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Analysis of Stopping Sight Distance (SSD) Parameters: A Review Study

Christian J. R. Samson[a], Qinaat Hussain[a], Wael K. M. Alhajyaseen[a,b,∗]

[a] Qatar Transportation and Traffic Safety Center, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar
[b] Department of Civil & Architectural Engineering, College of Engineering, Qatar University, PO Box 2713, Doha, Qatar

Abstract

Stopping sight distance (SSD) is one of the important elements in geometric highway design, which relies on the two key parameters, i.e., vehicle braking characteristics and drivers' reaction time. Previous studies have shown higher discrepancies in the coefficients of the SSD parameters, and therefore, making it difficult for practitioners what values to be followed. Therefore, this review study aims to compare deceleration rates and PRT values in different situations that can be applied to geometric highway design. To this end, two electronic databases were searched and relevant articles that reported drivers' perception reaction time (PRT) or deceleration rates in different situations were identified and included in the review. The obtained results showed that deceleration rates of vehicles ranged from 0.49 m/s^2 to 8.76 m/s^2 with a total weighted average of 2.82 m/s^2. On the other hand, PRT of drivers ranged from 0.48 seconds to 2.01 seconds, with a total weighted average of 1.21 seconds. The key factors that were assessed on deceleration rate of vehicles are surface condition; vehicle type; stimulus; and initial speed. Results of this study suggest that all these factors, except for initial speeds greater than 80 km/h, have a significant effect on deceleration rates of vehicles. The findings of this study could be used as inputs in geometric highway design calculations under different conditions.

1. Introduction

The World Health Organization (2018) has reported that 1.35 million people die each year on roads around the world. Road traffic fatalities is also ranked as the top cause of death for 5-29 age groups. Approximately 90% of road

∗ Corresponding author. Tel.: +974 44 03 66 79, Fax: +974 44 03 43 02
E-mail address: wyaseen@qu.edu.qa

crashes occur due to human error (i.e. speeding, distraction, and aggression) [1]. Together with the human error, other primary contributory factors that must be considered for safe roadway operations include vehicle, and roadway. Stopping sight distance (SSD) is a crucial factor that is used in highway design as it determines the available distance to stop and avoid obstruction.

According to the Green Book by the American Association of State Highway and Transportation Officials (AASHTO), the length of the road upfront and visible to the driver is referred to as sight distance [2]. On a road, the available sight distance should be sufficient for a vehicle traveling at or near the design speed to come to a complete stop before encountering a stationary obstacle in its path [2, 3]. SSD is the minimum sight distance required for a driver to stop the vehicle without colliding with upfront objects [2, 3].

As per AASHTO, the SSD can be computed in two different ways (eq. 1: highway is not on grade, eq. 2: highway is on grade):

$$SSD = 0.278Vt + 0.039 * (v^2/a) \tag{1}$$

$$SSD = 0.278Vt + v^2/[254 * ((a/9.81) \pm G)] \tag{2}$$

where "SSD" is the stopping sight distance (m); "v" is the design speed (km/h); "t" is the brake reaction time (s); "a" is the deceleration rate (m/s^2); and G is the grade rise/run (m/m)

The parameters depicting the SSD depends on the vehicle speed, perception-reaction time (PRT), and the deceleration rate. AASHTO sets the threshold deceleration rate and PRT at 3.4 m/s^2 and 2.5 seconds, respectively [2]. However, recent studies show that modern day vehicles can achieve higher deceleration rates due to the technological advancements, e.g., anti-lock braking systems (ABS) [4]. The aim of the ABS braking system is to prevent wheel locking during braking, that is, to guarantee that braking forces are distributed evenly across the wheels based on their cohesiveness with the surface. In general, vehicle braking is a complex procedure that differs in multiple situations. For instance, the deceleration behavior of passenger cars is higher compared to trucks due to the large difference in momentum (where a truck requires more work to stop) [5]. In addition, some studies indicate that vehicles traveling at higher speeds usually achieve higher deceleration rates [5, 6].

