.	Serious i.	Fatal i.	Total
22	Grosuplje-Ivančna G.*	2.933.559	2.323.969	5.152.200	10.409.727	1.945.728	2.323.969	5.152.200	9.421.896
653	Logatec-Vrhnika	2.065.465	4.260.610	5.152.200	11.478.274	1.017.765	2.323.969	2.576.100	5.917.834
667	Blagovica-Trojane*	1.167.437	387.328	-	1.554.765	359.211	-	-	359.211
643	Trojane-Vransko*	868.094	774.656	2.576.100	4.218.850	179.606	387.328	-	566.934
611	LJ Brod-Lj Šmartno	568.751	387.328	5.152.200	6.108.279	269.408	-	-	269.408
610	Lj Šmartno-Vodice	1.436.845	1.161.984	5.152.200	7.751.029	628.620	774.656	-	1.403.276
Total		9.040.150	9.295.875	23.184.899	41.520.925	4.400.338	5.809.922	7.728.300	17.938.560

* *Speed limit 100 km/h*

On average, the external costs of accidents due to excessive speed on these sections amount to around EUR 1.8 million annually (the year 2020 slightly lowers this average due to COVID movement restrictions). This is almost four times the cost of installing the average speed control on these sections, as the selected offer costs EUR 530.000 (interview).

Assuming that in Slovenia, like in the other countries where the average speed control is implemented, drivers would generally not exceed the speed limits anymore, it is possible to estimate, based on findings by [27] and [28], that such a system would result in 12 to 40 fewer minor injuries, 7 to 8 fewer serious injuries, and one fewer fatality in the analysed period. This means that if the system were installed back in 2014, the external costs of traffic injuries due to speeding would have dropped by around EUR 5.6 to 9.5 million. However, the plans for installing sectional speed cameras in Slovenia intensified only in 2017.

The other system, dynamic speed management, primarily aims to improve traffic flow and traffic safety, but it also affects the emissions and noise from traffic. In total, 15 motorway sections will at least partially have dynamic speed management implemented; six of these were identified as dangerous also in our analysis when taking into account speeding and rear-end collision accidents.

The traffic volume increased by almost 25% (CAGR = 2.4%) on the motorway access roads of the Ljubljana ring during the ten-year period, while the traffic structure has further deteriorated because of a faster increase of freight flows (CAGR = 3.8%), which contributes to the heterogeneity of traffic flows and negatively impacts traffic safety. Between 2014 and 2023, there were 2,304 injury accidents (9,313 accidents in total) on these sections, resulting in injuries to 780 people and almost EUR 70 million in external costs. As expected, almost 40% of accidents happened in heavy traffic. Total external costs of rear-end collisions over the ten-year period reached almost EUR 33 million, leaving 459 people injured, of which 4 fatally (*Table 7*).

Table 7 – External costs of all injuries and rear-end collision-related injuries on the sections where the dynamic speed management system will be installed [in EUR]; Source: authors, based on [15, 16, 18, 45]

Section		$AADT_{2023}$	$Index_{23/14}$	People injured (minor, serious, fatal) / External costs [in EUR]	
				All accidents	Rear-end-collision accidents
653	Logatec-Vrhnika	61.662	124	(69, 11, 2) / 11.478.274	(39, 6, 2) / 8.643.605
652	Vrhnika-Brezovica	70.139	122	(137, 11, 0) / 8.361.605	(105, 8, 0) / 6.241.724
651	Brezovica-LJ Kozarje	80.839	117	(26, 1, 1) / 3.741.719	(11, 0, 0) / 329.277
9	Brnik-Vodice	54.299	135	(31, 4,0) / 2.477.275	(23, 1, 0) / 1.075.816
10	Vodice-LJ Šmartno	60.335	131	(39, 2, 1) / 4.518.193	(21, 1, 1) / 3.592.048
11	LJ Šmartno-LJ Brod	62.000	125	(11, 0, 0) / 329.277	(3, 0, 0) / 89.803
12	Lj Brod-Šentvid	58.500	122	(12, 2, 0) /1.133.868	(7, 0, 0) / 209.540
13	Šentvid.Koseze	58.219	121	(9, 0, 0) /269.408	(2, 0, 0) / 59.869
44	Blagovica-Krtina	48.707	125	(86, 6, 1) / 7.474.416	(60, 2, 0) / 2.570.713
45	Krtina-Domžale	52.902	124	(38, 1, 1) / 4.100.930	(27, 0, 1) / 3.384.325
46	Domžale-Šentjakob	61.212	119	(43, 1, 0) / 1.674.502	(25, 0, 0) / 748.357
47	Šentjakob-LJ Zadobrova	72.000	112	(48, 4, 0) / 2.986.158	(23, 1, 0) / 1.075.816
622	Ivančna G.-Grosuplje	47.000	132	(65, 10, 0) / 5.819.009	(15, 1, 0) / 836.342
621	Grosuplje-Šmarje Sap	61.900	124	(24, 4, 0) / 2.267.735	(20, 4, 0) / 2.147.998
620	Šmarje Sap-LJ Malence	62.171	132	(69, 7, 3) / 12.505.061	(49, 1, 0) / 1.854.107
Total				(707, 64, 9) / 69.137.430	(430, 25, 4) / 32.859.340

