Traffic & Transportation

# Operating Vehicles' Speed Prediction Models

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**ABSTRACT**
Vehicle speed is one of the main factors that influence the occurrence and severity of the consequences of road traffic accidents. Operating speed can be defined, among other things, as the actual speed at which the largest number of road users drive in conditions of free traffic flow. It can be measured on existing roads, however, on newly designed roads it can only be predicted. For this reason, many researchers have examined the correlation between the elements of the road as well as its surroundings and operating speed. By determining the correlation, models for predicting operating speed were created. As part of this paper, the most significant models for predicting operating speed were analysed. Of course, the largest number of models are stochastic, but in recent years, models based on artificial intelligence, more precisely on deep learning, have also been created. Accordingly, the goal of this paper is to review the model for predicting the operating speed of vehicles while identifying opportunities for further research and improvement in this area.

**KEYWORDS**
operating speed; prediction models; road safety; road infrastructure.

## 1. INTRODUCTION

The main goal of the road transport system is the development of traffic in an efficient and economically acceptable manner, with an emphasis on road safety. Road safety is a global problem that affects many countries around the world. According to a report by the World Health Organisation [1], every year approximately 1.35 million people around the world die in road traffic accidents, with an even greater number of those injured. Due to the above, road traffic accidents are the eighth leading cause of death in the world, and the first for people aged 5 to 29 [2]. The largest number of fatalities was recorded in low and medium developed countries, where the infrastructure, vehicles and education regarding road safety are not at an adequate and satisfactory level. Consequently, road traffic accidents are today one of the most important public health problems faced by modern societies and their importance will increase in the future.

Through its report, the OECD (2018) [3] estimates that the social cost of road traffic accidents in the European Union is around 500 billion euros (or 3% of its GDP). This cost includes medical costs, loss of productivity, road infrastructure repair and reconstruction costs as well as other costs.

Internationally, it is generally assumed that about one third of fatal accidents are partially caused by speeding or inappropriate speed [4, 5]. Data from Australia indicate that speed is the cause of around 41% of road traffic accidents with fatalities and 24% of road traffic accidents with serious injuries [6], while on European roads speed is the cause of around 30% of all road traffic accidents with fatalities [7]. Similarly, analysing the circumstances that preceded the occurrence of serious road traffic accidents in the Republic of Croatia, it was determined that in 39% of serious road traffic accidents, speed was one of the potential causes of serious road traffic accidents, with speed itself being a potential cause in around 17% of serious road traffic accidents. In addition, it should be noted that the road infrastructure in combination with the driver is the cause of about 35% of serious road traffic accidents [2]. Speed is therefore a key factor in road safety, as it affects not only the occurrence of a road traffic accident, but also the severity of its consequences. Inadequate speed, often above posted speed limits, is responsible for a high rate of fatalities and many injuries.

Numerous studies have established a link between speed and the probability of road traffic accidents (*Figure 1*). An increase in average speed is directly related to the probability of a road traffic accident, as well as the severity of its consequences. For example, every 1% increase in average speed leads to a 4% increase in the risk of a fatal road traffic accident and a 3% increase in the risk of a serious injury road traffic accident [1].

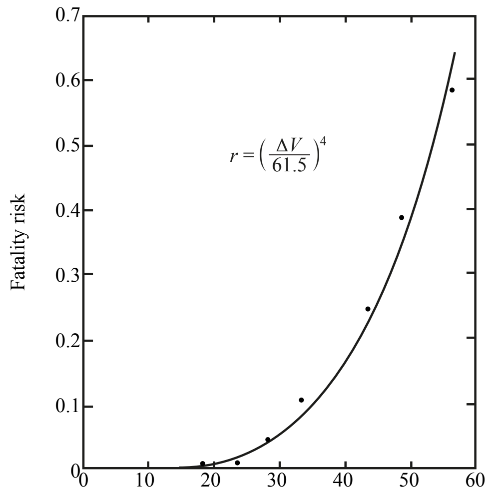


*Figure 1 – Relationship between speed and road traffic accident rate [8]*

In EU countries conducting comprehensive nationwide assessments of speed compliance on roads, it has been observed that between 35% and 75% of recorded vehicle speeds surpass the statutory limits [9].

## 2. TRAFFIC FLOW SPEED

The primary goal in road design is to provide geometric elements suitable for the speeds at which most vehicles travel on the road. Actual vehicle speeds may vary over time due to changes in traffic conditions on certain segments and due to changes in the road environment, road characteristics, speed limits, driver behaviour and vehicle types [10–12].

In general, speed is defined as the distance travelled per unit of time. In traffic engineering, several speed categories can be distinguished that have a function when determining the geometrical elements of the road:

- mean spatial speed of the traffic flow;
- mean time speed of the traffic flow;
- design speed;
- speed limit (maximum permitted speed);
- operating speed.

The mean spatial speed of the traffic flow is the arithmetic mean of the current speeds of all vehicles in the traffic flow on the observed road section [13]. Mean time speed of the traffic flow is the arithmetic speed of all vehicles in the traffic flow that pass through the observed section of the road in a certain period [13].

Design speed is defined according to the Croatian *Ordinance on basic conditions that public roads outside settlements and their elements must meet from the point of view of traffic safety* [14] as the highest speed for which complete driving safety is guaranteed in free traffic flow on the entire route, under optimal weather conditions and with good road maintenance.

Operating speed can be defined in several ways, for example as the actual speed at which a vehicle moves in free traffic conditions [15] or as the 85$^{th}$ percentile of the distribution of observed speeds used to measure operational speeds associated with a specific location or geometric characteristic [16]. It should be emphasised that the above refers to the cumulative function. In other words, eighty-five percent of drivers do not exceed the operating speed value in free flow conditions [17]. Free flow conditions occur when the traffic load is low enough for the road to provide a higher level of service. Times or periods of free traffic flow can be easily obtained based on data obtained from traffic counts. On extra-urban roads with light traffic, free flow conditions are present throughout the day, while on heavily trafficked urban roads, free flow conditions will occur sometime before the morning and after the afternoon peak and may also occur between peak hours [12].

Of all the aforementioned speeds, the operating speed stands out as the most important one. The reason for this is its deviation from the speed limit. In other words, the operating speed, in conditions of free traffic flow and in locations where there is no speed control, is usually higher than the speed limit [18, 19]. According to the research carried out on the roads in Bosnia and Herzegovina [20], more than 90% of vehicles were driving at a speed higher than the speed limit, where the average deviation of the operating speed from the speed limit was about 15 km/h. This is supported by data from counters installed on state roads in the Republic of Croatia. *Figure 2* shows the difference between recorded operating speeds in relation to the speed limit on roads in Croatia in 2021.