As for PRT, it can vary in different situations, for instance, an alerted and undistracted driver would react faster to a road event compared to distracted drivers [7]. Hence, it is crucial to determine coefficient for PRT under different conditions.

The AASHTO SSD model and those used in other countries have a lot in common. The PRT and the braking coefficients utilized at varied design speeds are the key assumptions in establishing the required SSD. Except for Australia (for greater speeds alone), Canada, South Africa, and AASHTO, which all use 2.5 sec for PRT, most nations utilized a PRT of 2.0 sec for rural roads [3].

Certain discrepancies can be found in the coefficient values of the SSD parameters. |These discrepancies could be due to the different situational aspects considered by each study, such as, the experimental procedure, type of data collection (driving simulator, controlled test-driving, naturalistic data etc.), scenario (distracted or undistracted), vehicle type (passenger cars or trucks), sample size etc. Nevertheless, literature review of relative studies that can be applied to traffic engineering design will be considered in this paper.

The main objective of this review is to understand the underlying factors that could affect the coefficient values of the SSD parameters (i.e., deceleration rate and PRT) and to increase the power and precision of these parameters for different situations. The outcomes of this study could be useful for models that consider SSD parameters under different situations, which can be applied to traffic engineering design.

2. Methods

Establishing search, inclusion, and exclusion criteria for our review study is a required practice to select relevant articles for determining appropriate values of the SSD parameters. Studies that report deceleration rates and/or PRT values of vehicles and drivers, respectively, in different situations will be included in the review.

Two electronic databases (SCOPUS and Google scholar) were used to search for relevant studies. To narrow the search criteria and include only relevant articles, comprehensive search terms were used. The search criterion was set as searching the term ("reaction time" OR deceleration) in the article title. In addition, to include relevant articles, the search terms such as (driving OR road* OR vehicle* OR traffic OR car*/title, abstract, keywords) were added to the

search criterion. Additional studies were found by searching reference lists from the included research and previously published reviews.

After conducting the search, we have excluded many articles based on their title and/or abstract that helped in identifying relevant articles that studied SSD parameters (deceleration rate and PRT). The included studies contained at least one of the two SSD parameters. Studies that were not reporting coefficient values for deceleration rate and/or PRT clearly (i.e., a graph with no stated values; or incomplete data) were excluded. Moreover, if the SSD parameters provided was not a specific value, but rather in a range, then average values were computed. In addition, it was important to ensure that all selected articles were related to road environments. There were some studies irrelevant to road environments (i.e. reaction times of people to an event who are not physically in a vehicle or driving simulator) that were also excluded from this review study. Next, articles that provided data from driving simulator experiments were only considered for PRT, not for deceleration rates of vehicles. This is to ensure that we evaluate deceleration capabilities of vehicles in the real-world scenarios.

After the inclusion of relevant studies, following data was extracted from each study: year of publication, sample size, country of data collection, pavement condition (dry/wet/slippery), tangent/curve, initial speed (km/h), data type (test-driving/naturalistic data/driving simulator), ABS (yes/no), vehicle type (passenger car/truck/mixed), stimulus (expected/unexpected event and/or emergency/normal braking), distraction (distracted/undistracted),complexity (simple/complex), mean deceleration (m/s^2), and mean PRT (secs).