The number of rear-end collisions is increasing over the years (CAGR = 4.5%). More than 43% of these accidents occur during the week between 6 am and 9 am, as shown in *Figure 6*.

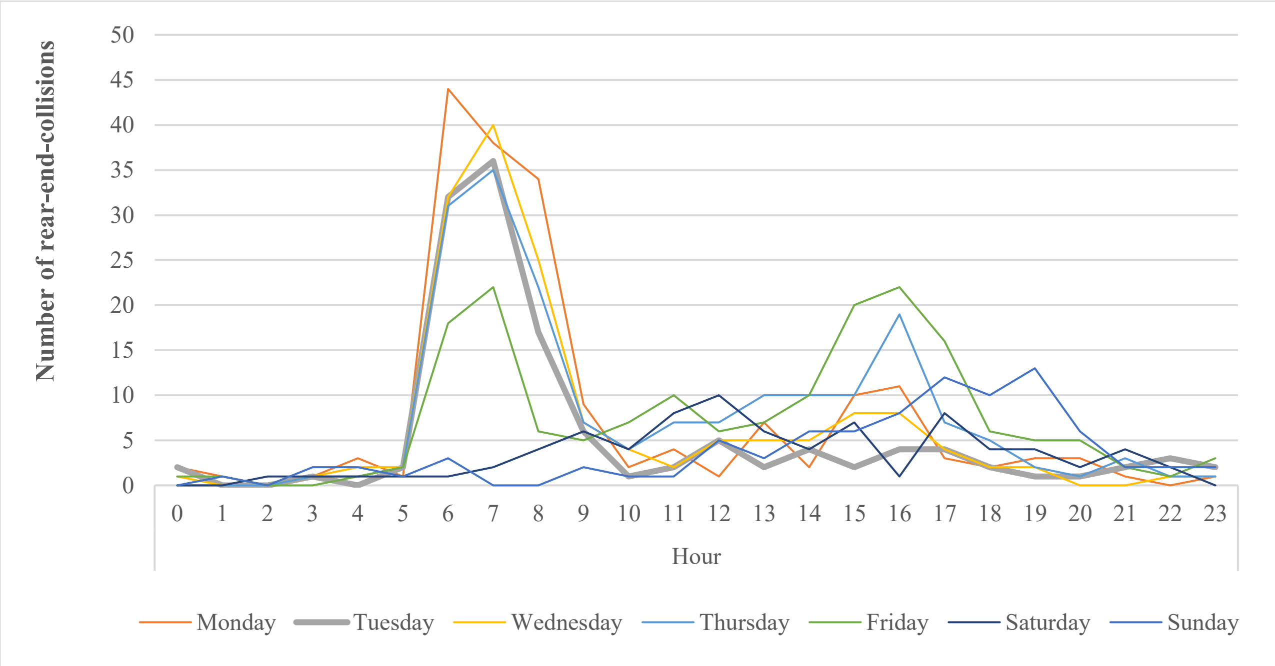

Figure 6 – The occurrence of rear-end collisions on motorway accesses to Ljubljana ring; Source: authors, based on [15]

If the number of accidents were reduced by about one-fifth, as previous studies suggest (e.g. Lee et al., 2006), the external costs of injury accidents would decrease by approximately 13 million EUR. In addition, there would also be fewer material damage accidents and consequently fewer accident-related traffic jams. Currently, traffic flows on these sections create high external congestion costs. There is no exact calculation on congestion costs around Ljubljana and access roads; however, each truck loses from 120 to 230 EUR/h in a traffic jam (interview). In EU countries, the cost of traffic congestion averages around 0.5% of GDP, while in Slovenia, the estimate ranges from around 1.9 to 4.2%, depending on the methodology used (calculated from [18]). Once the dynamic speed management is implemented, it is expected to reduce the travel time towards Ljubljana by approximately 5 minutes (interview).

