FACTORS INFLUENCING THE SPEED DIFFERENTIAL REACHED BY DRIVERS AND THE ROAD SAFETY AFTER DUSK

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Abstract

This study focuses on identifying factors that affect road safety at night. It also analyses the impact of road infrastructure on the speed differentials by drivers, on its individual elements, and provides correlations between the most important values defining the coherence of the road infrastructure design.

Key words

driving after dark, Road Safety (Road Traffic Safety), road infrastructure, road design coherence, speed differential

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1. Introduction

Research and accident databases show that the number of collisions and fatal accidents occurring on the roads after dusk is much higher than those occurring during the day. This is despite the fact that traffic at night is much lower than during the day. The average number of kilometres travelled at night is about 20% of all kilometres travelled during the day, but 40-50% of fatal accidents occur at night. This disproportion between daytime and night fatalities is even greater if one takes into account the night-time fatality rates, which are four times higher than the daytime rates [1,2]. Reports and databases [3,4]indicate that the severity of accidents is twice as high at night than during the day [5]. For example, in Italy, the average number of fatal accidents per 100 accidents is 3.4 at night and 1.9 during the day [6].Moreover, night fatality rates are higher on country roads than within cities. This is caused by worse illumination of non-urban roads and lower, relative traffic intensity, which encourages drivers to reach higher speeds, while reducing concentration, due to the greater monotony of the route, i.e. a smaller number of intersections, pedestrian crossings, islands, traffic lights, etc. The problem safety when driving at night is so serious that most of the latest road safety legislation in the European Union [7] requires member states to "ensure safety and sufficient visibility for road users under various conditions, including at night". This applies to new projects and changes to the existing road infrastructures.

2. Factors influencing road safety at night

There are a number of factors that negatively affect safety when travelling at night [1]. These include, but are not limited to: drowsiness [2], general circadian rhythm, low luminance conditions, glare, dark adaptation, road signs and markers, driver’s age and experience, general condition of the driver [3], visibility. Some researchers believe that voluntary risky decisions by drivers, especially young drivers [4], are an important factor in increasing the number of accidents at night. Drivers' vision problems related to low luminance are also a significant factor in increasing the number of accidents at night, due to the longer response time to a visual stimulus and longer information processing time [5]. Another aspect of night vision is glare [6], which can cause a temporary, significant deterioration in the driver's eyesight and a slower adaptation to the dark, which is a relatively slow process anyway.

In line with the latest approach to the road safety problems, good interaction between the user, vehicle and the road infrastructure is essential for safe road use. Road infrastructure information (usually in the form of boards and signs) supporting the mechanism behind driving the vehicle, i.e. perception-decision-action, must be easy to obtain and process in real time. In this context, driving at night places high demands on good visibility within the road infrastructure. Visibility on the roads, as well as the legibility of signs, are important components that are very helpful in achieving correct driver behaviour and meeting their expectations.

3. Elements of the road infrastructure

Elements related to the road geometry significantly affect the safety of vehicles travelling on it, regardless of the current time of day or night. Many studies on the factors influencing road safety show that the human factor, i.e. human errors, are the main causes of accidents [1], followed by road construction factors. In older studies [2] there was a theory that poor road information infrastructure at night may be one of the main causes of road accidents at night. Statistics on accidents while driving at night suggest that road conditions at night require increased attention already at the design stage of the road structure. However, modern road design criteria do not take this (night driving) into account, with the exception of concave curvature designs. In addition, the general knowledge of the road traffic and road safety at night is much poorer than that of daytime conditions. Parameters such as visibility, operating speed, road design consistency, driver abilities, perception and expectations may be more important for road safety when driving at night than during daytime driving. Especially when we take into account factors specific to night-time conditions, such as poor lighting or glare.

