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Measures of Functional Reliability of Two-Lane Highways

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Abstract: Rural two-lane highways are the most common road type both in Poland and globally. In terms of kilometres, their length is by far greater than that of motorways and expressways. They are roads of one carriageway for each direction, which makes the overtaking of slower vehicles possible only when there is a gap in the stream of traffic moving from the opposite direction. Motorways and express roads are dual carriageways that are expected to support high speed travel mainly over long distances. Express roads have somewhat lower technical parameters and a lower speed limit than motorways. Two-lane highways are used for both short- and long-distance travel. The paper presents selected studies conducted in Poland in 2016–2018 on rural two-lane highways and focuses on the context of the need for their reliability. The research was carried out on selected short and [longer road sections located in various surroundings, grouped in terms of curvature change rate CCR, longitudinal slopes and cross-sections (width of lanes and shoulders). The studies of traffic volumes, travel time and travel speed, as well as traffic density, will be used to analyze traffic performance and identify measures of travel time reliability. The analyzed roads were characterized by good technical parameters and significant variability of traffic volume throughout the day, week and year. Some roads experience congestion, i.e., situations in which traffic volume Q is close to or above respective road capacity C. In order to determine the form of the suitable reliability measures, it will be important to determine the extent to which a road's geometric and traffic characteristics impact travel speed and time. The paper presents well-known reliability measures for dual carriageways and proposes new measures, along with an evaluation of their usefulness in the assessment of the functioning of two-lane highways.

Keywords: reliability measures; two-lane highways; travel speed; travel time; empirical research

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1. Introduction

Reliability is a major criterion for assessing selected elements of technical infrastructure such as transmission [1], information technology (IT) [2] or energy [3] infrastructure. The reliability of road infrastructure is also the subject of many studies, because of the role the parameter plays in traffic performance [4,5] and the safety of road users [6–8]. In the case of road safety, speed tests and testing of speed's impact on road safety measures are very important. In the tests [9] floating car data were used to achieve the goal. Ensuring the reliability of road infrastructure at a level acceptable to road users is a key aspect of planning and design decisions [10,11].

There are not many reliability analyses of two-way highways in scientific literature. Instead, researchers focus mainly on dual carriageways, i.e., motorways [12–14], expressways [15–18] or other dual carriageways [19,20], inter alia, analyzing the impact of Intelligent Transport System (ITS) solutions [21–23]. In simulation analyses and field research [24], the impact of selected parameters on the level of service (LOS) under heterogeneous traffic conditions for a two-lane highway was identified. The work [25] also analyzed (LOS) on the basis of estimation of passenger car unit values. The research

[26] also pointed out the variability of traffic flow on individual road lanes. Some studies concern themselves with sections of motorways and expressways in urban areas [27–29]. Obtaining reliable data is an extremely important aspect of reliability studies. The work [30] presents various techniques for examining road traffic parameters. It compares the pneumatic tube detector method, video capturing method, moving observer method and the classic manual method. The studies [31] indicate the effectiveness of combining the moving observer method and digital image processing. The work [32] presents the effects of using stationary devices along the road to collect road traffic data. The research [33] provides an example of an effective use of video traffic monitoring. Modern techniques allow the use of Bluetooth technology to collect data on traffic parameters [34–36] and Lidar technology to collect data on road and its surroundings parameters [37–39].

Road traffic parameters depend on many factors, including the driver's psychophysiological characteristics, road and meteorological conditions [40]. A very important aspect influencing traffic conditions is constituted by road geometry, including the parameters of horizontal curves [41]. One factor related to driver behaviour is the distance between vehicles [42].

An example of research conducted on two-lane highways is provided by reliability analyses carried out on Poland's road network [43]. These studies were undertaken on higher standard roads managed by the General Directorate for National Roads and Motorways, with speed limits of 70–90 km/h, and a typical lane width of 3.5 m (with or without a hard shoulder). In Poland, these roads account for over 86% of all national roads, including motorways, expressways and accelerated main roads. According to the standards specified in the American method [44], these are first-class roads on which drivers expect travel speeds close to the speed limit. In Germany, a similar approach applies to roads with a similar function marked as EKLII and EKLIII [45].

The project [43] and work [14] also present studies on dual-carriageways, i.e., motorways, expressways and roads of lower technical class, on which speed limits in Poland are 140 km/h, 120 km/h and 100 km/h respectively. In Poland, motorways are roads of the highest technical standard, where traffic can be joined only through interchanges. In the case of expressways and other dual carriageways of the lower technical class, traffic can be joined through interchanges or through intersections (usually signalised).

The analyzed two-lane highways mainly support traffic functions typical of roads of higher technical classes, although they have a limited capacity (max. 3200 veh/h according to [44], approx. 2600 veh/h according to [45]) compared to high-speed roads (highways, expressways). Reliability, measured in terms of travel speed or time, is highly variable on the analyzed roads and depends on the time of day, day of the week or month. It also varies in the longer term (analysis by year). Therefore, it is necessary to identify the most important factors that influence their reliability levels and to indicate the best reference level for analyses conducted on two-lane highways.

The main aim of the analyses presented in the paper is to answer the research questions:

– Whether and to what extent selected traffic parameters impact the functional reliability measures of single carriageways and two-lane highways?
– Whether the measures and reference values for dual carriageways can be transplanted directly onto analyses of two-lane highways?

  An indirect aim pointing the directions of further research work revolves around answering the question of

– whether the statistical parameters describing travel time variability are sufficient to analyze and assess the reliability of a road section in a probabilistic approach that takes into account the risk of the occurrence of road incidents happening during travel speeds exceeding the speed limit?

The answers will provide the foundation for an effective transformation of the existing road network, enabling the attainment of a standard of travel that will be acceptable to road users.

The paper is divided into several parts which include a review of literature providing a description of the reliability measures used, selected results of empirical studies conducted on Poland's two-lane highways, and reliability studies conducted on a selected road section where use is made of GPS data. At the end of the paper, conclusions are drawn and directions for further work are stated.

2. Materials and Methods

2.1. Reliability Measures

Travel time reliability depends on a benchmark and therefore has no fixed value. Its value is influenced by a number of factors of various origins [46,47], including traffic factors (traffic intensity, types of vehicles), geometry, road's location and type of surroundings, the knowledge of which is necessary in order to identify the reliability process, interactions between the variables and the correct interpretation of the results.