3. Results and discussion

3.1. Analysis of deceleration rate

All comparative information of deceleration rates is enlisted in Table 1. A total of 13 studies were included that reported deceleration rates of vehicles. It can be read from the table that these rates differ extensively between the studies ranging from 0.49 m/s^2 to 8.76 m/s^2, which could be due to the different situational aspects considered by the studies. After categorizing the studies that reported the deceleration rates under common situational aspects, we calculated weighted average for each aspect, i.e., surface condition, vehicle type, stimulus, and initial speed. The weighted average was calculated by the sum of all the deceleration rates multiplied by their sample size, then divided by the sum of the sample size. Fig. 1 presents boxplots for each situational aspect together with the weighted average values for each situational aspect. The calculated weighted averages of deceleration rates are useful to differentiate between various situational aspects. As can be seen from the figure, the overall weighted average was equal to 2.82 m/s^2. Higher weighted average of deceleration rate (7.36 m/s^2) was obtained for a dry surface condition compared to the wet surface condition (3.87 m/s^2). This was expected since a dry surface condition can result to a larger mean deceleration rate for a vehicle during braking maneuvers since more time is required for the tires to achieve the required friction [8]. In addition, we obtained higher weighted average for the expected emergency braking, which could be due to the fact that participants were instructed to perform an emergency braking maneuver for an expected event [9]. In addition, test driving experiments with passenger cars achieved greater deceleration rates compared to other vehicle types (i.e., a truck) due to the large difference in mass. A vehicle with a large mass will require more work to stop than a vehicle with a small mass [5].

3.2. Analysis of PRT

All comparative information of driver PRT's from the 10 included studies are enlisted in Table 2. It can be read from the table that these PRT's differ between the studies ranging from 0.48 seconds to 2.01 seconds. After categorizing the studies that reported the PRT under common situational aspects, we calculated weighted average for each aspect, i.e., distraction, complexity, and stimulus (see Fig. 2). The overall weighted average of the PRT was 1.21 seconds. When it comes to the different situational aspect, lower PRTs were obtained by the drivers that were undistracted while driving and/or responding to an expected and simple road event. If a driver is distracted (such as using a mobile device or listening to music), less attention is allocated to the road while driving and that would result to a higher PRT [10]. Moreover, drivers require a longer time to react to an unexpected signal compared to an expected signal [11].

Table 1 Deceleration Rate Summary from Published Literature

[Source] (Year)	Sample size	Country	Pavement condition	Tangent/ curve	Initial Speed (km/h)	Data type	ABS	Vehicle type	Stimulus	Mean deceleration rate (m/s^2)
[6] (2007)	10	Lithuania	Dry	Tangent	40	TD	Yes	Passenger cars	Ex. + Eme.	8.00
					60					8.41
					80					8.76
					40		No			7.00
					60					6.89
					80					6.66
[8] (2010)	23	USA	Dry	Tangent	48	TD	Yes	Tractor	Ex. + Eme.	5.51
					97					4.59
			Wet	Curve	48					1.79
							No			1.37
[12] (2021)	2202	Canada	---	Tangent	Varies	ND	---	Mixed	Ex.	2.22
[13] (2010)	64	USA	---	---	72	TD	Yes	Passenger cars	Ex. + Eme.	6.18
	11								Unex. + Nor.	4.71
	58								Ex. + Nor.	4.31
[5] (2016)	3982	India	Dry	Tangent	92-100	ND	---	Passenger cars	Ex.	3.35
	5808				61-91					2.52
	902				20-60			Trucks		0.49
[14] (2007)	180	Italy	Dry	---	---	TD	Yes	Passenger car 1	Ex. + Eme.	6.35
	50							Passenger car 2		7.10
	180				---		No	Passenger car 3		8.14
	180						Yes	Passenger car 4		8.21
[15] (2017)	23	USA	---	Tangent	---	TD	Yes	Passenger car	Ex. + Eme.	5.39
[3] (1997)	26	USA	Dry	Curve	88.5	TD	Yes	Passenger car	Ex. + Eme.	5.30
				Tangent						5.59
			Wet	Curve						5.00
				Tangent						5.39
[16] (2007)	10	Poland	Dry	---	40,60 and 80	TD	Yes	Passenger car	Ex. + Eme.	7.45
[17] (2009)	35	Japan	---	---	Varies	ND	---	Mixed	Ex. + Nor.	3.92
[18] (2012)	110	India	Dry	Tangent	92-100	ND	---	Passenger cars	Ex. + Nor.	1.20
	61				20-60			Trucks		0.49
[19] (2005)	100	USA	---	Tangent	40-50	ND	---	Passenger cars	Ex. + Nor.	2.4
					50-60					2.39
					60-70					2.67
					70-80					2.52
					80-90					2.55
[4] (2021)	14	Turkey	Wet	Tangent	30, 60	TD	Yes	Passenger car	Ex. + Eme.	4.85