The driver's perception and expectations of the road shape differ significantly during a day and at night, resulting in different actions and behaviour on the same road segment during daytime and night-time driving. This applies in particular to the perceived, desired and applied speed for a given manoeuver. The ability of a road to enable drivers to move safely without surprising the driver with unexpected elements of the road infrastructure is called a coherent project. Design consistency evaluation is one of the most effective tools used by road designers to improve road safety. Inconsistent design may surprise the driver, which in turn may increase the probability of making mistakes by the driver, such as: incorrect speed selection, delayed reaction time, and dangerous manoeuvers while driving. The layout of a road is the route that it draws, defined as a series of horizontal straight sections and curves. The vertical structure of a road is defined by the profile of the road. It contains convex and concave curves and straight lines connecting them. Convex curves are those in which the position of the vehicle is lower at the start than at the end of the curve. Visually, they take the form of hills. In the case of concave curves, the position of the vehicle at the beginning is higher than at the end of the curve. A road cross-section shows the location and number of vehicle lanes, cycle lanes and sidewalks along with their lateral slope or incline. The cross-sections also show drainage elements, pavement structure and other elements not visible on the road surface.

4. Design coherence criteria and the road safety evaluation

Many factors and physical quantities related to the road design used by researchers to estimate its coherence can be found in the literature. For this purpose, terms such as operating speeds, differences in speeds reached by vehicles between individual road structural elements, vehicle stability, vehicle alignment coefficients or the mental load of the vehicle driver are used. The first two parameters seem to be the most useful in identifying anomalies in the interactions between the driver and the road [3]. Any disturbance between the designed smooth flow of vehicles on the road and the actual flow indicates a lack of coherence in the road design. Operating speed is defined as the speed chosen by drivers under conditions of free flow of vehicles. It involves taking into account, in the calculations, 85% of the vehicles with the most popular momentary speed value. from a number of measured vehicles **(V_{85})**, driving under the conditions of the free flow of vehicles on the road. The stability of the vehicle is related to the comparison between the lateral friction force that can be achieved by the vehicle and the lateral friction force required in a turn. In this respect, the inconsistency of the design means that the driver's expectations for keeping the vehicle within the lane are not being met, which could lead to the driver being unable to pass the curve without losing control of the vehicle. Lamm and colleagues [4], many years ago, developed a method for estimating the coherence of a design using the vehicle stability measurement. Vehicle alignment coefficients quantitatively describe the geometric features of a given road segment. Geometric inconsistency in the road design can occur when overall road alignment changes rapidly and suddenly in adjacent segments. Alignment factors quantify those elements of road geometry design that can most influence driver perception and behaviour, providing a simple method to measure design coherence. Driver Psychological Workload represents the level of driver attention resources required to meet both objective and subjective performance criteria, in which task requirements, external support, and prior experience may play an indirect role. This means that while driving, drivers use their mental powers to fulfil their main task of driving a vehicle along a certain route, based on their own estimates of the future conditions of mental work. The greater the estimated mental load, the more attention is given to completing the task. Therefore, a coherent roadway design allows drivers to perceive road alignment correctly, allocating a small amount of available mental resources, thus allowing a greater ability to avoid obstacles and continue navigating. The evaluation of the coherence of the design with the use of mental load is certainly the most attractive method, as it provides a direct measurement of the influence of the road condition on the driver's perception and his psychophysical condition. However, it is rather difficult to correctly determine the driver's workload without getting subjective results.

Therefore, to estimate the consistency of the road design and the safety of the vehicles travelling on it, the coefficients related to the measurement of the operating speeds reached by the vehicle and the calculation of the differences in speed reached by the drivers between the determined elements of the road infrastructure, are used.