General factors influencing road reliability include:

- The presence of traffic control–traffic signals, including in particular incorrectly designed control parameters, rail-road crossings,
- Daily, weekly or seasonal fluctuations in traffic,
- Occasional events—various types of events making the traffic flow value different from the typical values of the flow on this road (religious, public holidays, days off, etc),
- Road capacity—dependent on road geometry and a number of other factors e.g., the technical condition of road surface,
- Weather conditions, in particular snowfall, heavy or prolonged rainfall, fog,
- Road accidents and other road incidents blocking passing vehicles,
- Road works resulting in a taper of the road's cross-section, alternating traffic, temporary road blockage.

Considering the above division, it is possible to introduce a classification [48] that assigns the indicated factors to three different groups (Figure 1) on account of:

- Infrastructure, i.e., a road's geometry and its standard, including the road's curvature change rate CCR [49,50], longitudinal slope [51,52] and width [53,54] and traffic organization, including road works [55–57], temporary and permanent taper of the road's cross-section, and the presence of traffic lights [58,59],
- Road traffic, including traffic volume [60,61], its generic and directional structure [62,63] as well as road incidents [64,65],
- Road surroundings [66,67] and weather conditions [68–70].

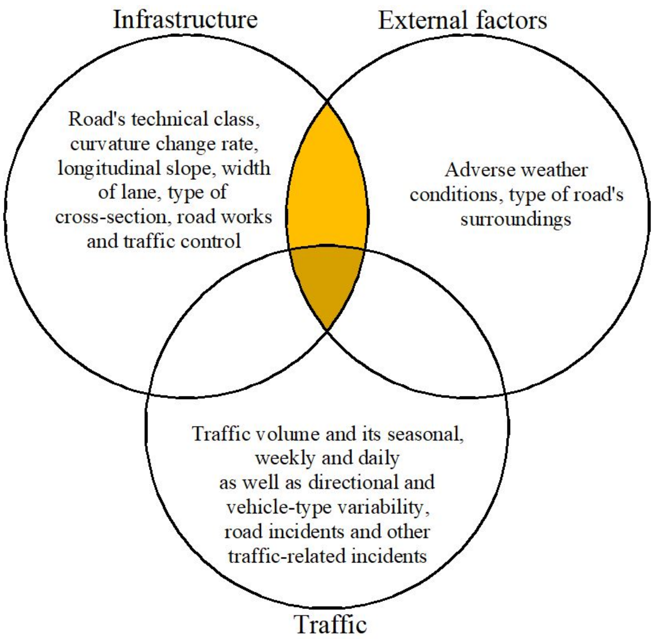

Figure 1. Interactions between sources of failure.

The diagram in Figure 1 shows interactions between the main sources of failure and the relationship between demand (traffic) and supply (infrastructure). The authors of paper [71] point out that the indicated interactions are the main determinants of road functionality. Both demand and supply vary over time, as both traffic and road capacity are influenced by various deterministic and random factors. Weather conditions, especially adverse ones, such as prolonged rainfall, snowfall, etc., have a significant impact on drivers' behaviour. The research [72–74] shows that road and intersection capacity decreases in such conditions by as much as 20%. The type of road surroundings resulting from the road's location often translates into the type of trips [75], which also determines drivers' behaviour. In cities and agglomerations where short trips, mostly related to commuting to work, shops, schools, and other facilities, predominate, the behaviour and expectations of vehicle drivers regarding traffic conditions and network reliability are completely different from such expectations outside cities, or during long-distance travel [O5] spread over a longer period of time. In the worst case scenario, all of these variables may affect travel time reliability. This situation occurs in the common sections of all three circles.

Over the past few decades, many studies have been conducted in the USA on existing roads to describe the reliability of travel times. In the research into and evaluation of reliability, generally available models were used, their modifications were created or completely new solutions were developed. Table 1 [76] shows an example of the application of reliability measures in practice, i.e., it lists selected US transport agencies and identifies indicators used by them to describe the functional reliability of roads.

Current methods of analysis [61] can be divided into:

- Statistical methods,
- Buffer time methods,
- Late travel indicators,
- Probabilistic methods,
- Skewness methods (treated as part of statistical methods in the paper).

Table 1. Reliability metrics used by selected US transport agencies

Agency	Reliability Metrics Used
	Buffer Index

Georgia Regional Transportation Authority and Georgia DOT	Planning Time Index
Southern California Association of Governments	On-Time Index
	Buffer Index
Washington State DOT	95th Percentile Travel Time
National Transportation Operations Colation (NTOC)	Buffer Index
Maryland SHA	Travel Time Index
	Planning Time Index

Below, the authors present selected methods of analysis, including their advantages and disadvantages.

2.1.1. Statistical Methods

One of the oldest approaches to the description of travel time reliability used by Abishai Polus in 1979 [77] was based on a simple measure—standard deviation δ, showing the variability of the metric's value in relation to its mean value (Equation (1)). The author was one of the first to indicate the travel time variable as the best measure with which to describe a road's functional reliability.

$$\delta = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (t_i - \bar{t})^2} \tag{1}$$

where:
n—number of travels,
t_i—i- travel time,
$\bar{t}$—average travel time.

The author defined a road's functional reliability using a measure of variability, i.e., travel time variance [78]. The higher the variance, the less reliable the road (Equation (2)).

$$R = \frac{1}{[Var(x)]^{\frac{1}{2}}} = \frac{1}{[E(x^2) - (E(x))^2]^{\frac{1}{2}}} \tag{2}$$

where: R—road's functional reliability, x—reliability measure (in this case–travel time), *Var(x)*—variance of reliability measure, *E(x)*—expected value of reliability measure.

The simplicity of the approach accounts for its advantage, while its low usefulness is a disadvantage because in most cases the empirical distributions describing the variability of travel time are not symmetrical and show considerable skewness. However, this did not prevent the development of these methods, and in subsequent editions, recommendations for reliability were developed based on the ranges of skewness as presented in publications [12,13,18]. The value of the standard deviation was used to build subsequent measures, such as the time window (Equation (3)) and the coefficient of variability (Equation (4)).

$$Time\ window = \bar{t} \pm \delta \tag{3}$$

$$Coefficient\ of\ variability = \frac{\delta}{\bar{t}} \cdot 100\% \tag{4}$$

where: $\bar{t}$— arithmetic mean of all travel times, δ—standard deviation of travel time.

The time window can have two values—one lower and another greater than the arithmetic mean by the value ±δ. The road user receives information about possible travel time discrepancies. In order to increase the scope of analyses, the δ may be multiplied.

The travel time variation coefficient can be used to compare travel time variability between days, weeks, or road sections.