Note: "TD" means Test Driving; "ND" means Naturalistic Data; "---" means the covariate was not mentioned in the

study; "Ex." and "Unex." means expected and unexpected events, respectively; "Eme. and Nor." means Emergency and Normal braking, respectively
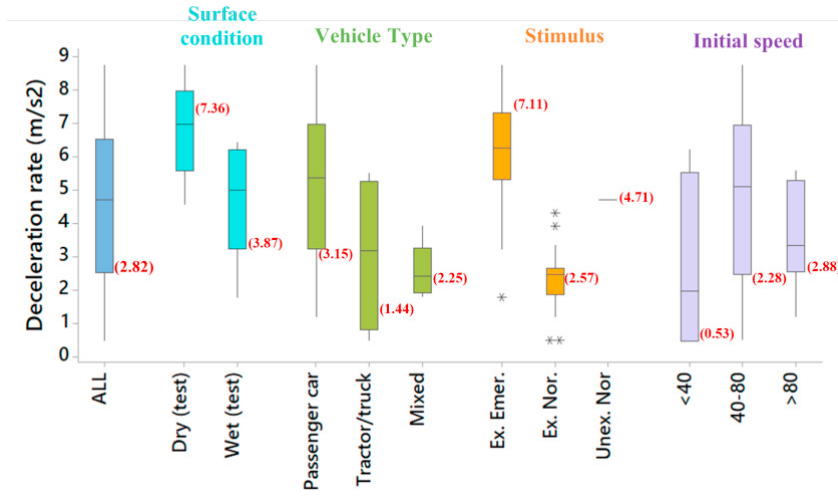

Fig. 1. Boxplots of Deceleration rates (m/s^2); the values between brackets indicate weighted average

Table 2 PRT Summary from Published Literature

| [Source] (Year)	Sample size	Country	Data type	Distracted/Undistracted	Complexity	Stimulus	Mean PRT (seconds)
[7] (2013)	94	Sweden	ND	Distracted	Complex	Ex. + Unex.	1.55
				Undistracted			1.3
[20] (2020)	15	Poland	TD	Undistracted	Simple	Ex.	0.775
[21] (1986)	64	USA	TD	Undistracted	Complex	Unex.	1.6
[22] (2018)	50	South Korea	DS	Undistracted	Complex	Ex.	2.01
[23] (2014)	30	Poland	TD	Undistracted	Complex	Unex.	0.65-1.6
[24] (1960)	87	USA	TD	Undistracted	Simple	Ex.	1.14
[25] (1982)	1,644	USA	ND	Undistracted	Complex	Unex.	1.21
[10] (2009)	27	USA	DS	Undistracted	Simple	Ex.	0.59
				Distracted (cellphone)	Complex		0.64
[13] (2010)	64	USA	TD	Undistracted	Complex	Ex.	0.55
[3] (1997)	26	USA	TD	Undistracted	Complex	Ex.	0.60

Note: "DS" means Driving Simulator
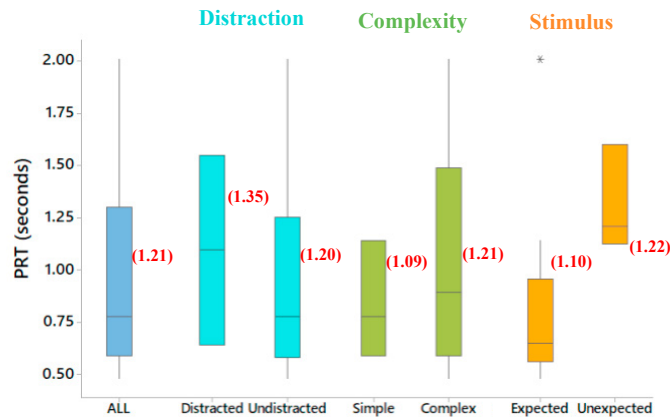
Fig. 2. Box plot of PRT's (seconds); the values between brackets indicate weighted average