7. DISCUSSION AND CONCLUSIONS

Speed affects accident risk, injury severity and the environment. Yet many drivers exceed the speed limits; during the period under review, excessive speed was identified as the primary cause in 26% of all traffic accidents on Slovenian motorways. Notably, this figure rises to 44% when considering only accidents resulting in injuries. Despite this, the planned installation of sectional speed cameras does not target the motorway segments where speed-related accidents are most frequent. Nevertheless, analyses indicate that the implementation of these cameras is expected to yield significant reductions in external costs of traffic safety. From this perspective, the investment is likely to deliver a rapid return.

If during this ten-year period the speed limits on the entire motorway network had been 10 km/h lower than currently prescribed, there would have been an estimated 6 to 23% fewer injuries, resulting in a decrease of external costs due to accidents from EUR 147 to EUR 270 million. According to Elvik's model, between 51 and 63 lives could have been saved (between 33 and 40%), and there could have been between 22 and 197 fewer seriously injured individuals. However, Elvik's exponential model for traffic safety prediction in relation to speed has some drawbacks; it assumes homogeneous traffic flow and behaviour, which is not the case in the real world. In addition, other factors, like vehicle age and type (e.g. vehicle safety features), or weather and road conditions, etc., can significantly affect crash outcomes. With sectional radars, the extreme behaviour of individuals can be limited.

On the other hand, congestion can lead to increased accident risk (rear-end collisions) and, for sure, negatively impacts the environment through stop-and-go rides. Besides large transit freight flows, Ljubljana is the most burdened Slovenian municipality in terms of work-related migration in both directions, as nearly 142,500 people from other municipalities commute to work there daily (or at different intervals), while about

25,200 of Ljubljana's working residents commute to work in other municipalities [46]. The combination of large-distance freight, regional and urban traffic flows results in congestion and traffic accidents.

Dynamic speed management has its roots in the 1970s and is nowadays considered a popular traffic management strategy, which is implemented in many countries around the world [47]. Theory and empirical trials suggest that improvements in traffic flow efficiency and stability can be achieved by reducing the maximum speed on motorways during peak periods to 80 or 90 km/h, as the motorway capacity is used most efficiently when traffic flows, and speeds do not vary much over time [48]. In addition, such speed limitation would reduce speed differences between lines, resulting in less switching in the lanes.

The automated system for dynamic speed management will regulate driving speed around 20 kilometres before a traffic jam, so drivers' discipline will be important. The problem might be the fact that only one sectional radar system will operate in the direction toward Ljubljana. In other countries, it has been shown that if there is no speed control and consequently no penalties, then even if speed limits are reduced by 10 km/h, the actual reduction is only about 3 to 4 km/h [49]. To make the system more functional, it would make sense to connect it to the average speed control on all sections, which will be covered by dynamic speed management.

The dynamic speed management system is complex. We do not have a cost estimate for the Slovenian system, but estimates from abroad range from around EUR 200,000 to EUR 600,000 per kilometre, depending on the system design (estimated from [50]), so the Slovene system might cost from EUR 16 million to EUR 48 million. With additional sectional radars, the full functionality of dynamic speed management could be reached. The costs of implementing dynamic speed management usually tend to exceed the benefits [41], but the external costs of accidents on the 15 sections to be covered by this system are around EUR 7 million per year. Let alone the external costs of congestion and emissions.

However, restrictive measures for traffic safety improvement are generally less well-received by the public compared to educational initiatives or infrastructure improvements [51]. For example, the introduction of stricter traffic penalties in Slovenia was met with considerable public resistance. Similarly, findings from the ESRA study, conducted across 39 countries in 2023, indicate that public support for restrictive traffic safety measures in Slovenia is below the EU average. This is particularly concerning given that self-reported behaviours among Slovenian road users, such as speeding, driving under the influence of alcohol or mobile phone use while driving, are more widespread in Slovenia than in the EU [52]. Consequently, it is reasonable to anticipate that increased traffic enforcement may initially face public opposition. However, empirical research would be necessary to substantiate this expectation. On the other hand, implementing dynamic speed management without effective enforcement mechanisms would likely render the measure ineffective. Considering that Slovenian residents frequently express dissatisfaction with congestion on motorways, especially near the capital, speed regulation and enforcement might be more readily accepted in these areas. Nonetheless, this remains a hypothesis that necessitates further investigation.

Only after the implementation of the two systems will the exact result be seen, and the predictions will be tested. This will provide a valuable foundation for further research and for evaluating the justification of extending sectional speed control to other segments of the Slovenian motorway network where speeding is a prominent issue. However, the expansion of sectional speed control across the entire network is unlikely. The Slovenian motorway system is characterised by a high number of exits (107 along less than 550 kilometres), which makes widespread implementation technically complex and financially demanding.