A measure that allows the comparison of traffic conditions between peak and off-peak times is the index of variation (Equation (5)).

$$Index\ of\ gualitative\ variation = \frac{V_{1,+95} - V_{1,-95}}{V_{0,+95} - V_{0,-95}} \quad (5)$$

where: $V_{1,+95}$, $V_{1,-95}$—upper and lower values between which there are 95% of travel times during the peak traffic period, $V_{0,+95}$, $V_{0,-95}$—upper and lower values between which 95% of travel times lie outside the peak hours.

The index of qualitative variation may apply to roads close to urban agglomerations, where increased traffic may occur because of urban traffic peaks. Due to the larger discrepancy between the peak and off-peak traffic, the value of the index is often greater than 1.0.

2.1.2. Buffer Time Methods

The term "buffer time" means extra time added to a specific activity in order to ensure no delays and an optimum time to reach the destination [79]. In the analysis of travel time reliability, it is the additional amount of time needed for the road user to reach their destination at their desired hour with a probability of 95%, taking the arithmetic mean of all travel times [18] (Equation (6)) as the expected travel time.

$$BT = t_{95} - \bar{t} \quad (6)$$

where: t_{95}—95th percentile of travel time, $\bar{t}$—average travel time.

The 95th percentile of travel time represents the worst possible traffic situation. This means that users may experience issues resulting in travel time delays in 1 out of 20 travels. Other percentiles can also be used depending on the needs of the research, e.g., 90th or 85th percentile [80].

The buffer time index (Equation (7)) is a derivative metric. It is calculated as the ratio of the buffer time to the arithmetic mean. This variable value exceeds 1.0. For example, a value of 1.7 means that in 95% of cases it takes 70% more time than the average travel time to reach the destination at the expected time [81]. Travel time reliability decreases as the buffer time index increases.

$$BTI = \frac{BT}{\bar{t}} \quad (7)$$

where: BT—buffer time, $\bar{t}$—average travel time.

Instead of average travel time, it is also possible to use median travel time. When the analyzed road section is divided into several sub-sections due to traffic volume or other factors differentiating individual road sub-sections, then the weighted average buffer time index can be calculated (Equation (8)):

$$BTI_i = \frac{\sum_{i=1}^{n}(BTI_i \cdot Q_i \cdot L_i)}{\sum_{i=1}^{n} Q_i \cdot L_i} \quad (8)$$

where: BTI_i—buffer time index for an i sub-section of the road, Q_i—traffic volume on i sub-section of the road, L_i—length of i sub-section of the road, n—number of sub-sections.

The BT, BTI and ABTI measures can be used to assess the reliability of city street networks and routes leading to daily destinations. These measures could be incorporated into GPS navigation systems to assist drivers in route planning. Other measures derived from the buffer time method are described below.

2.1.3. Planning Time

Planning time is the total time needed to reach the destination at the scheduled time with a 95% probability. The measure is easy to interpret and allows the user to plan the trip correctly. Comparing the 95th percentile from different hours shows the variability of road functional reliability over the course of the day. The measure is also important for the road manager, who, by using the PTI value, can classify the roads under his management in terms of reliability, as well as plan the reconstruction of sensitive sections of a road to improve travel time.

Another measure derived from PT is the planning time index (PTI), which informs how many times more time the road user needs to reach the destination relative to the travel time in free-flow conditions allowing the driver full freedom in choosing the speed (Equation (9)).

$$PTI = \frac{t_{95}}{t_o} \tag{9}$$

where: t_{95}—95th percentile of travel time, t_o—travel time in conditions perceived as free flow (Equation (10)).

$$t_o = \frac{3600}{v_f} \cdot L \tag{10}$$

where: v_f—travel time in free-flow conditions (determined e.g., based on [43–45]), L—length of road section.

PTI values exceed 0. Existing literature [82] allows us to find a categorization of *PTI* values in terms of service reliability level developed for practical use by road users, as well as road managers. It is recommended that the thresholds be adapted to the nature of the road (Table 2) [67].

Table 2. Thresholds values of *PTI* for individual levels of functional reliability.

Reliability Performance	*PTI* (–)
good	≤1.3
fair	1.3 ÷ 2.0
poor	>2.0

PTI is one of the variants of TTI, or travel time index, which can be calculated for any percentile (Equation (11)) .

$$TTI = \frac{t_x}{t_o} \tag{11}$$

where: t_x—any percentile of travel time.

Literature also contains other measures relating to situations of failure, i.e., the failure measure or the misery index, which show how many times more time is needed to make the longest trips in relation to the travel time in free-flow conditions (equation 12).

$$Failure\ rate = \frac{\bar{t}_{5\%}}{t_o} \tag{12}$$

where: $\bar{t}_{5\%}$—average travel time in the group of the longest trips, i.e., the 5th percentile; the so-called misery time.

All of the above-mentioned measures can be used separately or in combination (Figure 2) [46]. The latter option is more advisable and universal because it shows the size of various reliability measures and their comparison. The use of selected measures, and at best all measures, allows for a broader view of the issue of reliability and for finding appropriate solutions to improve traffic conditions.

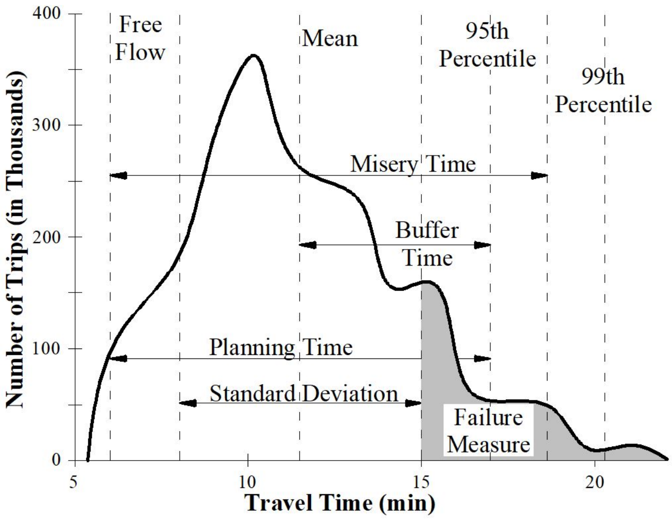

Figure 2. Chart with measures of the time buffer method.

In conducting research, it is important to select a suitable length of the road's section and research time to reflect the specific conditions on a given road and the objectives of the analyses. Time periods should be selected to reflect traffic conditions of a similar nature and intensity. It is recommended to conduct research and traffic observation on a continuous basis, using GPS devices and software. Morning and afternoon traffic peaks should not be combined in determining the 95th percentile [80].