3.3. Analysis of SSD

In this paper, we compared SSD curves using AASHTO's SSD formula (eq. 1) under four different situational aspects: surface condition; vehicle type; stimulus; and initial speed (see Fig. 3). The SSD curves in Fig. 3 were developed by taking speed as a continuous variable from 0 to 100 km/h, together with the different values of weighted deceleration rates that were computed for different situational aspects. In addition, t-tests [un-paired/two-tailed] were conducted to investigate significant differences between the different cases (e.g. wet vs. dry) for each situational aspect (e.g. surface condition). In general, a lower SSD value indicates a higher deceleration rate or a lower PRT value. Fig. 3(a) shows the SSD curves at different initial speeds. It is important to mention that data was only considered in the SSD curves for if the article clearly states the initial speed of the vehicle before braking. Significant differences were observed for the SSD curves between the different initial speeds, i.e., <40 km/h vs. >80 km/h ($t_{(200)}=8.52$; $p<.001$) and <40 km/h vs. 40-80 km/h ($t_{(200)}=7.92$; $p<.001$). However, there was no significant difference between 40-80 and >80 ($t_{(200)}=1.55$; $p=0.12$). This establishes that a vehicle can decelerate at a higher rate when travelling in greater speeds in comparison to a vehicle travelling in low speeds. This finding is in line with Jiang et al. [6], which formed deceleration diagrams with respect to speed and demonstrated a positive correlation between deceleration rate and speed for vehicles equipped with ABS.

In Fig. 3(b), the SSD curves for the type of vehicle show a significant difference between passenger cars and trucks ($t_{(200)}=-4.80$; $p<.001$). Passenger cars can decelerate at a higher rate compared to a tractor/truck mainly due to the difference in momentum (i.e. product of mass and speed), where a truck requires more work to stop. To further reinforce this observation, a naturalistic study by Bokare et. al [5] showed that passenger cars employ higher deceleration rates compared to trucks. A road environment consisting of mixed vehicles showed significant differences and obtained higher deceleration rates than trucks ($t_{(200)}=2.96$; $p=0.003$) and lower deceleration rates than passenger cars ($t_{(200)}=-2.14$; $p=0.03$).

Participants involved in an expected event demonstrated significantly lower SSD while performing an emergency braking maneuver compared to normal braking ($t_{(200)}=-5.31$; $p<.001$) as shown in Fig. 3(c). These results also agree with Fitch et. al [13] where the drivers' mean time to maximum brake pedal position was shorter for emergency braking than normal braking. The results for normal braking events for expected vs. unexpected also showed a significant difference ($t_{(200)}=3.54$; $p<.001$) meaning that drivers require shorter SSD for the expected events. This finding agrees with Green's conclusion [9] that a surprised driver would take longer than a driver who is aware of a road event.