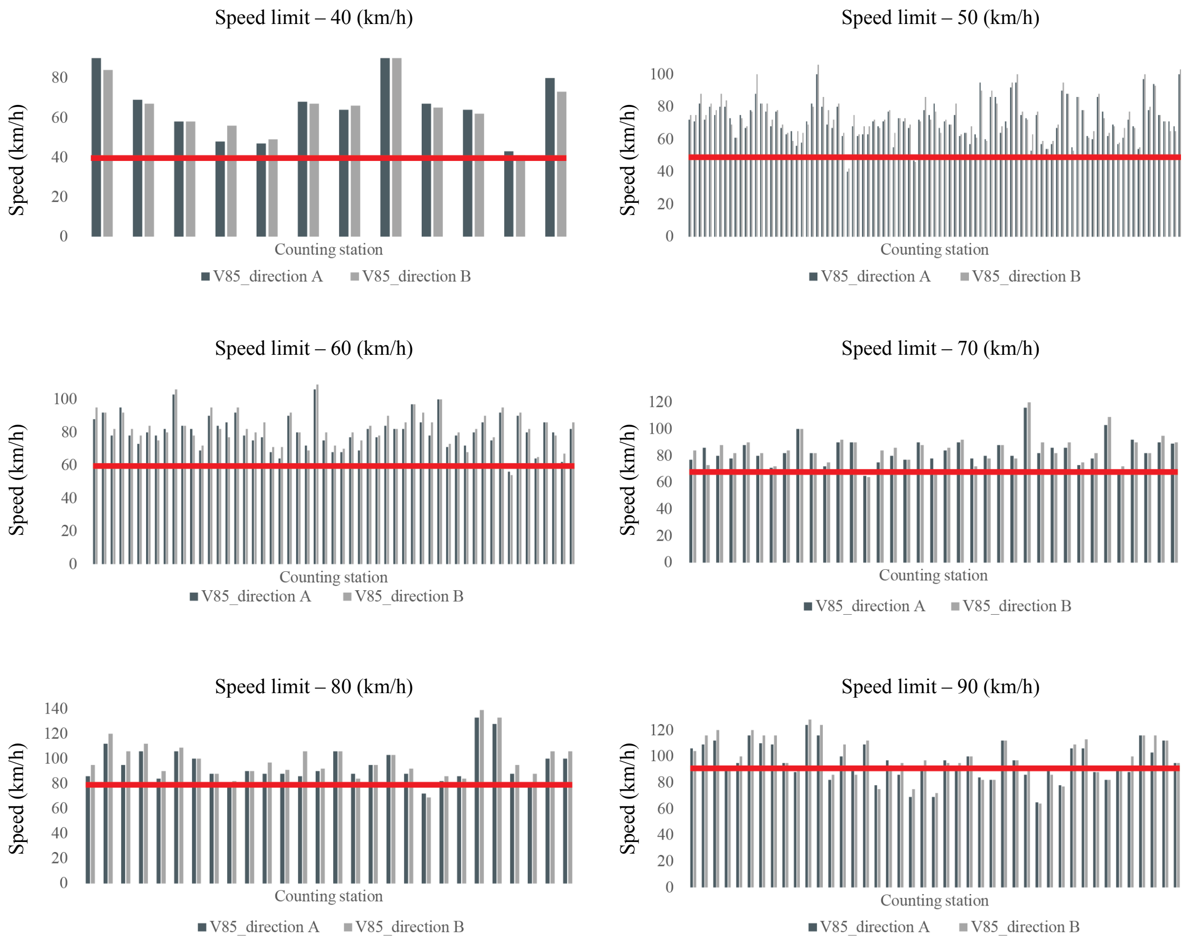


*Figure 2 – The difference between recorded operating speeds in relation to the speed limit on state roads in Croatia in 2021 [21]*

On average, on state roads in Croatia in 2021, the difference between the operating speed and the speed limit in conditions of free traffic flow was 26 km/h in locations where the speed limit is 40 km/h, 23 km/h in locations where the speed limit is 50 km/h, 22 km/h in locations where the speed limit is 60 km/h, 15 km/h in locations where the speed limit is 70 km/h, 19 km/h in locations where speed limit 80 km/h and 8 km/h in locations where the speed limit is 90 km/h. From the above data, it is clear that the deviation of the operating speed from the speed limit is inversely proportional to the speed limit. In other words, a larger difference between the operating speed and the speed limit was recorded in locations with a lower speed limit, and a smaller difference between the operating speed and the speed limit was recorded in locations with higher speed limits.

The aforementioned design speed is determined or influenced solely by the road designer, the road authority and legislation. On the other hand, the operating speed is influenced by the driver, the vehicle and the road (and its surroundings). In Europe, in general, 40–60% of drivers do not comply with the speed limit [22]. There are also significant differences in speeding on different types of roads. The largest percentage of drivers from European Union countries (28%) state that they do not comply with the prescribed speed limits on motorways, while this percentage is lower on state roads (19%), local roads (13%) and in urban areas (7%). It can be assumed that drivers will drive according to the speed limit if they consider it reasonable, or on the other hand, if the speed limit is not according to the limit which drivers consider appropriate given the characteristics of the road. Then it can be ignored and the entire speed control system is questionable [22].

Considering the trend of development of traffic, vehicles, road infrastructure and raising people's awareness of road safety, speed as a cause still has a large share in serious road traffic accidents. According to the Croatian data it was shown that the road infrastructure in combination with the driver is the cause of about 35% of serious road traffic accidents [2]. The above indicates that there is still a connection between road infrastructure and speed, and accordingly there is room for reducing the difference between the operating speed and the speed limit. With the aim of the latter, many research focused on a better understanding of the main factors that have an influence on the driving speed [23] and accordingly approached to predicting the operating speed.

## 3. OPERATING SPEED PREDICTION MODELS

As stated in the previous chapters, research shows that the road infrastructure in combination with the driver was the cause of about one third of serious road traffic accidents, according to which it can be concluded that the road infrastructure has an impact on the operating speed. On the existing, already built roads it is difficult and financially demanding to significantly change the infrastructure with the aim of influencing the reduction of operating speed. On the other hand, for new roads, it is useful to have information about the operating speed during the actual design, so that the design solution can influence the reduction of the difference between the operating speed and the speed limit.

As a result of the above, many studies examined the influence of the road and its surroundings on the operating speed and accordingly created models for predicting the operating speed. The largest number of models are stochastic, while a smaller number refer to those based on artificial intelligence, more precisely on deep learning.

