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SPEED MANAGEMENT AS A MEASURE TO IMPROVE ROAD SAFETY ON POLISH REGIONAL ROADS

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Abstract: *The article presents the issue of the implementation of speed management measures on regional roads, whose character requires the use of different solutions than those on national roads. The authors briefly described speed management measures, the conditions for their implementation and their effectiveness with reference to environmental conditions and road safety. The further part of the paper presents selected results of the authors' research into the speed on various road segments equipped with different speed management measures. The estimations were made as to the impact of local speed limits and traffic calming measures on drivers' behaviour in free flow conditions. This research found that the introduction of the local speed limits cause reduction in average speed and 85th percentile speed up to 11.9 km/h (14.4%) and 16.3 km/h (16.8%) respectively. These values are averaged in the tested samples. Speed reduction depends strongly on the value of the limit and local circumstances. Despite speed reduction, the share of drivers who do not comply with speed limits was still high and ranged from 43% in the case of a 70 km/h limit, up to 89% for a 40 km/h limit. As far as comprehensive traffic calming measures are concerned, results show decrease in average speed and 85th percentile speed up to 18.1 km/h and 20.8 km/h respectively. For some road segments, however, the values of average speed and 85th percentile speed increased. It confirms that the effectiveness of speed management measures is strongly determined by local circumstances.*

Key words: *speed, speed management, road safety.*

1. Introduction

The previous studies and experience related to the organization of traffic have clearly indicated that it is possible to achieve significant benefits in the area of road safety improvement through the consistent implementation of speed management. However, the effectiveness of speed management measures depends on their proper selection. It is advisable to take into account factors determining the tolerance of the introduced measures on the part of road users. The most important factors from among these include the topography of the road together with the land development and the use of its surroundings. Based on these, a road users subjectively estimates the perceived level of risk. Taking this fact into account, one should pay particular attention to regional roads whose technical standard is more diversified than in the case of the national road network. Regional roads display a diversity of technical classes and function with frequently occurring discrepancies between the road category and its actual function. In addition to this, regional roads are characterized by an uncontrolled accessibility and low geometric parameters of road segments and intersections as compared with drivers' expectations (e.g. narrow lanes, lack of sidewalk). This entails a greater need for speed limits and other speed management measures than in the case of national roads. The way in which these speed limits are introduced ought to be related to the previous assessments of the effectiveness of various speed management measures. With reference to national roads in Poland this types of studies were conducted in 2002-2008 (Gaca, Jamroz, et al., 2003-2008). The issue of local roads has been researched into with this respect on a larger scale since the year 2013. Some part of the research is carried out as a joint project of the Cracow University of Technology and the Gdańsk University of Technology (Jamroz, Gaca, et al., 2013).

One of the reasons behind the research into speed limits on regional and local roads was to find out to what extent the reduced technical parameters of roads and their diversified functions affect the level of tolerance for the general and local speed limits. Also, an important aim of the study was to fill in the gap in the knowledge on the effectiveness of selected speed reduction measures on local roads presenting lower technical standards. With a wider knowledge on this subject, it will be possible to prepare a more rational implementation of these measures in Poland.

The paper describes selected results of the research into speed limits. The results are important in the formulation of rules governing the implementation of speed management on local roads. The studies were carried out with the participation of authors as a part of national guidelines for speed management (Gaca, Kieć, et al., 2016). The description of the research results was preceded by a review of the most important experiences relative to speed management measures with a particular focus on the way in which they are selected.

2. Speed management measures and their implementation

In the Polish practice of engineering, the speed management is most often understood as introducing speed limits. Therefore, the authors see it purposeful to introduce a broader notion of speed management understood as a set of activities aimed at establishing reasonable speed limits and influencing the actual speed of vehicles through planning, infrastructure and traffic organisation solutions, as well as supervision, education and advanced technologies. Its primary purpose is to achieve a status quo in which the speed of vehicles shall be adapted to the conditions of traffic and road as well as could be considered potentially safe. In addition to this, correct speed management leads to reducing road noise level road and air pollutant emissions.