REFERENCES

[1] WHO. Road traffic mortality. 2025. https://www.who.int/data/gho/data/themes/topics/topic-details/GHO/road-traffic-mortality [Accessed 17th May 2025].

[2] WHO. Road traffic injuries. 2023. https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries [Accessed 17th May 2025].

[3] CINEA. *EU Road Safety: Towards "Vision Zero"*. Brussels; 2022.

[4] Debyser A, Kuzhym O. *Road traffic and safety provisions*. Brussels; 2024.

[5] Mekonnen AA, Sipos T. Crash prediction models and methodological issues. *Periodica Polytechnica Transportation Engineering*. 2022;50(3):267–72. DOI: 10.3311/PPtr.16295.

[6] Zanne M, Danchevska V. What can Republic of Macedonia learn from Slovenian transport planning? *Proceedings of the Fourth International Conference on Traffic and Transport Engineering ICTTE*. Belgrade; 2018.

[7] ETSC. *Fate of EU motorway safety in hands of MEPs*. Brussels; 2008.

[8] Hanzl J. Road truck accident rate in terms of major causes: A case study. *Periodica Polytechnica Transportation Engineering*. 2025;53(3):260–6. DOI: 10.3311/PPtr.38721.

[9] ECMT. *Road safety performance, National peer review: Russian Federation*. Paris; 2006.

[10] OECD. *Road safety: Impact of new technologies*. Paris; 2003.

[11] Turner BM, et al. *Guide for safe speeds: Managing traffic speeds to save lives and improve livability*. Washington DC; 2024.

[12] Ötvös V, Tóthné Temesi K, Krizsik N. Analysis of children's road crashes in Hungary. *Periodica Polytechnica Transportation Engineering*. 2024;53(1):58–66. DOI: 10.3311/PPtr.37963.

[13] EC. *Speed and speed management*. Brussels; 2018.

[14] Sipos T. Cognitive dissonance on sustainable mobility. *Acta Polytechnica Hungarica*. 2023;20(5):31–40. DOI: 10.12700/APH.20.5.2023.5.3.

[15] Policija. 2025. Prometna varnost. https://www.policija.si/o-slovenski-policiji/statistika/prometna-varnost [Accessed 15th Jun 2025].

[16] OPSI. 2025. Prometne obremenitve od leta 1997 dalje. https://podatki.gov.si/dataset/pldp-karte-prometnih-obremenitev [Accessed 15th Jun 2025].

[17] OPSI. 2025. Prometno delo na državnih cestah od leta 1990. https://podatki.gov.si/dataset/povprecni-letni-dnevni-promet-pldp-na-drzavnih-cestah-od-leta-1991 [Accessed 3rd Jun 2025].

[18] Pretnar G, et al. *Zunanji stroški prometa; Izračun za Slovenijo*. Ljubljana; 2024.

[19] Cameron MH, Elvik R. Nilsson's Power Model connecting speed and road trauma: Applicability by road type and alternative models for urban roads. *Accid Anal Prev*. 2010;42(6):1908–15. DOI: 10.1016/j.aap.2010.05.012.

[20] OECD/ITF. *Speed and crash risk*. Paris; 2018.

[21] ETSC. *Reducing speeding in Europe*. Brussels; 2019.

[22] Ragnøy A. *Automatic section speed control: Results of evaluation*. 2011.

[23] Statista. 2025. Ranking of European countries by number of permanently installed speed cameras for traffic in 2023. https://www.statista.com/statistics/1201490/speed-cameras-permanent-traffic-countries-europe/ [Accessed 21st May 2025].

[24] Pilkington P, Kinra S. Effectiveness of speed cameras in preventing road traffic collisions and related casualties: systematic review. *BMJ*. 2005;330(7487):331–4. DOI: 10.1136/bmj.38324.646574.AE.

[25] Karpenko M, Prentkovskis O, Skačkauskas P. Numerical simulation of vehicle tyre under various load conditions and its effect on road traffic safety. *Promet - Traffic&Transportation*. 2024;36(1):1–11. DOI: 10.7307/ptt.v36i1.265.

[26] Soole DW, Watson BC, Fleiter JJ. Effects of average speed enforcement on speed compliance and crashes: A review of the literature. *Accid Anal Prev*. 2013;54:46–56. DOI: 10.1016/j.aap.2013.01.018.

[27] Høye A. Safety effects of section control - An empirical Bayes evaluation. *Accid Anal Prev*. 2015;74:169–78. DOI: 10.1016/j.aap.2014.10.016.