When it comes to the surface condition, we considered only those articles that clearly states that the vehicles' performance was tested on dry or wet surfaces. In this regard, the SSD for the dry conditions was significantly lower than that for the wet conditions ($t_{(200)}=-3.37$; $p<.001$) as shown in Fig. 3(d). This could be due to the fact that wet road surfaces can cause skidding effects and hence less friction during braking maneuvers [8].
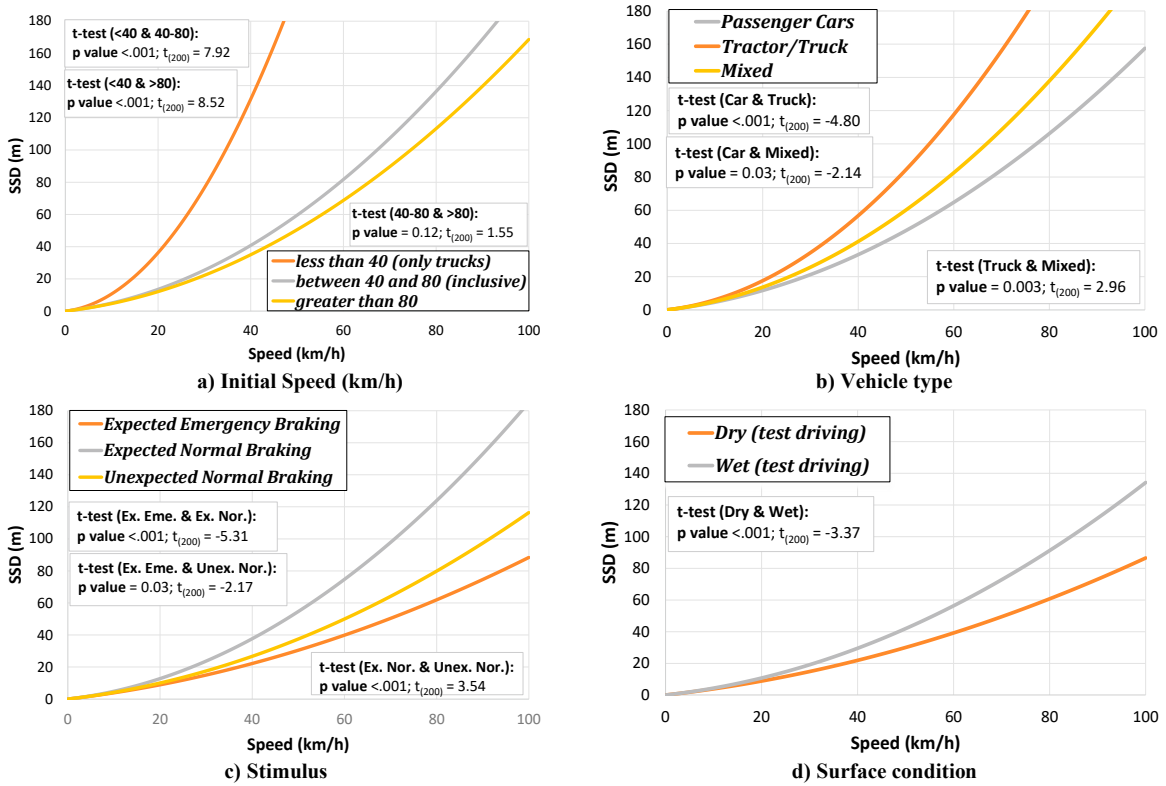
Fig. 3. Impact of decelerates rates on SSD based on different situational aspects

4. Conclusion

This study reviewed different studies that reported deceleration rates of vehicles and PRT in different situational aspects. The study was important in a way since there were higher discrepancies in the coefficients of the SSD parameters. In this regard, 23 studies were included in the review that reported either deceleration rate or PRTs. Overall, the results showed the deceleration rates ranged from 0.49 m/s^2 to 8.76 m/s^2 while PRT values ranged from 0.48 to 2.01 seconds based on the different situational aspects. The situational aspects considered by different studies extensively influence the SSD and the intensity of a braking maneuver. For instance, we observed higher SSD values for wet road conditions compared to the dry road conditions. In addition, passenger cars can decelerate at a greater rate than trucks, resulting in lower SSD values. Furthermore, the type of stimulus greatly affects the SSD, where higher deceleration rates are achieved during an expected emergency braking situation. Finally, we also observed that higher deceleration rates could be achieved if the initial speed (before braking) is higher. Practitioners searching for the coefficient values of SSD parameters for specific situations could make use of the weighted values obtained in this study. More specifically, the findings of this study could be used as inputs in geometric highway design calculations under different situational aspects.

Acknowledgement

References

[1] Lewin I. Driver training: A perceptual-motor skill approach. Ergonomics. 1982;25:917-24.

[2] Officials T. A Policy on Geometric Design of Highways and Streets. AASHTO. 2018.

[3] Fambro DB, Fitzpatrick K, Koppa RJ. Determination of stopping sight distances: Transportation Research Board; 1997.