Stochastic models are based on the correlation between operating speed and road infrastructure, while including geometric elements and elements of the cross section of the road, environment, speed limit, type of terrain, etc. [24]. A smaller number of studies also included the driver factor [25–27]. Considering different patterns of driver behaviour [28], it can be assumed that operating speeds of traffic flows on roads with the same characteristics would not be the same in different countries. Accordingly, but also given the previously mentioned fact that the road infrastructure in combination with the driver is to a considerable extent the cause of serious road traffic accidents, there is a lot of room for work and progress in this area.

The highest operating speeds can be achieved in conditions of free traffic flow. In other words, in a free traffic flow, the speed of the vehicle is affected by the route of the road, and the interaction with other vehicles is minimal. Therefore, it can be assumed that interaction with other vehicles does not have a significant impact on operating speeds [29]. To observe only the conditions of free traffic flow, the authors used a minimum time sequence of 5 seconds [25, 29–35] when analysing the data, which was proposed by Fitzpatrick et al. (2005) [34] and Boroujerdian et al. (2016) [29] as the minimum value at which the vehicle spacing is sufficient to ensure free traffic flow. This is supported by the fact that most of the research was conducted on extra-urban roads, where drivers can develop higher speeds due to less presence of intersections, vulnerable road users, geometric characteristics and layout of the traffic network as well as higher speed limits [36]. In addition to the above, the largest number of included studies were conducted on single-carriageway roads with one road lane in each direction, while a smaller number investigated the operating speed on dual-carriageway roads with two and/or more road lanes in each direction [31, 37–45]. In doing so, the operating speeds of passenger cars were most often examined, while a part included heavy-good vehicles (sometimes also including buses) [33, 34, 38, 40–43, 46–54]. Of the aforementioned, only Medina and Tarko (2007) [47] conducted their research exclusively for heavy-good vehicles. In order to collect data, researchers most often used speed radars and laser devices, video cameras and GPS systems, while a smaller number of studies were conducted on driving simulators [43, 50, 55]. In addition to the above, by collecting data from mobile phones, it is possible to obtain high-quality data on the operating speeds of vehicles, which are available, for example, on *Google Maps* [56, 57] or *TomTom* [58]. At the same time, the models for predicting operating speeds were not made based on data available from *Google Maps* and *TomTom*.

Analysing the position of the road, i.e. the horizontal and vertical road route guidance the research focused mostly on predicting the operating speed in horizontal curves, on tangents and in a combination of horizontal curves and tangents as well as in vertical curves and/or slopes. At the same time, it was shown that different parameters affect the operating speed in the specified road positions. Linear regression is most often used when predicting operating speeds using combinations of different independent variables [59]. In horizontal curves, the most significant independent variable was the radius of the horizontal curve. On tangents, the set speed limit has the greatest impact on the operating speed, similarly to vertical curves and/or slopes, where along with the speed limit, the longitudinal slope and width of the road lane have a statistically significant effect on the operating speed. Models for predicting operating speed in different road positions are analysed in more detail through the following sub-chapters, and in the last sub-chapter, models based on artificial intelligence are analysed.

A summary of the literature is presented in *Table 1*.

### 3.1 Horizontal curves

Since it has been shown that road infrastructure is to a considerable extent the cause of serious road traffic accidents and that speed as a potential cause occurs in a significant share of serious road traffic accidents, the research was based on the influence of the geometric and traffic parameters of the road infrastructure and its environment on the operating speed. The research was partly focused on testing the operating speed on single-carriageway roads with one road lane for each direction [25, 30, 32, 33, 47–49, 52–54, 59, 61–67, 69, 70], and part of the research refers to dual-carriageway roads with two or more road lanes for each direction [19, 31, 33, 34, 39, 40].

When researching operating speed on horizontal curves on all types of roads, the radius of the horizontal curve turned out to be statistically the most significant variable [46, 52, 59, 64, 66, 70] (*Figure 3*).

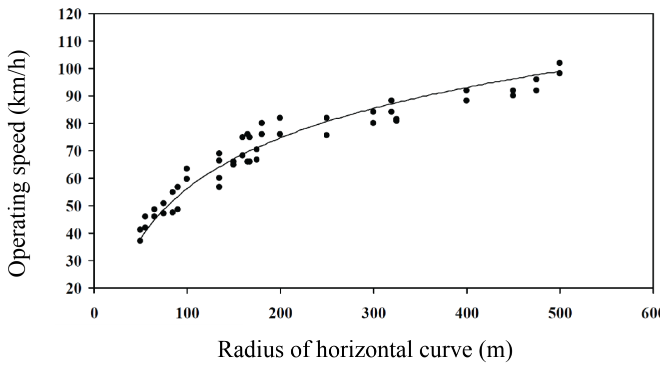


*Figure 3 – Relationship between radius of horizontal curve and operating speed [59]*

On single-carriageway roads with one lane for each direction Wang et al. (2018) [52] found that operating speeds decrease significantly when the radius of the horizontal curve is less than 300 metres, but also