[28] Vadeby A, Howard C. Spot speed cameras in a series - Effects on speed and traffic safety. *Accid Anal Prev*. 2024;199:107525. DOI: 10.1016/j.aap.2024.107525.

[29] ETSC. *Section Control: towards a more efficient and better accepted enforcement of speed limits?* Brussels; 2009.

[30] Autostrade per l'Italia. Safety interventions, technologies and tools. 2025. https://www.autostrade.it/en/tecnologia-sicurezza/sicurezza/il-tutor [Accessed 2nd Jun 2025].

[31] Borsati M, Cascarano M, Bazzana F. On the impact of average speed enforcement systems in reducing highway accidents: Evidence from the Italian Safety Tutor. *Economics of Transportation*. 2019;20:100123. DOI: 10.1016/j.ecotra.2019.100123.

[32] Sándor Z, Monostori Á. Traffic analysis of specific motorways with different usage characteristics in Hungary with the method of section control. *Acta Technica Jaurinensis*. 2020;13(3):211–45. DOI: 10.14513/actatechjaur.v13.n3.554.

[33] Sándor Z. Possible Traffic Safety Effects of the Implementation of Section Control in Hungary. *Acta Technica Jaurinensis*. 2020;13(4):309–23. DOI: 10.14513/actatechjaur.v13.n4.557.

[34] Kupper J. Section control in Germany – findings for the first setup. *Urban Plan Transp Res*. 2021;9(1):336–46. DOI: 10.1080/21650020.2021.1905055.

[35] Schnuer C. Second average speed camera enters test phase. https://delano.lu/article/second-average-speed-camera-en [Accessed 4th Jun 2025].

[36] Daniels S, Focant N. Dynamic speed limits, European road safety decision support system, developed by the H2020 project SafetyCube. 2007.

[37] D. Frejo JR, Papamichail I, Papageorgiou M, De Schutter B. Macroscopic modelling of variable speed limits on freeways. *Transp Res Part C Emerg Technol*. 2019;100:15–33. DOI: 10.1016/j.trc.2019.01.001.

[38] van Nes N, Brandenburg S, Twisk D. Dynamic speed limits; effects on homogeneity of driving speed. In: *2008 IEEE Intelligent Vehicles Symposium*. IEEE; 2008. p. 269–74. DOI: 10.1109/IVS.2008.4621229.

[39] SWOV. Speed and speed management. *SWOV fact sheet*. The Hague; 2021.

[40] Lee C, Hellinga B, Saccomanno F. Evaluation of variable speed limits to improve traffic safety. *Transp Res Part C Emerg Technol*. 2006;14(3):213–28. DOI: 10.1016/j.trc.2006.06.002.

[41] De Pauw E, Daniels S, Franckx L, Mayeres I. Safety effects of dynamic speed limits on motorways. *Accid Anal Prev*. 2018;114:83–9. DOI: 10.1016/j.aap.2017.06.013.

[42] ETSC. *Setting appropriate, safe, and credible speed limits*. Brussels; 2010.

[43] Kuhn B. *Efficient use of highway capacity summary*. Washington, DC; 2010.

[44] Zanne M, Groznik A, Twrdy E. The costs of traffic accidents due to the heterogenization of traffic flows on Slovenian motorways. *Economic and Business Review*. 2016;18(2). DOI: HTTPS://DOI.ORG/10.15458/85451.22.

[45] inflation.eu. Historic inflation Slovenia - CPI inflation. [Accessed 17th Jun 2025].

[46] SURS. 2023. Večina delovno aktivnih oseb odhajala na delo v drugo občino. https://www.stat.si/StatWeb/News/Index/12751 [Accessed 15th Jun 2025].

[47] Soriguera F, Martínez I, Sala M, Menéndez M. Effects of low speed limits on freeway traffic flow. *Transp Res Part C Emerg Technol*. 2017;77:257–74. DOI: 10.1016/j.trc.2017.01.024.

[48] Bliemer M, Raadsen M. *Does slower driving make us go faster? Thinking outside the box*. Sydney: The University of Sydney business school, The Institute of transport and logistics studies; 2018.

[49] ECMT. *Speed management*. Paris; 2006.

[50] CDOT. *Variable speed limits guidelines*. Denver; 2023.

[51] Alonso F, Useche SA, Faus M, Esteban C. Assessing users' perceptions of four types of road safety measures. *Transport Problems*. 2022;17(2):137–49. DOI: 10.20858/tp.2022.17.2.12.

[52] Pires C, et al. *Measuring road safety performance and culture: A comparative study of 39 countries*. IATSS Research. 2025;49(3):335–52. DOI: 10.1016/j.iatssr.2025.07.001.