[4] Koylu H, Tural E. Experimental study on braking and stability performance during low speed braking with ABS under critical road conditions. Engineering Science and Technology, an International Journal. 2021;24(5):1224-38.

[5] Bokare PS, Maurya AK. Acceleration-Deceleration Behaviour of Various Vehicle Types. Transportation Research Procedia. 2017;25:4733-49.

[6] Kudarauskas N. Analysis of emergency braking of a vehicle. Transport. 2007;22.

[7] Dozza M. What factors influence drivers' response time for evasive maneuvers in real traffic? Accident Analysis & Prevention. 2013;58:299-308.

[8] Bayan F, Cornetto A, Al A, Ashley D, Sauer E. Brake Timing Measurements for a Tractor-Semitrailer Under Emergency Braking. SAE International Journal of Commercial Vehicles. 2010;2.

[9] Green M. "How Long Does It Take to Stop?" Methodological Analysis of Driver Perception-Brake Times. Transportation Human Factors. 2000;2(3):195-216.

[10] Bellinger DB, Budde BM, Machida M, Richardson GB, Berg WP. The effect of cellular telephone conversation and music listening on response time in braking. Transportation Research Part F: Traffic Psychology and Behaviour. 2009;12(6):441-51.

[11] Johansson G, Rumar K. Drivers' Brake Reaction Times. Human factors. 1971;13:23-7.

[12] Fu C, Sayed T. Comparison of threshold determination methods for the deceleration rate to avoid a crash (DRAC)-based crash estimation. Accident Analysis & Prevention. 2021;153:106051.

[13] Fitch G, Blanco M, Morgan J, Wharton A. Driver Braking Performance to Surprise and Expected Events. Proceedings of the Human Factors and Ergonomics Society Annual Meeting. 2010;54.

[14] Vangi D, Virga A. Evaluation of emergency braking deceleration for accident reconstruction. Vehicle System Dynamics - VEH SYST DYN. 2007;45:895-910.

[15] Muttart J, Fisher D, Kauderer C, Bartlett W, Peck L, Guderian S, et al. Influence of Riding Experience on Glance Behavior, Brake Response Time and Deceleration Rates by Drivers and Motorcyclists2017. 461-8 p.

[16] Nagurnas S, Mitunevičius V, Jan U, Wach W. Evaluation of veracity of car braking parameters used for the analysis of road accidents. TRANSPORT. 2007;22:307-11.

[17] Naito A, Miyajima C, Nishino T, Kitaoka N, Takeda K. Driver evaluation based on classification of rapid decelerating patterns2009. 108-12 p.

[18] Maurya AK, Bokare PS. Study of Deceleration Behaviour of Different Vehicle Types. International Journal for Traffic & Transport Engineering. 2012;2(3).

[19] Wang J, Dixon KK, Li H, Ogle J. Normal Deceleration Behavior of Passenger Vehicles at Stop Sign–Controlled Intersections Evaluated with In-Vehicle Global Positioning System Data. Transportation Research Record. 2005;1937(1):120-7.

[20] Droździel P, Tarkowski S, Rybicka I, Wrona R. Drivers 'reaction time research in the conditions in the real traffic. Open Engineering. 2020;10:35-47.

[21] Olson P, Sivak M. Perception-Response Time to Unexpected Roadway Hazards. Human factors. 1986;28:91-6.

[22] Kim J-T, Kim J-Y, Jokhio S. Study on drivers' perception-reaction times against different types of traffic signals2018.

[23] Jurecki RS, Stańczyk TL. Driver reaction time to lateral entering pedestrian in a simulated crash traffic situation. Transportation Research Part F: Traffic Psychology and Behaviour. 2014;27:22-36.

[24] Gazis D, Herman R, Maradudin A. The Problem of Amber Signal Light in Traffic Flow. Operations Research. 1960;8:112-32.

[25] Sivak M, Olson PL, Farmer KM. Radar-measured reaction times of unalerted drivers to brake signals. Perceptual and Motor Skills. 1982;55(HS-036 264).