*Table 1 – Concise literature review*

| Year | Authors | Country | Vehicle categories analysed | Road type | Road position (HC, VC, T) | Speed measurement method | Analysed variables (significant) | Model |
|---|---|---|---|---|---|---|---|---|
| RESEARCH PAPERS | | | | | | | | |
| 2005 | Misaghi and Hassan [33] | Canada | PC, HGV | 1X2 | HC and T | multiple devices | R, CCR, e, | V85=94.3+8.67·10-6 R2 |
| 2005 | Fitzpatrick et al. [34] | USA – Texas | all vehicle categories | 1X2 | T | Laser | AD, SL | V85=25.9+0.83·SL−0.054AD |
| 2007 | Dell'Acqua et al. [35] | Italy | PC | 1X2 | T | Laser | CCR, RLW, SL, R | V85c=2073.7·(1/R)+31029·(1/R2)+0.87Venv |
| 2007 | Medina and Tarko [47] | USA | HGV | 1X2 | HC and T | Laser | SL, VL, LST, RLW, R, e, CL, | Va=TS−0.7164(TS−Vhc)+0.022La |
| 2008 | Gong and Stamatiadis [60] | --- | PC | 2X2 | HC | speed radar | R, CL, LS, e, AADT, ITL, OTL | V85inner lane=51.520+1.567ST-2.795MT-4.001PT-2.150LSI+2.221ln(CL)<br>V85outer lane =60.779+1.804ST-2.521MT-1.071LSI-1.519ICI+0.00047R+2.408·(CL/R) |
| 2008 | Abdul-Mawjoud and Sofia [59] | Iraq | PC | 1X2 | HC | speed radar | Δ, CL, TL, TS, LST, AADT | V85=17.5+0.42·V85as+0.068·R |
| 2008 | Memon et al. [61] | Pakistan | PC | 1X2 | HC and T | GPS system | R, CL, Δ, ac85, LST, CCR | V85=40.4-(1571/R)+0.613Max,V85T+0.0244CL-0.163Δ |
| 2008 | Perco [32] | Italy | PC | 1X2 | HC and T | Laser | R, CL, ITL, OTL, e, LST, CW, RLW, CCR | V85=121.78-(544.78/√R) |
| 2010 | Zuriaga et al. [48] | Spain | all vehicle categories | 1X2 | HC and T | GPS system | Ls, NC, NT, RLW, CCR | V85=1/(0.00948323+0.000015201·CCR) |
| 2011 | Abbas et al. [53] | Malaysia | A, HGV | 1X2 | HC and T | Laser | R | V85HMC=0.67V85HAT-(3479/R)+31.2 |
| 2012 | Memon et al. [49] | Pakistan | all vehicle categories | 1X2 | HC and T | VBox | R, LU, CL | V85mc=42.8−1.4D+0.627Max,V85T-0.02CL |
| 2013 | JacSL and Anjaneyulu [54] | India | A, HGV | 1X2 | HC and T | GPS system | R, CL, Δ, LST, ITL, VL | V85=65-(1009.9/R)-0.053CL |
| 2013 | Zuriaga et al. [62] | Spain | PC | 1X2 | HC and T | GPS system | R | Δ85V=9.051+(1527.328/R) |
| 2014 | Bella et al. [63] | Italy | PC | 1X2 | HC and T | GPS system | R, CCR, CL, Δ, TL, LST | V85c=118.085-0.05CL-(2188.49/R)-0.812·e |
| 2015 | Echaveguren et al. [64] | USA | PC | 1X2 | HC and T | GPS system | LS, R, TL | V85=1.05TS+0.103√R |
| 2015 | Eboli et al. [65] | Italy | PC | 1X2 | HC and T | GPS system | Ls, R, LU, CCR, LS | V85=0.858·V85i-1+0.037R-1.288 |
| 2016 | Shallam and Ahmed [66] | India | PC | 1X2 | HC | speed radar | R, Δ, VL | V85=15.657-(163.69/√R)+0.24Δ+0.57 VL |
| 2016 | Boroujerdian et al. [29] | Iran | A, HGV | 1X2 | VC | Video camera | LST, TS, SL, TL, RLW | Lnstdev=0.4+0.27RLW+0.07LST(1/LST)-0.1VHC1 |
| 2016 | Russo et al. [25] | Italy | PC | 1X2 | HC and T | Laser | Ls, CCR, RLW, AD, R | V85HZ=11.77·RLW-882.1·((1/R)0,7)<br>V85T=96.6+0,0007·exp(RLW)-0.05·CCR+4.28·log(Ls)-0.53·AD<br>V85HCandT=104.59+3.99·log(Ls)-0.07·CCR-1670·(1/R) |
| 2016 | Hashim et al. [30] | Egypt | PC | 1X2 | HC and T | GPS system | R, ITL | V85HC=99.885-(3880.21/R)<br>V85T=84.34+(0.593·√ITL) |
| 2017 | Yan et al. [42] | China | A, HGV | MLR | HC and VC | GPS system | R, CCR, LU, RLW, TL | Va=141.03·exp[-1.35·10-4·(Fr200)-6.78·10-5·(Ff250-Ff100)] |
| 2017 | Cvitanić and Maljković [67] | Croatia | PC | 1X2 | HC and T | GPS system | R, CL, Δ, e, TL | V85c=2.9+8.23lnR+0.364V85T |
| 2018 | Maji et al. [38] | India | A, HGV | 2X2 | HC | Video camera | Lc, Δ, CL, LS | V85=84.304+0.052CL-0.156Δ |
| 2018 | Maji and Tyagi [39] | India | PC | 2X2 | HC | Video camera | R, CL, Δ | V85=38.735-(1461.805/R)+0.56V85bc+0.018CL |
| 2018 | Wang et al. [52] | --- | A, HGV | 1X2 | HC | multiple devices | R, V85HAT | --- |
| 2018 | Llopis-Castello et al. [68] | Spain | HGV | 1X2 | HC and VC | GPS system | R, CL, Δ, ITL, CCR, LST, e | V85=73.76-(46.45/e0,0072R) |
| 2018 | Wang and Wang [43] | China | all vehicle categories | 2X2 | HC and VC | GPS system | LST, CL, VCL, ΔCc | V85c=-1.7-0.8CL+0.006K+0.57ΔCc + 426.3AIC |
| 2018 | LSLo et al. [69] | Portugal | PC | 1X2 | HC and T | GPS system | LU, CW, AD, AADT | --- |
| 2019 | Sil et al. [40] | India | A, HGV | 2X2 | HC | Video camera | R, CL, Δ, ITL, LS | V=13.26-(0.11 LU) |
| 2019 | Choudhari and Maji [50] | India | A, HGV | 1X2 | HC and T | Driving simulator | R, ITL, CL, e | 85MSR=(1388.42/R)+0.05ITL+2.872 |
| 2020 | Malaghan et al. [70] | India | PC | 1X2 | HC | GPS system | R, CL, LU, Δ | V85=72.10+0.02R−0.01CL−01, LU |
| 2020 | Sil et al. [41] | India | A, HGV | 2X2 | HC | Video camera | CL, Δ, ITL | V85=56.36-0.27Δ+0.11CL+0.06ITL |
| 2020 | Maji et al. [46] | USA | all vehicle categories | 1X2 | T | Laser | CW, SR, SL, AADT | V85=4.395+0.889SL+0.084SR |
| 2020 | Malaghan et al. [70] | India | PC | 1X2 | T | GPS system | ITL, OTL | V85T=46.71+5.47ln(ITL) |
| DOCTORAL DISSERTATIONS | | | | | | | | |
| 2006 | Wang [71] | USA | PC | All types of roads in urban areas | HC and T | GPS system | Onr, AD, SL, RLW, r, NRL, PSP, pp, mp, LU | V85tangent=50.503+(10.386·NRL)-(0.079·Onr)-(0.129·AD)-(0.211·If)+(4.816·cp)-(6.824·PSP)-(5.104·pp)+(5.299 LU1)+(5·237 LU2)<br>V85hor_curve=57.558+(4.899·NRL)+(1.193·RLW)-(0.059·AD)+(2.557·mp)-(1.308·cd)-(0.074·On-r)-(7.805·pp)-(3.187·PSP) |
| 2007 | Gong [31] | USA | PC | 2X2 | HC | speed radar | R, CL, LS, e, AADT, ITL, OTL | V85inner lane=50.937-1.567ST-2.795MT-4.000PT-2.150LSI+2.221ln(CL)<br>V85outer lane=60.779+1.804ST-2.521MT-1.071LSI-1.519ICI+0.000472R+2.408·(CL/R) |
| 2020 | Mintie [51] | Ethiopia | all vehicle categories | 1X2 | HC and T | speed radar | R, CL, ITL, e, LS, Δ | V85=85.13-0.05·CL-(3704/R)-3.12·ln(ITL) |
| MODELS BASED ON ARTIFICIAL INTELLIGENCE | | | | | | | | |
| 2015 | Ma et al. [44] | China | data not available | MLR | data not available | Microwave traffic detectors | --- | --- |
| 2017 | Ma et al. [45] | China | data not available | MLR | data not available | GPS system | --- | --- |
| 2018 | Li et al. [72] | China | PC | 1X2, 2X2 | data not available | --- | --- | --- |
| 2019 | Wang et al. [73] | China | data not available | All types of roads in urban areas | data not available | Detectors for the automatic identification of vehicles | --- | --- |