Above the authors show selected more important measures used in the description of reliability of dual carriageways, where road features (road geometry) have a much smaller impact on driver behaviour, speed and travel time than on single carriageways, on which additionally vehicle overtaking occurs. The measures were subject to verification, analysis of variability and usefulness, and the possibility of adjusting their form to the analyses of two-lane highways. Traffic on single-carriageways is characterized by a significant variability of traffic intensity and speed over time and the presence of all types of vehicles on single lanes supporting traffic in two directions. Destinations are also more varied than on dual carriageways, which support mostly long-distance trips. Single-carriageways are used mainly in everyday travel, hence the assessment of their reliability is extremely important from the point of view of the average road user and road manager. Unfortunately, this type of road is omitted from the literature on reliability assessment. The next chapter will present selected results of travel speed studies conducted in the period 2016–2018 in Poland on two-lane highways [43], along with the indication of the extent to which statistically significant factors affect the travel speed and its variability relevant from the point of view of reliability analysis.

2.2. Travel Speed Research on Two-Lane Highways

This chapter presents selected results of research conducted as part of project [43] focused on the variability of travel speed and impact factors resulting from geometric, traffic and location features. The tests were carried out in favourable weather conditions, with very good visibility on selected road sections without intersections or other traffic disturbances.

When traffic volumes are not high, travel speed and thus travel time are significantly affected by the road's geometric features, such as road (CCR), radius and turning angle of the horizontal curve, longitudinal slopes, road width and type of cross-section, as well as traffic factors, including those related to the share of heavy vehicles in traffic. In view of the continuous changes in the car fleet, the roads' technical condition and geometry as well as drivers' behaviour, empirical research should be constantly updated, which was recently done and included in [43], resulting, among others, in a new regression model used to estimate travel speed on two-lane highways.

The tests were carried out in selected road cross-sections, at the beginning and end of the analysed section (speed and travel time were examined), and numerous trips behind the leader were made with continuous recording of data on the speed of moving vehicles (the leader).

The driving speed profile behind the leader was determined empirically using a GPS device. The influence of selected geometric features on vehicles' travel speed (free flow, no platoon traffic) is shown in Figure 3. The diagram shows that apart from the presence of horizontal curves, speed is also significantly affected by the length of the sections preceding the curves. It is assumed that a length of the section before the horizontal curve in excess of 400 m has no effect on the free-flow speed of vehicles. The chart shows speed limits for this road section due to the presence of horizontal curves and the values of superelevation on the curve implemented to ensure the safe passage of vehicles. Safe journeys should be made in accordance with the speed limit on the road. The chart shows that the speed limit is exceeded by approx. 10 km/h, which is informally allowed on Polish roads. From the point of view of the needs of road safety and the needs of road network reliability, preventive measures should be applied that would force drivers to drive within the speed limit, just like in other European countries which have a low number of deaths per 100,000 accidents. The impact of the presence of horizontal curves on travel speed and thus travel time is clearly visible.

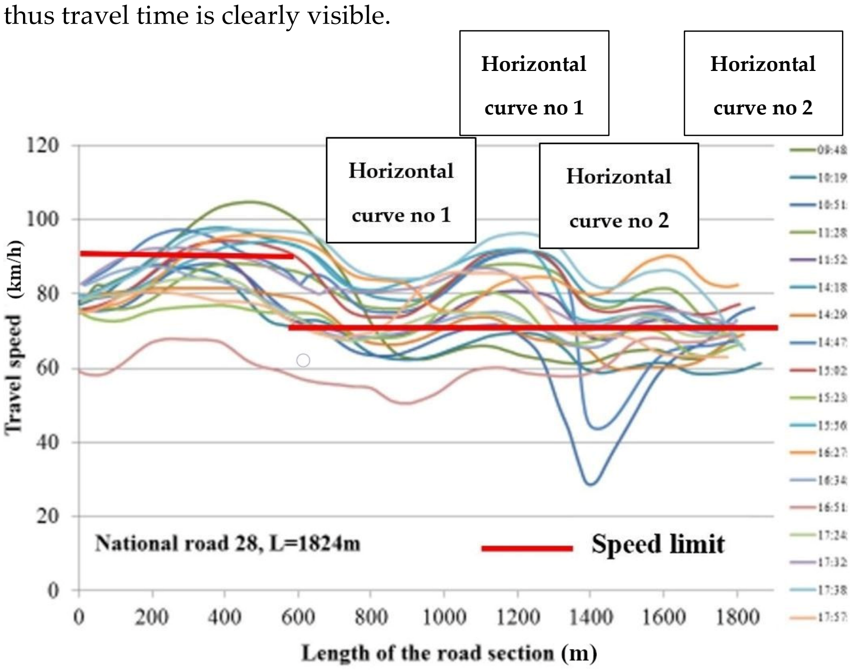

Figure 3. Selected drives behind the leader showing the impact of horizontal curves located close to each other on the variability of vehicles' free-flow speed.

Using the empirically collected data from 96 sections of two-lane highways with a length of 1 km to 5 km [43], relating to features of traffic, road and surroundings (Table 3), relationships were created showing the variability of travel speed, and thus indirectly also travel time. Selected interactions of travel speed and traffic volume, CCR and the interaction of the road's longitudinal slope and the share of heavy vehicles on two-lane highways are presented below. The significant dispersion of points arises from an aggregation of data from all research sites (96) and directions of traffic (192) and the differences between them.

Figure 4 shows a slight influence of traffic volume on the speed of vehicles and additionally illustrates the number of overtakes typical of two-lane highways. The number of overtakes depends on the traffic volume across the road's cross-section, traffic's directional structure and the number of slow-moving vehicles. Road's CCR undoubtedly has an influence on the number of overtakes. The greater the CCR, the smaller the number of overtakes. High values of CCR often coexist with high values of longitudinal slopes.

Table 3. Technical parameters of two-lane highways covered by the RID-I–50 Project.