It has long been proven that the expected and actual behaviour of drivers on the road can vary greatly. Many practical experiments have shown that the real speeds reached by vehicles on the road are much higher than the theoretical values used for calculations when designing a given road. This dependence called into question the current methods of estimating the speed of vehicles, which are then used to design road infrastructure. Therefore, the value described as operating speed - **(V_{85})** is used as the basis for the road design estimates. This value is taken as a measure of the behaviour of drivers on the road. In order to estimate the operating speed for each structural element of the road and to check whether it is higher than assumed in the road design, one needs to compute the difference in registered speed of drivers achieved in front of each horizontal road element. This is known as speed differentials. The speed differential is conventionally expressed as the difference in operating speeds between the midpoint of a straight section and the centre of the following curve **(ΔV_{85})**. The design process should be conducted in such a way as to reduce these differences to a specific, acceptable level. From the point of view of the driver's perception and road safety, the connections of the straight road and the curve are the most common and of the greatest practical importance. Large differences in speed achieved by drivers between two adjacent road elements indicate abrupt changes in road characteristics, surprising drivers, which can lead to unexpected manoeuvers and accidents. The biggest challenge is to determine the appropriate operating speeds for the geometry of the straight-curve road infrastructure at the road design stage and to determine the differences in speeds of driving through these elements. According to this approach, the most dangerous point on the road is when a straight stretch of road ends and a curve begins. Many ways of modelling operating speeds have been described. Most of them are based on the geometrical features of the road, which leads to very large differences in the values for individual models [5]. Hitherto, several parameters have been proposed for estimating the speed differential. Notwithstanding the fact that **ΔV_{85}** is considered to be the most effective, if not the only way to assess design consistency to assess road safety, Hirsh [vi] argued that simply subtracting the speed values read from the two points previously mentioned underestimates the speed reduction scale of individual drivers, because it is based on point independent velocity distributions at each measured location. Later studies confirmed this theory [7]. Therefore, it has been proposed to use other parameters, based on the determining the speed reduction for two successive road elements by each driver individually. McFadden and Elefteriadou [8] proposed a new measure - IAS 85, based on the analysis of the speed profiles of individual vehicles. The IAS 85 is defined as the 85th percentile of the distribution of the maximum speed reductions experienced by each driver, calculated on the basis of the maximum speeds of the last 200 meters of straight and minimum cornering speeds. Misaghi and Hassan [9] proposed **$\Delta_{85}V$**, defined as the difference in speed under free flow conditions, which is not exceeded by 85% of drivers. This speed differential parameter is calculated from the speeds assumed by each driver at two fixed points: at the start of the straight section, approximately 100 m before the start of the road curve, and at the halfway point of the curve. Then Bella [10] showed that computing the speed difference from the speeds recorded at two fixed locations **(ΔV_{85} and $\Delta_{85}V$)** leads to an underestimation of the speed difference. Much better results were obtained with the use of parameter IAS 85, which by definition is calculated on a certain section of the road, and not at a specific point. Consequently, it can be seen that the estimation of the speed difference largely depends on the data availability when compiling the speed profile of each driver. Today, many researchers agree that IAS 85 is one of the most effective indicators for coherent road design and road safety evaluation [xi], because it best reflects the driver's need to change speed along a stretch of the road, made up of curves and straight sections. The main reason for this claim is that, unlike **ΔV_{85}** and **$\Delta_{85}V$**, which calculate the value of the speed difference between two fixed locations, the IAS 85 ensures that the computed speed difference is the maximum taken by drivers between a straight section and a curve. Moreover, this parameter is the best indication of the difficulties of drivers in maintaining a constant speed along the route.

Despite proposing precise methods of determining the speed differential, most of them focus on driving during the day, ignoring night conditions. One of the few studies providing information on design coherence during night-time conditions was that carried out by Hu's team [12]. They developed a model of acceleration and deceleration when approaching and departing from a horizontal turn on a complex two-lane country highway under night-time conditions. The authors found that braking and accelerating while approaching and leaving a curve showed a wider range of values at night than during the day, compared to previous studies on the same type of road. Another research team [13] measured the speed differential during simulated night driving to identify critical road situations that were not detected during the road design coherence evaluation in simulated daytime driving. The analysis of the results showed that the studies of the speed differential during the day are not able to provide sufficient data to determine the hazards occurring at night.

Speed differential and determining safety

Various studies have proposed different criteria for evaluating project coherence, but relatively few of them took into account the relationship between the cohesion indicators and the actual accident rates. The most common of these interactions are the safety criteria recommended by Lamm [14], developed on the basis of the analysis of velocity and collision data using linear regression models (in particular, criterion II based on **(ΔV_{85})**. The consistency of the design is evaluated based on the value of speed reduction **(V_{85})** between successive road elements using the parameter **ΔV_{85}**. According to the criterion II of the linear regression model, a "good" road design is one in which the value of the difference in operating speeds of the 85th percentile, measured from the beginning of the straight section to the road curve **(ΔV_{85})**, is less than 10 km/h, the design is "correct", if **ΔV_{85}** is between 10 and 20 km/h and the design is "bad" if **ΔV_{85}** is greater than 20 km/h. There are no safety limits or ranges for IAS 85 or **ΔV_{85}**, that would define safety or not, although both are proven to be the most effective for determining speed differential and in consequence, the best parameters for evaluating the design integrity and safety. There are few studies in the literature that propose a correlation between the various parameters describing the speed differential phenomenon (IAS 85, $\Delta_{85}V$ and ΔV_{85}), the values of which are used as limit values for the Lamma criteria. Several mathematical models proposing the correlation between the quantities mentioned are presented below.