*R – curve radius (m); CA – curve angle (°/100 m); CL – curve length (m); Δ – deflection angle (°); e – elevation (%); TL – tangent length (m); VL – visibility length (m); TS – tangent speed (km/h); SL – speed limit (km/h); RLW – road lane width (m); Lnstdev – Ln standard deviation; LST – longitudinal slope of tangent (%); VHC1 – 1 if it is a passenger car (otherwise 0); K – vertical curvature rate (% per unit length); ITL – incoming tangent length (m); OTL – outgoing tangent length (m); VCL – vertical curve length (m); V85as – 85th percentile of approaching speed (km/h); V85HMC – 85th percentile speed in the middle of horizontal curve (km/h); V85HAT – 85th percentile speed on the incoming tangent of a horizontal curve (km/h); ΔCc – curvature change speed between the combined curve and the upcoming segment; AIC – Akaike information criterion; Venv – speed of the environment (km/h); AD – access density; SR – skid resistance; CW – carriageway width (m); Va – speed in acceleration transition (km/h); Vhc – vehicle speed in horizontal curve (km/h); La – the length of the acceleration transition section (m); V85T – 85th percentile speed on tangent (km/h); CCR – curvature change ratio (°/km); ac85 – 85th percentile of maximum acceleration in curve (m/s2); LS – longitudinal slope; AADT – annual average daily traffic (veh/day); Ls – segment length; NC – number of curves; NT – number of tangents; V85bc – 85th percentile speed before curve (km/h); ST – shoulder index (1 – paved; 0 – other); MT – median index (1 – guardrail not present; 0 – guardrail present); PT – pavement index (asphalt – 0; concrete – 1); LSI – longitudinal slope index of the road segment (≥0,5% – 1; other – 0); ICI – incoming curve index (if the incoming segment is a curve – 1; other – 0); cp – curb presence (0 – not present; 1 – present); Onr – objects near road (trees, poles); If – intersection frequency on tangent; NRL – number of road lanes; PSP – pedestrian sidewalk presence (0 – not present; 1 – present); pp – street parking space present (0 – not present; 1 – present); mp – median presence (0 – not present; 1 – present); LU – land use (0 – commercial; 1 – residential; 2 – other); cd – curve direction (left; right); PC – passenger car; HGV – heavy goods vehicle; 2X2 – dual–carriageway road (each carriageway has two one–way road lanes); 1X2 – road with one carriageway and two road lanes in the opposite direction; MLR – multi–lane roads; HC – horizontal curve; VC – vertical curve and/or slope; T – tangent.*

that with the increase in the radius of the horizontal curve, the vehicles' speed stabilises. Similarly, Russo et al. (2016) [25] state that a radius of a horizontal curve greater than 400 metres has a negligible effect on the operating speed. Shallam and Ahmed (2016) [66] found that the radius of the turn has the greatest influence on the operating speed at the top of the turn ($R^2$=0.86), and that the curve-entering speed is affected by the visibility length, with a slightly smaller correlation recorded ($R^2$=0.58). In addition, it has been shown that a sharp curve vertical sign significantly reduces the curve-entering speed [52]. Some authors mention the horizontal curve length and the deflection angle as variables that have a statistically significant impact on the operating speed [70, 62]. The deflection angle of the curve refers to the angle between the outgoing and incoming directions [74] (*Figure 4*).

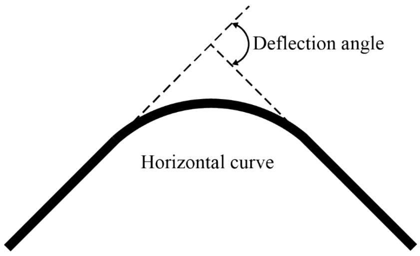


*Figure 4 – Deflection angle of horizontal curve*

On dual-carriageway roads, statistically the most significant variables were the curve length, the deflection angle of the curve and the radius of the curve [38, 39–41, 60]. It was found that the speed in the middle of the curve increases proportionally with the length of the incoming tangent [41]. The length of the curve turned out to be statistically the most significant variable in the research conducted by Maji and Tyagi (2018) [39]. The authors found that drivers start to pay attention to the horizontal curve about 50 metres before the curve's beginning because then they perceive the length of the curve. In the middle of the curve, the radius turned out to be statistically the most significant variable, indicating that it is only when entering the curve that drivers experience the effect of curvature and adjust their speed accordingly. Similarly to single-carriageway roads, on dual-carriageway roads, it has been shown that there is no statistically significant difference in operating speeds for curves with radii greater than 400 metres [40]. For this reason, Sil et al. (2020) [41] limited their research to horizontal curves with a radius of less than 430 m. Their research was conducted for passenger cars and trucks. Accordingly, different models were created for the mentioned groups of vehicles. Similar research was also carried out by Sil et al. (2019) [40] and Maji et al. (2018) [38]. The latter [38] determined that the operating speed of the passenger car in the horizontal curve depends mostly on the curve length and the deflection angle, whereby the operating speed increases with the increase of the curve length or the decrease of the deflection angle of the curve. On the other hand, in the case of heavy goods vehicles, it was shown that the operating speed in a curve depends mostly on the deflection angle and the longitudinal slope of the road before the curve. Also, the research showed that, on average, in a curve, passenger cars drove 17 km/h faster than trucks, which was also confirmed by Sil et al. (2019) [40]. Gong and Stamatiadis (2008) [60] conducted a study on 63 horizontal curves on four-lane dual-carriageways roads. They determined that the operating speed on the inner and outer road lanes differed statistically, therefore, separate models were created for the inner and outer road lanes. For the inner road lane, shoulder type, median type, pavement type, longitudinal slope of the previous segment and curve length were found to be statistically significant variables. For the outer road lane, shoulder type, median type, longitudinal slope of the previous segment, curve length and curve radius were found to be statistically significant variables. Also, it was shown that asphalted shoulders have an impact on higher speeds, while the lack of a guardrail in median, as well as the longitudinal slope, affect the reduction of speed.