Road Design Parameter	Range of Parameters
Design speed S_d (km/h)	40–100, road serpentine 15–30
Speed limit S_{SL} (km/h)	40–90
Technical class of road	Z–S
Horizontal curve radius R_H (m)	30–3200
Vertical curve radius R_V (m)	not specified
Type of cross-section	1 × 2; 2 + 1
Lane width s (m)	3.0–3.5
Hard shoulder width s_{up} (m)	0–1.5
Average weighted longitudinal slope i (m)	0.1–9.0
Length of measured section L (m)	400–3900
Curvature change rate CCR (g/km)	0–630
Percentage of sections where overtaking is possible p_w (%)	0–100
Access—point density A_p (A_p/km)	0–42

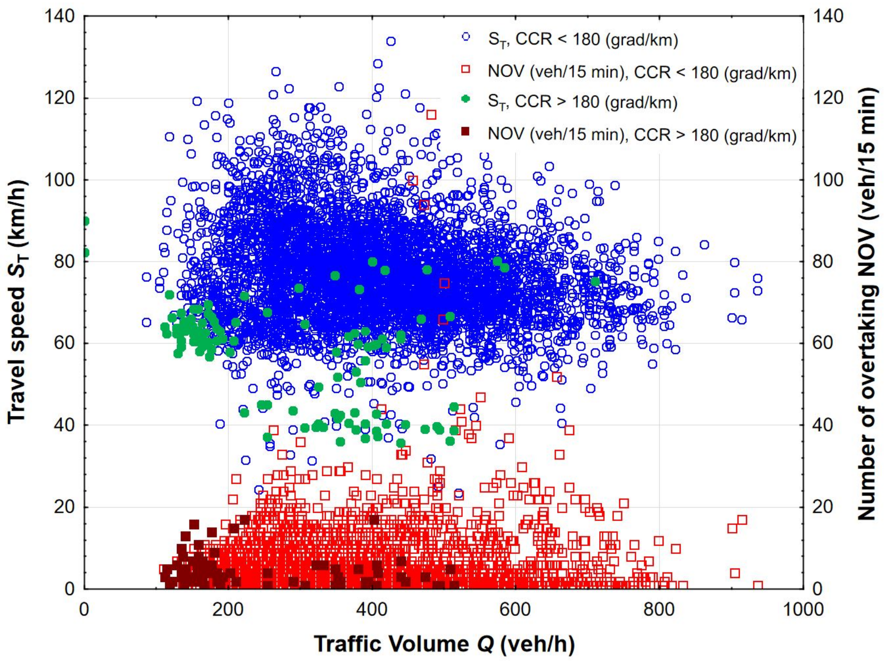

Figure 4. Interaction between travel speed, the number of overtakes and traffic volume throughout a road's cross-section, with the traffic density below 30 veh/km. Curvature change rate CCR divided into two groups–below and above 180 grad/km. The sample size is 12,565 cases.

With the traffic volume in a road's cross-section exceeding 800 veh/h, the number of overtakes is much smaller. This is due to traffic characteristics as well as road characteristics. In these circumstances, drivers will not overtake for safety reasons and follow a slow-moving vehicle until it can be overtaken. The more tortuous the road, the fewer overtaking manoeuvres.

The impact of a road's CCR on a vehicle's travel speed is very significant (Figure 5). Apart from a reduction in the median and average values of speed, the range of vehicle speed variability also decreases as the road CCR increases. The speed dispersion is much smaller on roads with greater rather than smaller CCR. The greater the road's curvature change rate CCR, the smaller the standard deviation of travel time and the greater the kurtosis. The chart also shows that the types of speed distributions in the distinguished ranges of CCR for the entire data set, including for low and high traffic volume, deviate from the normal distribution. High dispersion of speed at low curvature change rate CCR is due to a road's features and the possibility of overtaking slow-moving vehicles. At high CCR, a significant share of platoon traffic is manifest leading to smaller speed dispersion.

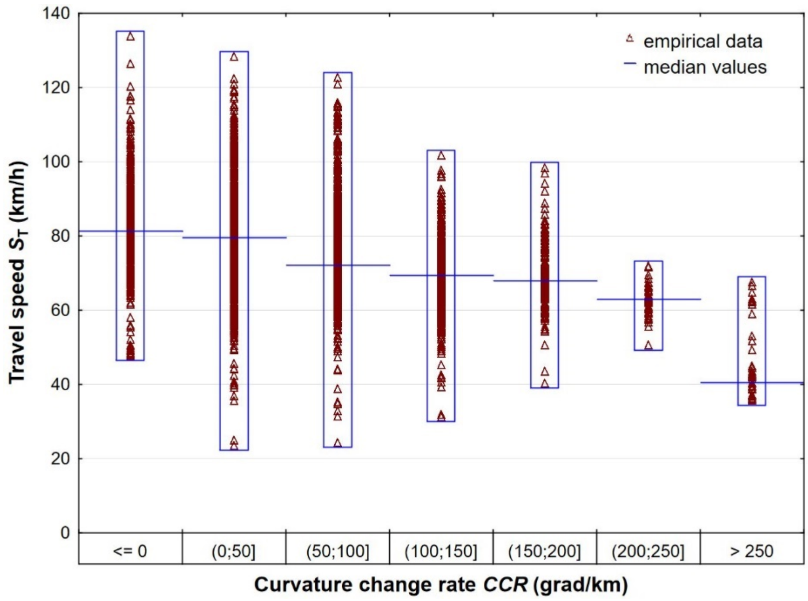

Figure 5. Interaction of travel speed and a road's curvature change rate CCR.

Figure 6 shows the combined impact of a road's longitudinal slope and the share of heavy vehicles in traffic on vehicles' travel speed. The statistical analyses carried out in [43] show that a road's longitudinal slope alone does not have as strong an impact on speed as a variable of the product of longitudinal slope and the share of heavy vehicles in traffic. A decrease in the impact of longitudinal slope in relation to previous studies [83] results from the improvement of the vehicle fleet in Poland. Nowadays, the capabilities of vehicle engines usually guarantee a smooth drive on a road with a variable longitudinal slope. Only heavy goods vehicles slow down when driving up or downhill, thus limiting the travel speed of other road users.

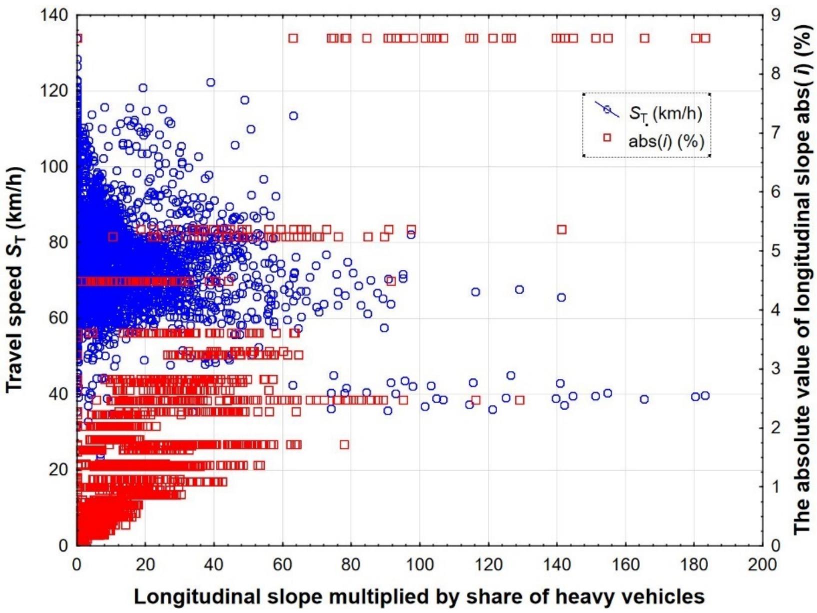

Figure 6. Interaction between travel speed and the combined effect of slope and the share of heavy vehicles.