McFadden and Elefteriadou [21] collected vehicle speed data at 21 locations in two different geographic regions of the US. The locations were selected on the basis of several criteria in order to isolate the horizontal road curve, so that this parameter had a significant impact on the speed change of drivers. The selection criteria covered a rural area with such topography that the designed and actual speed of vehicles reached on this section did not exceed 120 km/h; lane width from 3.05 m to 3.66 m; shoulder width from 0 to 2.44 m; arch length from 90 m to 250 m; degree of curvature from 1 to 15 degrees; arc radius between 150 m and 1,800 m; straight section length greater than 200 m, traffic volume from 500 to 4,000 vehicles per day, ground level differences between -5% and 5%. The authors compared IAS 85 and ΔV_{85} in selected locations. The results showed a significant difference between the two speed differential parameters. Specifically, they found that the IAS 85 was, on average, twice as large as the ΔV_{85}. Therefore, if someone used existing operating speed models that estimate the coherence of the design, and based on the difference in speed in the 85th percentile of drivers, at a given location, in order to determine the speed reduction of 85% of drivers, one needs to multiply the expected speed difference by 1.97 according to the equation (1):

$$IAS\ 85 = 1{,}97 \cdot \Delta V_{85}. \qquad (1)$$

Park i Saccomanno [27] found that the empirical relationship between these two values is as shown in equation (2).

$$IAS\ 85 = 1{,}595 \cdot \Delta V_{85}. \qquad (2)$$

The authors recorded field data of individual vehicle speeds from 18 configurations of straight sections and curves on two-lane sections of rural highways. The site selection criteria included a number of factors: ground level with a vertical gradation of less than 4%; driving in daytime conditions; good weather conditions (dry surface, unlimited visibility); only passenger vehicles running at intervals greater than 10 s were taken into account. The average results for the parameter IAS 85 turned out to be about 1.6 times greater than the estimated results for ΔV_{85} for the same data set. Although this value is slightly lower than the results obtained by McFadden and Elefteriadou [21], the results show that the IAS 85 gives higher values than the ΔV_{85} for the straight-curve configuration.

Misaghi and Hassan [21] compared $\Delta_{85}V$ and ΔV_{85} on 20 configurations of straight sections and curves with different geometrical road design features (horizontal curve radius, length, level gradation, etc.). The locations were selected on four different two-lane sections of non-urban motorways. Several constraints also influenced the choice of location: rural area; relatively low traffic (Average Annual Daily Traffic - AADT, less than 10,000 vehicles per day); marked and paved roads with a constant lane width; no intersections controlled by stop signs or traffic light along the 0.8 km curve; lack of functionality that may create an unusual threat (e.g. narrow bridge); arc radius greater than 1200 m and total arc length greater than 100 m. The authors found the following empirical relationship between $\Delta_{85}V$ and ΔV_{85}, which is shown in equation (3):

$$\Delta_{85}V = 0{,}97 \cdot \Delta V_{85} + 7{,}55. \qquad (3)$$

In each case, it could be observed that the magnitude of ΔV_{85} caused an underestimation of the magnitude of the speed reduction at fixed locations. Bella et al. [23] used a driving simulator to calculate the numerical relationship between the above-mentioned parameters. Simulators offer many advantages when it comes to estimating a wide variety of driving factors. They ensure obtaining objective results in conditions safe for drivers, and also enable the testing of drivers' reactions in dangerous conditions, which would be unthinkable in real conditions. Moreover, many variables can be controlled in a virtual environment as opposed to real conditions. Additionally, selected road scenarios in the simulator may be identical for all participants of the experiments. It has been proven that even low-budget simulators can provide interesting answers to research questions [1].