In addition to the above, it was shown that the driver's age and gender influence the operating speed in curves. According to research by Wang et al. (2018) [52], younger drivers (25 years and younger) drove an average of 2.25 km/h faster than other age groups. Likewise, men drove an average of 1.13 km/h faster than women.

It should be noted that many studies have established that the speed in a horizontal curve is influenced by the incoming tangent, therefore road segments in which there are combinations of horizontal curves and tangents are often analysed. This is covered in more detail in the next sub-chapter.

### 3.2 Horizontal curves and tangents

Although the largest number of studies was dedicated to predicting the operating speed in horizontal curves, part of the research examined the operating speed of the transition from a tangent to a horizontal curve and vice versa. Also, a smaller number of studies predicted operating speeds separately on tangents [25, 30, 34, 35, 46, 70, 71].

In the context of this paper, tangents can be defined as road segments on which drivers achieve and maintain the desired speed, depending on the length of the segment itself [70]. Accordingly, the tangent length proved to be a statistically significant variable in most studies [30, 35, 49, 50, 65, 70] (*Figure 5*).

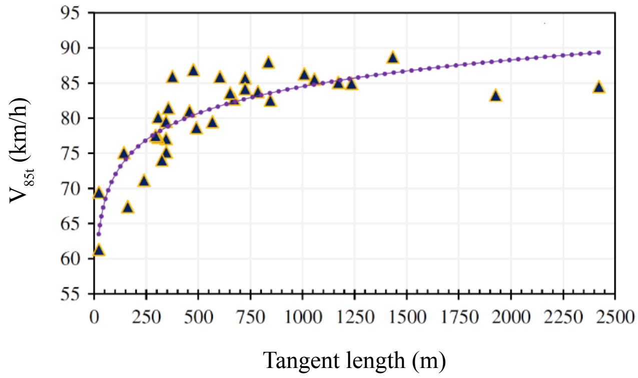


*Figure 5 – Relationship between tangent length and operating speed [70]*

According to Zuriaga et al. (2010) [48], operating speed cannot be achieved on tangents shorter than 90 metres. Malaghan et al. (2020) [70] determined that the stronger initial acceleration ends after 250 metres of the length of the tangent, after which the acceleration is gentler until the operating speed is reached. The above was also concluded by Dell'Acqua et al. (2007) [35] who conducted research on tangents from 50 to 750 metres long preceded by horizontal curves. The authors found that the operating speed on a tangent depends on the tangent length and the operating speed on the previous horizontal curve. On the other hand, Fitzpatrick et al. (2005) [34] conducted research in urban and extra-urban areas and found a strong correlation between the set speed limit and the operating speed on tangents. Other parameters that showed an impact on the operating speed are the access density, median type, the presence of parked vehicles and pedestrians. The number of pedestrians was inversely proportional to the operating speed. Also, on the extra-urban tangents, it was shown that the pavement width proportionally affects the operating speed. Contrary to research [75–77], Fitzpatrick et al. (2005) [34] did not find a statistically significant relationship between operating speed and road lane width. Maji et al. (2020) [46] conducted research at 251 locations in Oklahoma and created three operating speed prediction models for roads with a higher speed limit (80–105 km/h), for roads with a lower speed limit (56–72 km/h) and for roads with various speed limits, the last of which proved to be the most accurate. The most statistically significant variables were the set speed limit and the skid resistance of the pavement for roads with all speed limits. On the other hand, for roads with lower speed limits, only the set speed limit turned out to be a statistically significant variable. In the case of roads with higher speed limits, the most statistically significant variables were the set speed limit, the IRI (International Roughness Index) and the skid resistance of the pavement. The last two variables proved to be inversely proportional to operating speed. The assumption is that greater roughness and unevenness of the road surface reduces driving comfort, which means that drivers reduce their speed.

In addition to models separately for horizontal curves and separately for tangents, it is also important to show research on road segments with a combination of horizontal curves and tangents, i.e. transitions from a horizontal curve to a tangent and vice versa. Similarly to the model for predicting operating speed in horizontal curves, the radius of the horizontal curve turned out to be one of the statistically most significant variables [25, 30, 32, 47, 49–51, 61–65, 67].

Along with the radius of the horizontal curve, curvature change ratio proved to be particularly significant on roads that were designed with few tangents and many horizontal curves [32]. Hashim et al. (2016) [30] determined the highest speeds on the tangent which decreased suddenly just before entering the curve and increased suddenly when exiting the curve. Similar results were obtained by Dell'Acqua et al. (2007) [35] who conducted a survey of segments where the tangents (lengths from 50 to 750 metres) were preceded by horizontal curves. The authors found that the operating speed on a tangent depends on the tangent length and the operating speed on the previous horizontal curve. Memon et al. (2012) [49] concluded that drivers slow down when entering a curve and achieve the lowest speed in the middle of the curve. Thereat, the curve length, the radius of the curve and the operating speed on the incoming tangent were found to be the most significant variables. According to Zuriaga et al. (2010) [48] the operating speed on the tangents between horizontal curves is affected by the visibility length. Namely, the authors found that drivers on sections with shorter visibility tend to slow down in order to reduce the possible braking distance in the event of an obstacle on the road. Furthermore, drivers perceive a curve already at a distance of 200 metres, after which they begin to slow down in order to achieve a speed at which they can continue driving through the curve [50].