Analysis of changes in a road's geometric features along the analyzed road sections shows that their impact on drivers' behaviour is varied and significant. When analyzing speed variability and thus travel times over a longer section (over 5 km), such a road section should be divided into sections that are homogeneous in terms of the described geometric and location features. The structure of traffic volume does not usually change significantly along the length of the road section and over the analyzed period of time. The division of the section into shorter sections allows you to analyze changes in travel speed and times and to eliminate places limiting travel speed and time e.g., by rebuilding the section.

The research shows that a road's geometric parameters and the share of heavy vehicles on roads with a significant longitudinal slope have a significant impact on the travel speed and thus travel time, including in free flow conditions. Therefore, these factors have a significant impact on the reliability of two-lane highways and should be included in reliability measures.

3. Results and Discussion

3.1. Functional Reliability of Two-Lane Highways

The functioning of two-lane highways differs significantly from that of dual carriageways in terms of the number and nature of factors affecting the speed of vehicle movement. In the case of two-lane highways, it is the traffic characteristics that mainly determine vehicle speed. Road features do matter but play a secondary role due to a need to adjust them to the high technical class of the road, its function and expected high travel speed in the early stages of the road's design. In the case of two-lane highways, the functional assessment of the road is significantly affected not merely by traffic characteristics, but by the geometric characteristics of the road and of its surroundings as well. Current computational methods mainly aim to assess the quality of traffic performance through analysis of measures of conditions including the average travel speed and the percentage of driving time in platoons [44], traffic density [43], [45] and other indirect metrics such as the degree of capacity utilization or the reserve capacity. These measures are mainly used by road managers for decision-making, design or operational purposes.

Reliability measures related mainly to travel time (described in Section 2) may be used by road managers and additionally by road users to plan travel time or make up-todate decisions on route selection if the data are provided on an ongoing basis e.g., via navigation systems. Road managers may also use reliability measures to analyze the functioning of the road in order to decide on the reconstruction of road sections in order to improve the road's standard and speed and shorten travel time.

3.2. Scenario Analysis and Reliability Measures of Two-Lane Highways

Analyses of the reliability of road functioning are based on the decisions of road users who drive along the road and generate travel times adequate to the traffic situation. Road managers can analyse such trips and on this basis decide on the type of measures that can be put in place to reduce travel times and improve road reliability and traffic safety. Such analyses can be conducted for the entire road or for selected sensitive road sections.

Time-related measures of reliability (Section 2) are closely related to road speed, which is limited by law, or locally by road signs. In the case of two-lane highways, the location of road signs often results from the characteristics of the road and the need to ensure safe passage. Free flow travel at speeds close to the permitted speed limit usually means a high level of functional reliability for people who are aware of the route they are taking. There is some synergy between the local speed limits set by road managers in hazardous locations and travel time reliability related to this speed.

The research conducted in [43] shows that roads with lower technical parameters have a lower capacity value, therefore, increased traffic relatively quickly leads to an unfavourable level of service and a significant increase in travel time as seen in Figure 7. The green colour representing a smooth drive does not change on the access sections of the serpentine at either of the analyzed times, and the colour of the highly winding sections does change, indicating a low travel speed in increased traffic [84].

Figure 7. Change in the travel speed caused by a road's geometrical features and traffic features. The left panel shows the situation at 2:30 pm in conditions of a higher traffic volume, and the right one at 8:30 pm when traffic volume is low.

A justified and correct location of speed limit signs reflecting the local technical parameters of the road and traffic safety considerations should correspond well with a speed reflecting the 85th percentile and indirectly with the possible capacity of a given road section, as traffic volume reaches the optimum value. Thus, it can be noted that the travel time determined by the speed limit on the road is the appropriate travel time reference value in operational reliability analyses. If a road section consists of several subsections with different speed limits, the average weighted speed and travel time should be determined. The above studies show three possible scenarios of functional reliability analysis in relation to two-lane highways:

Scenario 1: The road is functioning reliably. Travel time is similar to the travel time at the speed limit (85th percentile) or possibly higher. Traffic volumes Q in both directions are much lower than road capacity C (V/C < 0.5). Overtaking is mainly determined by the road's geometry, i.e., its CCR and longitudinal slopes, etc. Drivers' acceptance level of traffic performance is high.

Scenario 2: Traffic volumes in both directions are much higher than in scenario 1 (V/C ranges from 0.5 to 0.9), and overtaking is limited both by the road's geometry and by higher traffic volumes of the analyzed direction and the opposite one. In drivers' opinion, the road may be functioning reliably and unreliably. Variability of the traffic volume affects traffic performance, and that's why drivers' acceptance level of traffic performance may differ.

Scenario 3: The road functions unreliably. Travel time is long and drivers, who travel at a much lower speed than the permitted speed, find it unacceptable. Traffic volume is close to or exceeds road capacity (V/C > 0.9). Overtaking is not possible due to high levels of traffic volume. Geometric factors play a minor role. Drivers' acceptance level of traffic conditions is very low.

The use of the limit speed as a reference value for determining reliability measures does not disqualify the use of other types of speed and thus travel times (statistical parameters). However, from the point of view of road and traffic characteristics, traffic safety needs, and the needs of practical application, this value is the most appropriate one for two-lane highways. Having analyzed the reliability measures used (Section 2), the planning time index (Equation (13)) and the travel time index (Equation (14)) are the most suitable metrics for two-lane highways, assuming that the base travel time refers to the permissible speed on the road or other local limits when a road section is divided into shorter sub-sections (in which case it is advisable to determine the weighted average PTI_{SL} and TTI_{SL}). The thresholds values of PTI_{SL} and TTI_{SL} for individual levels of functional reliability are presented in Table 2. The indicated division of the section corresponds to the three analyzed reliability scenarios described in this chapter.

$$PTI_{SL} = \frac{t_{95}}{t_{SL}} \quad (13)$$

$$TTI_{SL} = \frac{t_x}{t_{SL}} \quad (14)$$

where: t_{95}–95th percentile of travel time, t_x—any percentile of travel time, t_{SL}—travel time determined by speed limits on the road.