Speed management consists of activities from the following areas:

- engineering – designing a road infrastructure with parameters facilitating the selection of appropriate speed, the use of physical measures regulating the speed of vehicles, introducing reasonable speed limits,
- supervision – monitoring of drivers' compliance with regulations and speed limits in force.
- education – informing drivers of the impact of speed on road safety, increasing drivers' awareness in terms of the introduced speed limit reduction measures.
- emergency services – enabling emergency services to reach the accident site as fast as possible.
- Speed management should be taken into account not only at the stage of the planning and designing of road infrastructure, but also when it's already in use.
- Among the many engineering measures affecting the vehicles' speed reduction, the following can be listed:
- zone and local speed limits using road signs,
- optical reduction of the width of the lane with the use of a horizontal marking,
- physical narrowing of the road cross-section (one or two-sided),
- traffic islands and a pedestrian refuge,
- raised intersections and pedestrian crossings,
- speed bumps and speed humps,
- horizontal deflection, chicanes,
- converting junctions into roundabouts and mini roundabouts,
- deflecting the vehicle trajectory by the approach to the intersection,
- vibro-acoustic marking.

Only the most beneficial measures, in terms of effectiveness and application costs, tend to be chosen from the group of potential measures suitable for practical application. However, it should be noted that the effectiveness of particular solutions can be strongly determined by local circumstances.

An important tool used in speed management are the rules for determining speed limits, which may be:

- general limits (based on the assumption that roads with similar characteristics can be safely used under ideal conditions with certain maximum speeds),
- zone or local speed limits, most often resulting from the increased risk of accidents in place where the speed limit is introduced.
- The key factors to be taken into account when deciding on zone or local speed limits are (Austroads, 2014):
- accident data (causes and types of accidents, frequency of occurrence, severity of accidents in conjunction with the vehicle speed),
- the geometry of the road and its equipment (width, the field of visibility, curves, intersections, accessibility, barriers etc.),

- road function (arterial roads, collector roads, local roads),
- road users (including the occurrence and size of the pedestrian and cyclist flow),
- the current speed limit,
- actual vehicles speed,
- road environment (including the intensity of the development of the road environment, the potential impact of traffic on inhabitants, including noise, air pollution, separation of the communities, the density of access points to the road),
- the opinion of the local community (inhabitants should have the opportunity to express their concerns and preferences for lower speed limits and their position should be considered).

As an example of the procedure for setting the speed limits, let us present the Australian method, in which the determination of the relevant speed limit is performed in two steps (Austroads, 2010). Step 1 consists in determining the speed limit on the basis of the characteristics of the road (municipal/suburban, one-lane/two-lane, function, flat/hilly/mountainous area, etc.). Step 1 results in the so-called initial speed limit. In step 2, on the basis of the initial speed limit and the appropriate profile of the safe speed limit, the appropriate speed limit is established. Safe speed profiles allow for taking into account road features influencing the likelihood of the accident occurrence and its severity (e.g. the presence of separators dividing lanes going in opposite directions, side obstacles in the road environment). In the case where the restriction resulting from the characteristics of the road is higher than the limit determined by the characteristics of the road, the speed limit at a given road can be increased.

Another method of determining the appropriate speed limit is the approach aiming at the minimisation of the accident impact. Widely described in the foreign literature, this method consists in establishing speed limits based on the biomechanical tolerance i.e. tolerance of the human body to automobile collision impact. The main challenge in this case is the management of the collision force so that no user is exposed to forces that can cause death or serious injury. Table 1 presents a list of allowed speed values in the approach favouring the minimisation of crash effects for various crash types.

Table 1. Biomechanical tolerance of the human body in the event of crash (Austroads, 2005)

Type of the crash	Biomechanical tolerance [km/h]
car/pedestrian	20-30
car/motorcycle	20-30
car/tree or pole (side impact)	30-40
car/car (side impact)	50
car/car (head-on)	70

Apart from establishing the relevant speed limit in a given area, it is equally important to specify the length of the road segment with speed limit. Below there are a few examples of specifying a particular length taken from abroad practice:

- In the USA, in Massachusetts and Ohio it is recommended that the length of a segment with a particular speed limit be equal to at least 0.8 km. In Texas, in turn, the length of the transition zone (buffer zone for the progressive reduction of speed on a suburban road to the speed limit effective in a given locality) must be no less than 0.3 km. Near a school, such zone can have the length of 60-90 m. In Alaska, the length of the speed limit zone shall be determined on the basis of the distance which a vehicle will travel within 25 seconds with the maximum speed determined for this zone (FHWA, 2012a);
- In Canada, the minimum length of the speed limit zone cannot be shorter than 0.5 km (FHWA, 2012a);
- In the UK, in order to avoid too many changes in speed limits on roads, it is assumed that the minimum length of the speed limit segment should be no less than 600 m. With lower speed limits, 400 m is admissible, whereas in the case of access roads or roads with the speed restriction to 30km/h – 300 m (DOT, 2013);
- On two-lane rural roads in Ireland, the speed limit should cover the minimum distance of 3 km. Also, no more than two changes in limits should be introduced on a road segment of 10 km. If the distance between the built-up areas is small (5 km or less), it is appropriate to apply a single speed limit on the road connecting them (DTTAS, 2015).

The change in the value of the speed limit should occur near the place where there is a significant change in the land development or where the road parameters significantly change.

Irrespective of the method of determining the speed limits and the length of the segment on which they will be effective, particular attention should be paid to the perception of the road by drivers and their expectations as to the speed possible to develop at a chosen road segment. If the driver does not acknowledge the need for a speed restriction, they will not obey it. The conclusion to be drawn is that, e.g. speed restrictions aiming at the reduction of air pollution, in the absence of other "visible" reasons for this restriction, do not always produce the intended effect.

Therefore, before introducing local speed limits, it is widely recommended to introduce other solutions affecting the improvement of road safety. In some cases, the construction of e.g. a cycling path or a sidewalk can more effectively improve the safety of vulnerable road users than a speed restriction on a short segment.

The problem of exceeding the permissible speed limit must be analysed in conjunction with the knowledge of a number of factors determining the drivers' speed. There are numerous works devoted to these issues and their synthesis can be found in (Gaca, 2002; Gaca, Kieć, 2005, Martens, Comte & Kaptein, 1997; Szczuraszek, 2008, Ahie, Charlton & Starkey, 2015, Gaca, Kieć, 2015). In order to quantify the impact of the characteristics of the roads and their surroundings on the speed parameters, regression models are built, the examples of which are given below:

- The estimation of the average speed of vehicles on the suburban road (speed limit of 50 km/h, speed measurements made in the daytime) (Gaca, Kieć, 2015):

$$V_{av} = 70.07 - 1.96 \cdot L - 1.83 \cdot GS + 0.319 \cdot GZ_{50} + 0.169 \cdot T + 0.140 \cdot LZ + 3.55 \cdot C1 + 0.81 \cdot C2 - 4.36 \cdot C3 \quad (1)$$

- The estimation of the average speed of vehicles on the approach to the horizontal curve on two-lane rural road (Jessen, et al., 2001):

$$V_{av} = 55.0 + 0.5 \cdot VL - 0.00148 \cdot AADT \quad (2)$$

- The model for the estimation of the average speed on urban road with a limit of 50 km/h (Schüller, 2010):

$$V_{av} = 48.75 + 1.31 \cdot Ps + 0.88 \cdot \ln(Lskp) + 3.0 \cdot \ln(Bp) + 6.86 \cdot P2x2 - 4.99 \cdot Fh - 2.39 \cdot Fm + 2.74 \cdot Fa + 6.39 \cdot Fb - 1.62 \cdot Stj \quad (3)$$

where:

- V_{av} – average speed of vehicles in free flow in the daytime [km/h],
- L – length of road segment [km],
- GS – density of intersections [number/1 km],
- GZ_{50} – density of development at a distance of 50 m away from the road [%]
- T – share of through traffic (%),
- LZ – average distance between development and the edge of the road (m),
- C1, C2, C3 – the symbol of the road cross-section type (respectively: with bitumic shoulders, ground shoulders and sidewalks). Variable assuming value 1 in the formula (1) if a given cross-section occurs or 0 if it does not,
- V_{85} – 85th percentile speed [km/h],
- VL – speed limit on road [km/h],
- AADT – average annual dly traffic,
- Ps – type of street in network structure (ring road – assumes the value of 0, radial road – assumes the value of 1.0),
- Lskp – length of the segment between the give-way intersections [km],
- Bp – width of the lane taking into account an adjacent bike lane, if it occurs.
- P2x2 – multilane road cross-section (assumes the value of 1.0 if it occurs and 0 if it does not),
- Fh, Fm, Fa, Fb – symbols used to describe the functions of the street and its surroundings, Fh – dominant commercial function, a city centre; Fm – mixed functions; Fa – no dominant functions, unilaterally development; Fb – no dominant functions, no development (variables assuming the value of 1,0 if a given case occurs or 0 if it does not).
- Stj – condition of the road – a variable equals 1.0 in the case of a poor pavement condition and a cobbled road. It equals 0 if the road is in good condition.

When taking into account speed models developed in Poland and abroad, the most frequent and statistically significant quantitative and qualitative variables are: road width, intersections density, density of access points, density of pedestrian crossings and bus stops, curvature degree, value of the speed limit, type of the cross-section, type of shoulder, intensity of the development in the road surrounding, road/street function, time of day. What transpires from the cited speed models is the fact that not all of these variables occur in models simultaneously.

The above speed models suggest that with the same speed limit the average speed of vehicles in the free flow differs significantly depending on the characteristics of the road and tend to be higher than the limit prescribed. Thus, various measures are taken in order to enforce on drivers a greater compliance with speed limits and adjusting their speed to the local conditions on the road.

3. The effectiveness of speed management measures

3.1. Speed management and road safety

The effectiveness of speed management measures in the context of improving road safety can be analysed using direct methods (accident data) or indirect methods describing potential threats.

The influence of speed management measure on road safety can be indirectly assessed through estimating the value of the quotient of the assumed average of the expected value of road safety measure (e.g. number of accident) on a road section with the applied traffic calming measure and the average of the expected road safety measure on the control section fitted with no evaluated measure. That factor, named in the Highway Safety Manual as CMF (Crash Modification Factor), is a fundamental indicator of the assessment of the impact of various treatment on road safety in the USA (Crash Modification Factors Clearinghouse, n.d.; HSM, 2010). The selected values of this factor, estimated on the basis of foreign studies, and in relation to the different speed management measures, location (local, regional and national roads) accident types and their severity, are summarised in Table 2.

Estimating the impact of any speed management measure on road safety can also be made using intermediate criteria, for example the change of vehicle speed caused by a particular measure. The legitimacy of adopting speed as an indirect criterion of road safety assessment is confirmed by both foreign and domestic research. A statistical relationship between the speed and road road safety is logical and has been repeatedly proven (Gaca, 2002, Cameron & Elvik, 2010; Elvik, et al., 2009; Gargoum, El-Basyouny, 2016).

In order to estimate the impact of the change in vehicle speeds on the change in road safety, the so-called “power model” can be used (Cameron & Elvik, 2010). It allows to predict the change in the number of accidents and their victims based on the

Table 2. Estimated values of the CMF coefficients with various measures aiming at reducing speed (Crash Modification Factors Clearinghouse, n.d., www.cmfclearinghouse.org)

Measure	**Area**	***CMF***	**Accident type**	**Accident severity**
decreasing the limit by 9 km/h	all	1.17	all	all
decreasing the limit by 16 km/h	all	0.96	all	all
decreasing the limit by 24-32 km/h	all	0.94	all	all
speed bumps	urban, suburban	0.5 - 0.6	all	serious and slightly injured
transverse rumble strips	urban, suburban	0.66	all	all
	urban, suburban	0.64	all	serious and slightly injured
area-wide or corridor-specific traffic calming	urban	0.89 – 0.94	all	serious and slightly injured
raised pedestrian crossings	urban, suburban	0.54 -0.7	all	serious and slightly injured
raised intersections	none	1.05	all	serious and slightly injured
converting intersections into low-speed roundabouts	all	1.099	all	all
	all	0.473	all	crashes
the introduction of edge line lanes on tangent and curve	suburban	0.963	related to the speed	all
raised bike crossing	none	1.09	vehicle - cyclist	serious and slightly injured

knowledge of the difference in average speed “before” and “after” a given measure is applied. To do this, the following formula is used:

$$W_1 = (V_1/V_0)^a \cdot W_0 \quad (4)$$

where:

- W_0 – a selected criterion of road safety in the period before the introduction of the measure,
- W_1 – a selected criterion of road safety in the same period after the introduction of the measure,
- V_0 – average speed before the introduction of the measure [km/h],
- V_1 – average speed after the introduction of the measure [km/h],
- a – parameter of a model whose value may be assumed based on literature or determined individually based on regression analysys.