In a transition from a tangent to a horizontal curve and vice versa, the tangent and the horizontal curve are successive geometric elements of the road route. Namely, according to Lamm et al. (1999) [78] if the difference in speed is less than 10 km/h due to successive geometrical elements of the road route, it is considered a "good design solution". If the speed difference is between 10 and 20 km/h, it is considered an "acceptable design solution", and if the speed difference is greater than 20 km/h, it is considered a "bad design solution". Accordingly, to determine the consistency of the design solution regarding the operating speed, some authors examined the difference between the operating speed on a tangent and the operational speed in a horizontal curve ($\Delta V_{85}$). It turns out that $\Delta V_{85}$ will not show a real speed reduction since they are different on the tangent and in the horizontal curve. In addition, a driver who corresponds to the 85$^{th}$ percentile of speed on a tangent may not be the same for the 85$^{th}$ percentile of speed on a horizontal curve. For this reason, the 85$^{th}$ percentile speed differential ($\Delta_{85}V$) was used. $\Delta_{85}V$ is the 85$^{th}$ percentile of the speed difference between a tangent and a horizontal curve [70]. In other words, after calculating the difference in speed on the tangent and in the horizontal curve for each driver, these differences are sorted in order from the smallest to the largest and $\Delta_{85}V$ represents the 85$^{th}$ percentile of the speed differences thus ordered. Following the above, some authors determined $\Delta V_{85}$ and $\Delta_{85}V$ and then compared them [48, 62, 70]. In all three studies, $\Delta_{85}V$ was slightly higher than $\Delta V_{85}$. During the development of the model based on $\Delta_{85}V$, a strong negative correlation with the radius of the horizontal curve was determined, which indicates that by reducing the radius of the curve, the difference between the operating speed on the tangent and the operating speed in the horizontal curve increases. Also, some authors investigated another parameter, the 85$^{th}$ percentile of maximum speed reduction (85MSR). The above refers to the 85$^{th}$ percentile of all recorded differences between the highest speed a driver achieves on a tangent and the lowest speed they achieve in a horizontal curve. In order to obtain relevant data, it is necessary to use speed collection methods in all parts of the road segment (e.g. GPS system). In other words, obtaining 85MSR is not possible by pointwise speed data collection. Therefore, Zuriaga et al. (2010, 2013) [48, 62] used a GPS system to collect speed data to determine the relationship between 85MSR and various geometric characteristics. It was found that the radius of the horizontal curve and the curvature change ratio have a statistically significant impact on 85MSR [24]. Memon et al. (2012) [49] found that maximum speed on tangent, radius of horizontal curve and curve length were the most significant variables impacting the 85$^{th}$ speed in the middle of horizontal curve. A similar study was conducted by Bella et al. (2014) [63] and it was determined that the tangent length and the deflection angle are the most significant variables at 85MSR.

### 3.3 Vertical curves and/or slopes

One part of research was conducted only on vertical curves [29, 79] while the other part examined the combination of horizontal and vertical curves and/or vertical slopes [38, 42, 55]. At the same time, it should be noted that the research were predominantly carried out on single-carriageway two-way roads where greater longitudinal slopes are possible.

The research, conducted by Chen et al. (2017) [79], found the longitudinal slope as a statistically significant variable. Boroujerdian et al. (2016) [29] carried out a study on 21 uphill and downhill tangents in Iran, where they included two groups of vehicles in the study; passenger cars and trucks. The research showed that the initial speed and the set speed limit as well as the longitudinal downhill slope of the tangent are statistically the most significant variables on the downhill tangents. Also, the longitudinal downhill slope up to 3% on tangent had the effect of increasing the speed. With a greater increase in the downhill slope, decreases in speeds were recorded. Almost the same results were obtained for the uphill tangents. At the same time, it was shown that the length of the uphill direction up to 380 metres affects the increase in speed, after which it starts to fall. On convex curves, visibility length and set speed limit found to be the most significant variables [80]. In addition to the above, it should be noted that a statistically significant difference between the speeds of passenger cars and trucks was established, with higher speeds recorded for cars on the downhill as well as the uphill [29].

Yan et al. (2017) [42] conducted a study on multi-lane dual-carriageway roads in China, covering both passenger cars and trucks. As part of their model, the longitudinal slope turned out to be a statistically significant variable. It was shown that the speeds varied less when the longitudinal slope changed from -2% to 2%, i.e. they varied more when the longitudinal slope was greater than 3% or -3%. The smallest changes in speeds were recorded on longitudinal slopes from -1% to 1%, which were shown not to be perceived by drivers as longitudinal slopes at all. Similar results were obtained by Llopis-Castello et al. (2018) [68] who conducted research on trucks. The authors found that the radius of the horizontal curve and the longitudinal uphill slope greater than 3% in the zone of the horizontal curve affect the operating speed. At the same time, the longitudinal slope had a greater impact on loaded than on empty trucks. The longitudinal downhill slope did not prove to be statistically significant, although minor changes in speeds were recorded.

Wang and Wang (2018) [43] conducted an examination of the change of operating speeds on four different combinations of vertical routing of a road: a combination of an uphill longitudinal slope and a horizontal curve; a combination of a downhill longitudinal slope and a horizontal curve; convex curve on tangent; concave curve on tangent. In doing so, the authors investigated the influence of the geometric parameters (length of the segment, longitudinal slope, vertical curvature rate) of the road infrastructure on the increase or decrease in speed. The lowest rate of speed reduction was found with the combination of a downhill longitudinal slope and a horizontal curve. Combinations of uphill longitudinal slope and horizontal curve showed the least variability of speeds. The largest percentage of speed reduction and the smallest percentage of speed increase were recorded for convex curves on tangents. The lowest percentage of constant speed and the highest percentage of speed increase were found on concave curves. In addition to the above, the authors state that the characteristics of adjacent segments also have a significant impact on speed changes.

### 3.4 Models based on artificial intelligence

Even though most operating speed prediction models are statistical, in recent years operating speed has begun to be predicted using artificial intelligence methods. Ma et al. (2015) [44] first proposed a LSTM (Long Short-Term Memory) neural network model for traffic speed prediction using data obtained through microwave traffic detectors installed on Beijing avenues. The authors used mean absolute percentage error (MAPE) and mean squared error (MSE) as efficiency measurement parameters. Similarly, Wang et al. (2019) [73] collected traffic data in Xuancheng (China) for 90 days on a road network consisting of 112 road segments that were used for deep learning purposes and for subsequent validation of the results. The authors proposed a deep learning framework based on the classification of the road network into critical segments, which helps in extracting variations in traffic flow. Each thus separated critical segment is modelled with a bidirectional long short-term memory neural network (Bi-LSTM NN).

The disadvantage of the LSTM model is that it cannot extract the spatial features of traffic data and has poor results in predicting with multiple road segments. To better extract the spatial features of the data, some scientists use a convolutional neural network (CNN) [45, 81]. Ma et al. (2017) [45] used CNN for speed prediction in their research in Beijing, where their model learned traffic as images, which can achieve better extraction of spatio-temporal traffic features. The authors converted the traffic dynamics of time and space into 2D images through a time-space matrix (according to the horizontal axis as time and the vertical axis for each road), each unit of which stores each section of the road and the traffic speed at a certain time. Accordingly, they obtained spatio-temporal correlation of traffic flow through CNN.