Additionally, other statistical measures cited in Section 2 can be used to describe travel time variability. When the road is located near a large agglomeration and the influence of urban activity on traffic variability is noticeable, the buffer time index referring to the average value may also be used, as long as it is calculated separately for individual sub-sections of the road's section with different speed limits (Equations (7) and (8)).

3.3. Sample Reliability Analysis for A Selected Road Section

A section of a two-way highway marked as national road No. 47 between Rabka Zdrój and Klikuszowa, Poland was selected for analysis and was subsequently divided into two subsections. The first subsection, 1459 m long, starts outside the section with a 2 × 2 cross-section, and the second, 750 m long, consists of straight subsections of the road and a horizontal curve as denoted with the red arrows in Figure 8. The speed limit along the first subsection is 90 km/h, and within the second section, the speed limit of 60 km/h was introduced due to the presence of the horizontal curve having a large angle and a small radius. The speed limit of 60 km/h ensures safe vehicle driving on the road curve reflecting its technical parameters, including the superelevation used. Driving at a higher speed increases the risk of the vehicle skidding off the road and thus the occurrence of a traffic blockage, which would adversely affect the functional reliability of the analyzed road section.

The road traffic parameters were measured on the selected section of the road (Figure 8) around the clock, for 12 consecutive days of the week, i.e., from 13:15 on 13 May 2021 until 13:10 on 25 May 2021 using the GPS technology. The travel times of all vehicles (without a break-down into light and heavy vehicles) were obtained automatically from Google-associated paid applications for one direction, i.e., Kraków–Zakopane. The data were collected at 15-min intervals for which the average value of travel time was determined, with a break-down for each of the analyzed subsections (Figure 8) The introduction of a division of time into 15-min intervals results from the classic and practical approach to the study of traffic volumes and traffic conditions [O2]. The HCM method [O6] also indicates analyzing changes in traffic conditions in consecutive 15-min intervals as one of the possible analysis periods.

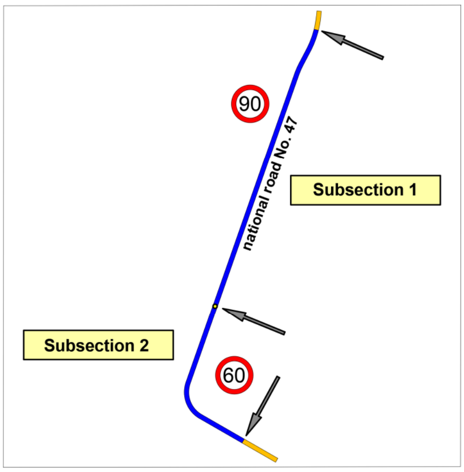

Figure 8. Analyzed section of the road divided into two subsections with speed limits of 90 km/h and 60 km/h.

Observation of the traffic volume on the analyzed section of the national road reveals considerable variability of traffic during the 24 h time period, in relation to work-related, recreational and tourist traffic. The traffic volume on the national road No. 47 on weekend days often exceeds road capacity and contributes to congestion. Table 4 summarizes the statistical parameters describing the variability of travel time in consecutive 15-min intervals of the analyzed 12-day period, with a break-down into two analyzed road subsections. Additionally, the table specifies the unit travel time t_{100} (s/100 m) relating to two subsections of the road having the same length of 100 m. The summary aims to show the impact of different road features on travel time. Eliminating the impact of the different lengths of individual road subsections on travel time will allow comparison of the statistical parameters describing the variability of the unit travel time on a straight part of the road (subSection 1) and on a horizontal curve (subSection 2), with different speed limits in place on the road (Figure 9) and under the same traffic and weather conditions.

Table 4. Statistical parameters describing travel time variability determined for subsequent 15 min. time intervals.

Variable	Subsection	Sample Size	Average	Median	Min	Max	Percentile 5%	Percentil e 95%	Standard Deviation	Coefficient of Variation

t_{100} (s/100 m)	1	1090	4.7	4.7	4.0	11.0	4.2	5.6	0.61	12.9
t (s)	1	1090	69.2	68.0	58.0	160.0	62.0	81.0	8.96	12.9
t_{100} (s/100 m)	2	1090	6.0	5.5	4.4	35.0	4.8	7.9	2.1	35.2
t (s)	2	1090	44.8	41.0	33.0	264.0	36.0	59.0	15.8	35.2

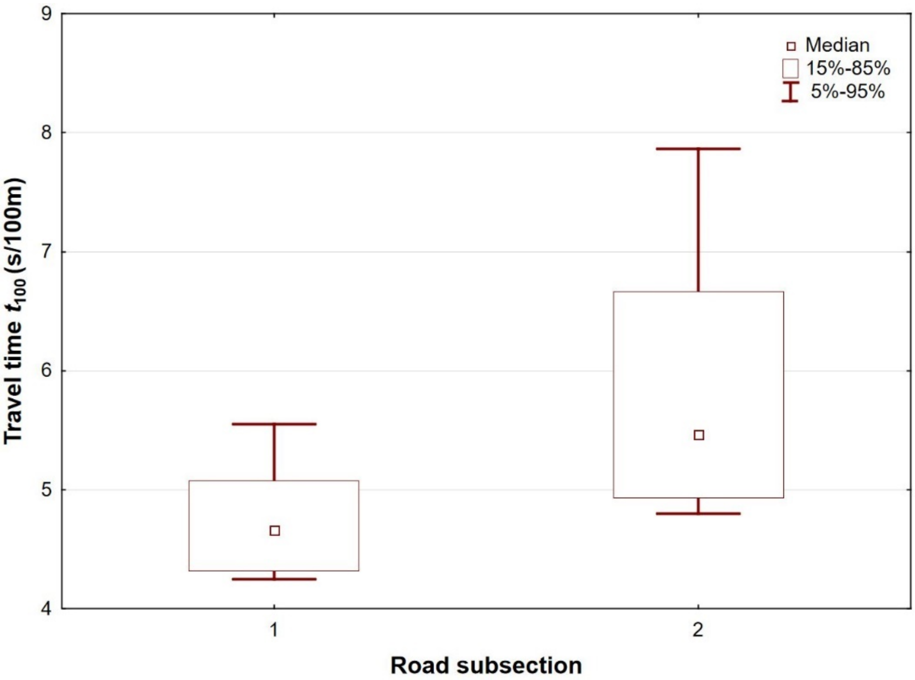

Figure 9. Comparison of 50, 85 and 95% quantile of unit travel time t_{100} determined for a 100 m length of subsections 1 and 2.