An important assumption when using relation (4) is that only speed changes between “before” and “after” periods, and other determinants which affect road safety remain the same.

Based on the research described in (Cameron & Elvik, 2010), the following values of parameter *a* in the equation (4) were estimated (Table 3).

By adopting the values of parameter *a* provided above in the case of roads in urban areas, one can calculate, for instance, that lowering the speed limit of 60 km/h to 50 km/h, with 60 km/h as the average speed at the start and the actual reduction in speed by 3 km/h, would decrease the number of accidents with fatalities by 12%, and the overall number of accidents by 6%. By increasing the degree of respect for the introduced limitation and reaching the actual reduction in average speed by 5 km/h, one would achieve a decrease in the number of accidents with fatalities by 21%, and the overall number of accidents by 10%.

Table 4 summarises results of research concerning the impact of the reduction of the existing speed limit on the change in the number of accidents and their victims and on reducing the average speed of vehicles (Austroads, 2010).

The above-cited examples illustrate well the importance of additional measures of enforcing the respect for speed limits by drivers. The lack of such measures means that the actual reduction in average speed after the introduction of the “new” speed limit is usually ca. 1/4 of the difference between the “new” limit and the one previously in force (Elvik, et al., 2009; Gaca & Kieć, 2005; Gaca, Jamroz, et al., 2003-2008).

In accordance with research carried out abroad and described in (FHWA, 2012b), speed bumps are very effective, contributing to the reduction of the average speed of vehicles by ca. 32 km/h, while speed cushion – of ca. 27 km/h. Research conducted in Poland also confirms this effectiveness. Raised pedestrian crossings, which constitute an obstacle similar to linear speed bumps, usually cause a reduction in average speed by 4.0 ÷ 6.5 km/h. It should be noted, however, that the introduction of speed bumps causes the local speed reduction with its increase on the sections between the bumps, which is an undesired phenomenon due to the exhaust emissions (increased number of manoeuvres of acceleration and braking). Therefore, it is appropriate to use complex traffic calming measures causing the effect of an even reduction in speed on a designated segment of a road.

The introduction of the mini roundabouts and small roundabouts instead of regular intersections leads to the average decrease in average speed by 36 km/h and 54 km/h respectively.

In addition to physical traffic calming measures, less restrictive measures can be applied, for example vertical signs with the recommended speed which inform drivers about the speed at which they should be moving in a given area. Using such signs allows to reduce the speed of vehicles by 3.2 ÷ 5 km/h (FHWA, 2012b).

Table 3. The value of parameter a in the “power model” equation (Cameron & Elvik, 2010)

Type of accident	Roads in rural areas		Roads in urban areas	
	Value of factor *a*	**Confidence interval 95%**	**Value of factor *a***	**Confidence interval 95%**
With fatalities	4.1	2.9 ÷ 5.3	2.6	0.3 ÷ 4.9
With fatalities and serious injured	2.6	-2.7 ÷ 7.9	1.5	0.9 ÷ 2.1
With casualties in total	1.6	0.9 ÷ 2.3	1.2	0.7 ÷ 1.7

Table 4. The impact of the reduction in speed limits on the average speed and on the reduction in the number of accidents (Austroads, 2010)