In the above research, speed is predicted mostly based on traffic conditions, while the impact of the driver-vehicle-road system on the actual speed profile is ignored. To compensate for the aforementioned shortcomings, Li et al. (2018) [72] established an SVM (Support Vector Machine) model based on a genetic algorithm for traffic speed prediction, using various factors of the driver-vehicle-road traffic system, such as driving habits (driver), vehicle condition (vehicle), geographic information (road) and traffic flow (traffic). Urban, extra-urban roads and motorways were analysed. The authors used the root mean square error (RMSE) and the correlation coefficient R as efficiency measurement parameters. They concluded that their optimised SVM model based on the genetic algorithm is more accurate than other artificial intelligence algorithms.

## 4. DISCUSSION AND CONCLUSION

Operating speed is an element that undoubtedly has its role in road safety, and its increase contributes to the probability of a road traffic accident and its more serious consequences. On the existing, already built roads it is possible to measure operating speed using different methods, however, on newly designed roads it can only be predicted. This alone imposes the necessity of safe design in a way that the element of operating speed is included in the design solution. Accordingly, numerous studies have approached the development of operating speed prediction models.

As part of this review, the most significant worldwide research on operating speed prediction models were analysed. Most of the existing models are stochastic, but in recent years methods based on artificial intelligence have started to be applied. The majority of the research was based on extra-urban single-carriageway roads with one road lane for each direction, while part of the research also investigated dual-carriageway roads. In addition, it should be noted that the research was dominantly related to horizontal curves and tangents, and less to vertical curves. The research was conducted as a correlation between the road (and its surroundings) and operating speed. Accordingly, in most of the research, the radius of the curve turned out to be the most significant independent variable when it comes to horizontal curves, and in the case of tangents, the speed limit and the tangent length. Although a smaller number of studies were conducted on vertical curves, the longitudinal slope turned out to be statistically the most significant variable when exceeding 3%.

Given the aforementioned, potential further research conclusions could include the following:

1) Previous research has covered parameters related to operating speed and its impact on road safety, but further research is possible to further expand this area. For example, a small number of studies have been conducted at locations with different combinations of vertical curves, so it would be fruitful to examine the effect of constant vertical slope and combination of concave and convex curves on operating speed. Also, no research was found that examined operating speeds for roads with a 2+1 road profile with alternating overtaking lanes in one or the other direction. In addition to the above, the influence of oncoming vehicles from the opposite direction, i.e. passing-by vehicles, on operating speed is not known. Although research has established a correlation between operating speed and traffic equipment and signalling, the tests are not detailed enough. For example, no comparisons were made of curves of the same radii with the same design elements, but with different presence/lack of traffic equipment and signalling (for example, chevron signs, traffic lane widths, guardrail, etc.).
2) Since design speed, according to most legal regulations governing the design of road infrastructure, is a parameter that defines the limit values of design and traffic-technical elements of road infrastructure, it would be rather interesting to test its validity as a variable. In other words, it would be useful to examine the correlation between design speed and operating speed.

3) In addition to the aforementioned research on the influence of road infrastructure, i.e. the characteristics of the road and its surroundings on operating speeds, some researchers have turned to the human, i.e. the driver, as the main factor. According to Eboli et al. (2015) [65] the main control element in the traffic system is the driver who specifically determines the direction and speed of the vehicle at every moment during driving. Similarly, Lobo et al. (2018) [69] state that speed is one of the most important factors in traffic and that the driver's perception of operating speeds on different road routes, and thus travel time, strongly influence the driver's choice of route as well as the traffic situation consequently. Those are some of the reasons why certain authors studied the drivers' behaviour [38], [54] or used driving simulators as measuring devices for predicting the operating speed. In simulated situation, it is possible to create a controlled environment under predetermined conditions that are applicable to all subjects, collect data on driving patterns, and investigate interactions between drivers and road features, especially the geometric characteristics of the road alignment [48, 50, 63]. Maji and Tyagi (2018) [39] point out that in many cases, emotional state and physical exhaustion are the reasons for the decline in the ability of drivers, especially professional ones. As it is clear, according to the above, that the driver themselves have the greatest influence on the operating speed, it would be interesting to make a comparison of the operating speeds of the same drivers on roads of the same or almost the same characteristics, but in different countries or in different environments.
4) It follows from the above that some of the differences in operating speed prediction models can be attributed to different patterns of driving behaviour [41]. Moreover, Özkan et al. (2006) [28] compared the differences in (aggressive) driving behaviour of drivers of different nationalities and cultures, specifically between Finnish, British, Greek, Iranian, Dutch and Turkish drivers. They found that Greek drivers committed aggressive offenses more often than other nationalities and that they showed more anger and intolerance towards other road users. British, Dutch and Finnish drivers proved to be the least aggressive of the tested nationalities, while Iranian and Turkish drivers were placed between the previously mentioned two groups. Consequently, it can be concluded that in different nationalities and cultures there are different patterns of behaviour in traffic that undoubtedly affect the operating speed [25]. Taking into account the above fact, it can be concluded that the pattern of driver behaviour in one country and its influence on operating speed is not the same as in other countries or cultures. Consequently, the applicability of the models created so far on roads in different countries/cultures is questionable.

Although the number of research on operating speed based on artificial intelligence has increased in recent years, no work was found that was based on the principle of big data. Therefore, further research where big data were based on artificial intelligence would be interesting.

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**Modeli predviđanja operativnih brzina kretanja vozila**

## Sažetak

Brzina kretanja vozila jedan je od glavnih čimbenika koji utječu na nastanak i težinu posljedice prometnih nesreća. Operativna brzina se između ostalog može definirati kao stvarna brzina kojom se kreće najveći broj sudionika u prometu u uvjetima slobodnog prometnog toka. Ona se može izmjeriti na postojećim cestama, međutim, na novoprojektiranim cestama se može samo predvidjeti. Iz tog su razloga mnogi istraživači ispitivali korelaciju između elemenata ceste i njene okoline te operativne brzine. Utvrđivanjem korelacije kreirani su modeli predviđanja operativne brzine. U sklopu ovog rada analizirani su najznačajniji modeli predviđanja operativne brzine. Dakako, najveći broj modela su stohastički, ali posljednjih su godina kreirani i modeli bazirani na umjetnoj inteligenciji, točnije na dubokom učenju. Shodno navedenom, cilj ovog rada je pregled modela predviđanja operativne brzine kretanja vozila uz utvrđivanje mogućnosti za daljnja istraživanja i unaprjeđenje ovog područja.

## Ključne riječi

operativna brzina; modeli predviđanja; sigurnost prometa; cestovna infrastruktura.