The analyses revealed a much greater value and variability of the unit travel time t_{100} along the horizontal curve (Section 2) than along the straight stretch of the road (Section 1). They showed a significant impact of the presence of the horizontal curve, markings limiting the speed to 60 km/h and road safety devices (roadside barriers) on the speed of vehicles, and thus on travel time. The impact of the presence of horizontal curves on travel speed will be the greater, the greater the number of horizontal curves on the analyzed section (Figures 5), and when the horizontal curves have a small radius and a superelevation along the curve which are not adjusted to the speed limit on the road. The situation is made worse by the road's design featuring large turning angles and small curve radii at the same time. Then the parameters of the horizontal curve do not allow for driving along the curve at a speed of 90 km/h and there appears a need to introduce a speed limit necessitated by the requirements of traffic safety (Figures 3 and 8). In most cases, drivers adjusted their speed (85% quantile) to the applicable speed limit on the road, accepting the reasonableness of vertical markings ensuring safe driving on the curve, and thus accepting the increased travel times resulting from its presence.

Table 5 presents the results of planning time index analyses conducted in a classic way (Equation (9)) and in the way proposed in the paper (Equation (13)), i.e., relating to the travel time in accordance with the speed limit enforced on the road. The travel time t_0, in conditions considered to allow free flow was determined based on the American recommendations [44]. Method [44] states that the initial speed of vehicles in free flow traffic can be determined by increasing the speed limit on a two-way highway by 15 km/h.

Table 5. Summary of calculation data and analysis results regarding *PTI* and PTI_{SL} values.

Subsection	t_{95} (s)	t_0 (s)	*PTI* (Equation (9))	t_{SL} (s)	PTI_{SL} (Equation (13))
1	81.0	50.0	1.62	58.4	1.39
2	59.0	36.0	1.64	45.0	1.31

Comparing the results of the analyses, it can be concluded that the classical analysis performed on the basis of Equation 9 yields much worse results than in the case relating to travel time in accordance with the speed limit. In both cases, in accordance with the criteria in Table 2, the same fair level of functional reliability was obtained. The classical approach refers to much higher travel speeds typical of free flowing traffic. An analysis performed in this way results from vehicle drivers' expectations which are overestimated and inconsistent with applicable regulations, expectations which ignore road safety. It is worth noting that any increase in vehicle speed above the applicable speed limit increases the risk of road incidents. In the analyzed case, the risk will be much greater on a horizontal curve than on a straight stretch of the road (risk of the vehicle skidding off the road at a higher speed).

When assessing the road's functional reliability in a dependable manner, apart from the impact of traffic variability, one should also take into account the possibility of traffic jams resulting from road incidents. When these occur, they block the possibility of driving on a two-way highway, and their high frequency, e.g., due to increased travel speed, reduces the level of the road's functional reliability and the reliability of the analyses. The number of road incidents strongly corresponds to the traffic volume on the road and therefore it is important to maintain vehicle speed below the speed limit by applying appropriate preventive (fines) and engineering measures (speed limit signs, speed cameras, sectional speed measurements, etc.). By showing a slightly worse functional reliability of the road in the classic approach (referring to the free flow speed), it is possible to incorrectly assess the functional state of the road and incorrectly plan financial outlays. Therefore, the conducted analyses indicate a very strong correlation between functional reliability measures and road safety levels, defined, inter alia, in terms of geometric parameters and applicable speed limits.

4. Conclusions

The research carried out on two-way highways allowed to achieve the goal of the analysis and provided an answer to the research question. The geometrical differentiation of two-lane highways has a significant impact on drivers' behaviour and the speeds they achieve, and, consequently, on travel times. On the analyzed roads, especially when there are heavy vehicles in traffic, one can often observe platoon driving with vehicles following the leader. Its duration depends not only on the volume of heavy vehicle traffic and traffic from the opposite direction but also on the geometric features of the road, such as CCR, longitudinal slope, the width of the road and the type of shoulder. Travel time may also be occasionally inflated by adverse weather conditions that adversely affect drivers' behaviour and road capacity, as well as other random incidents on the road often occurring due to increased travel speeds. On the basis of Polish research, the influence of these factors on travel speed and thus on travel time as well as a road's functional reliability was demonstrated. Analyses of the currently used reliability measures conducted mainly for dual carriageways indicate the need for an appropriate reference level that will reflect the road type and its standard. The reference parameter should combine the appropriate road and traffic characteristics from the point of view of describing reliability, functionality and traffic safety. The paper proposes that permissible speed is the best reference level for two-lane highways. The proposed parameter is different from that recommended for dual carriageways of high technical parameters. The speed limit on single carriageways changes rather frequently along the road and depends on the road's characteristics, indicating to drivers the safe and reliable travel speed.

Reliability analyses require therefore that a road section be divided into shorter sub-sections. The influence of traffic characteristics (traffic volume and structure) differentiates travel time in relation to the time resulting from the speed limit, and its comparison with the marginal values allows classifying individual sub-sections and the entire section's functional reliability.

Current reliability analyses barely take into consideration the need to relate the reference level (arising e.g., from the free flow speed or various quantiles of travel speed) to the needs of road safety (resulting e.g., from the applied speed limits on the road or from risk analyses of road incidents). Often it is difficult and complicated to determine the value of free flow speed and, consequently, such determination may not correspond to the actual conditions. Pertinent literature does not assess the value of the difference between travel time arising, e.g., from the 85% quantile and the travel time resulting from the speed limits enforced on the road. The size of the analyzed difference may be related to the indicators concerning the number of road incidents and the risk of their occurrence. Further analyses and studies in this field are necessary, not only for single carriageways but also for dual carriageways. The paper shows gaps in research in the field of continuous traffic tests and reliability analyses into two-lane highways, and indicates the need to develop and quantify reliability measures, thanks to which actions can be taken to improve traffic flow on the analysed roads. The use in the presented analyses of a tool for continuous measurement of travel time using GPS devices installed in vehicles and mobile phones allowed for analysis of the variability of travel time on the analyzed road section over a long period of time, and thus allowed indicating the impact of selected road and traffic factors and the need to incorporate traffic safety recommendations into reliability analyses. In the development of methods of road reliability analysis, it is necessary to develop tools for the continuous collection and analysis of traffic data.

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