Researchers recreated a two-lane country road, with dry surface, in the conditions of free flow of vehicles, in day and night conditions. They compared the parameters: IAS 85, $\Delta_{85}V$ and ΔV_{85}. They found the following correlations between the individual parameters:

$$IAS\ 85 = 2{,}4 \cdot \Delta V_{85}. \qquad (4)$$

$$IAS\ 85 = 1{,}08 \cdot \Delta_{85}V + 6{,}35. \qquad (5)$$

More than twice the value of the IAS parameter in relation to ΔV_{85} confirms the general relationship between these two parameters, although the difference is greater than in the other cases. The authors attribute this difference in values mainly to differences in the straight-curve configurations used to compute mathematical relationships.

The first comparison presented here is IAS 85 and ΔV_{85}, evaluated by analysing driver speed profile data obtained under daylight conditions. In accordance with all the previously presented reports [20,22,27] it was found that the IAS 85 has the greatest speed reduction value compared to other parameters. Therefore, the parameter ΔV_{85} significantly underestimates the individual speed reductions experienced by the drivers as it is based on independent speed distributions at two fixed points, rather than taking into account the speed profile of the drivers along a given straight-curve section. On the other hand, in the night conditions, even higher values of IAS 85 were obtained than in the daytime conditions. This means that the value of ΔV_{85} under night-time conditions is even more underestimated. On the other hand, taking into account the speed profiles of drivers along the entire studied section, instead of point-by-point, may be very useful for estimating the difficulties of drivers in perceiving the road infrastructure at night. This is a very important issue, because, according to what Bella and Calvi [16], wrote, limiting vehicle speed analyses only to daytime conditions may overlook the fact that some road infrastructure elements can become very dangerous at night, which cannot be seen during the day.

Based on the simulator tests on straight sections and curves in night conditions, it was shown that the driver's behaviour, both during the day and at night, depends not only on the visibility on the road, but also on the geometry of the horizontal elements of the road infrastructure. If the curve was "sharp", i.e. it had a radius below 100 m, then no significant differences were observed in the speeds reached, either during the day or at night, because the driver saw that the turn was sharp in both cases. The situation was similar in the case of straight sections of the road. If the section was less than 200 m long, the cruising speeds of the vehicles at night and during the day were also similar. This was due to the fact that the driver saw a given element of infrastructure in its entirety, whether in daylight or illuminated by the headlights. On the other hand, in the case of long curves, with a relatively larger radius, above 100 m, and straight sections with a length of more than 200 m, the situation changed. During the day, the driver had much better visibility than at night, when he could only see the headlights at a distance. Thus, the speeds reached by drivers during the day on both types of road elements were higher than at night. However, there is one aspect that is not usually included in tests on driving simulators. It is drowsiness and the natural daily cycle. Under simulated conditions, it is not possible to simulate drowsiness.

5. Summary

Taking into account both the literature reports and the available research results, it can be considered certain that night conditions are much more demanding to the drivers. This is because at night there are a number of factors that do not appear during the day, regardless of weather conditions. These include: reduced visibility, the possibility of dazzling the driver, slower reaction time, drowsiness, etc. All this increases the number of road accidents at night compared to daytime conditions. An additional problem is that, until recently, road designs did not take into account night conditions, assuming they were identical to daytime conditions. Numerous studies have shown that this assumption is incorrect. Therefore, many countries began to modify the existing ones and create completely new road designs, trying to maximize the level of road safety during the day and at night. The basis for change in the projects include studies by many researchers using driving simulators. Simulators are very useful for this type of research, as they do not expose participants to the risk of an accident, and provide invaluable data on the reactions and behaviour of drivers on the roads. The researchers used certain characteristic quantities (operating speeds, speed differentials) to capture the correlation between them. Research in the simulator has proven that road safety depends not only on the condition and skills of the driver, but also on the road infrastructure, i.e. its elements. Thus, thanks to changes in the road design, it is possible to significantly improve the road safety. There are still many aspects to be investigated, including the safety impact of factors such as the driver's overall circadian rhythm and his mental strain. These are factors that are difficult to investigate directly, so it is necessary to carefully prepare a research experiment that gives reliable, reproducible results. Another very important factor related directly to road safety is the use of telephones and other electronic devices by drivers while driving. This problem is still relevant, and the number of accidents caused by inattentive drivers is not decreasing.

Factors influencing the speed differential reached by drivers and the road safety after dusk.

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