Country	Speed limit reduction [km/h]	Changes in average speed	Reduction in the number of accidents and its victims
Denmark	from 60 km/h to 50 km/h (local roads)	3-4 km/h	number of fatalities – 24%, serious injured – 7%, slightly injured – 11%
Germany	from 60 km/h to 50 km/h	-	number of accidents – 20%
Australia (New South Wales)	from 60 km/h to 50 km/h (local roads)	0.94km/h	number of accidents with fatalities -45%, with injured– 22%, the total number of accidents – 23%, accidents with pedestrians – 40%
Australia (Victoria)	from 60 km/h to 50 km/h (local roads)	2-3 km/h	number of accidents with fatalities -21%, with serious injured – 3%, with slightly injuries – 16%, with casualties –12%, fatal accidents with pedestrians – 25%, accidents with serious injured pedestrians –40%
Australia (Southern Australia)	from 60 km/h to 50 km/h (local roads)	3.8 km/h	number of accidents with casualties – 20%, number of serious injured –20%, slightly injured from – 23% to – 26%, fatalities – 40%
Australia (Queensland)	from 60 km/h to 50 km/h (local roads)	5 km/h	number of accidents with fatalities –88%, number of accidents with casualties – 23%
Australia (Western Australia)	from 60 km/h to 50 km/h (local roads)	1 km/h	number of accidents with fatalities –21%, number of accidents with pedestrians – 51%
Australia (ACT)	from 60 km/h to 50 km/h (local roads)	–	total number of accidents – 2.1% (statistically insignificant)
Australia (Victoria)	from 60 km/h to 40 km/h (temporarily, on commercial streets)	–	number of accidents with casualties –8%, number of accidents with pedestrians – 17%

The above examples of research results clearly confirm that, due to speed reduction, the most effective speed management measures are the physical traffic calming measures. Despite that, the decision about their introduction should be preceded by an analysis of the effectiveness of the application of other solutions, such as vehicle activated signs, intensive supervision, installing or removing the line separating lanes or allowing parking along the road. It should also be remembered that physical traffic calming measures cannot be used freely, for example on main arteries, or roads often used by emergency services.

3.2. Speed management and environmental aspects

Modern speed management policy aims not only at improving road safety, but also at protecting the environment and health (ETSC, 2008). Speed management can be a very effective method of fighting the problem of excessive CO_2 emissions, because fuel consumption, and thus carbon dioxide emissions, is dependent on the speed of vehicles (Fig. 1).

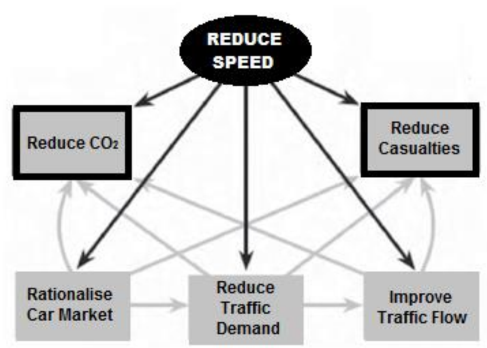


Fig. 1. The impact of the reduction of speed on road safety and reducing CO_2 emissions (ETSC, 2008)

The impact of speed management on environment is widely featured in foreign literature (Austroads, 1996, Bel, Rosell, 2013., COWI & ECN, 2003, ETSC, 2008; Soole, Watson & Fleiter, 2013). The authors of a French government programme showed that total compliance with speed limits would lead to a reduction of CO_2 emissions by 3 million tonnes per year, which is equivalent to a 2% reduction of emissions of this gas. Even greater benefits were indicated in the research conducted in the Netherlands, in which it was estimated that conducting activities in speed management results in a decrease in carbon dioxide emissions by 4-10%.

The analyses carried out in relation to German motorways suggest that the introduction of 120 km/h and 100 km/h speed limits would reduce carbon emissions by 10% and 20%, respectively. The results of research carried out for the Austrian motorways have shown that the introduction of a 100 km/h speed limit on a 30 km-long section of a motorway leads to a reduction in CO_2 emissions by 11%.

In the United Kingdom, researchers created a model to calculate the emission reduction between 2006 and 2010 for two variants, i.e. for introducing a 110 km/h and 95 km/h speed limits. Studies have shown that for the first scenario, carbon dioxide emissions decreased by ca. 1 million tonnes per year, and for the second one, by 1.88 million tonnes per year.

It is estimated that reducing the speed limit from 100 km/h to 80 km/h on roads in Italy would help to reduce fuel consumption by 387.9 tonnes per year, and to reduce the emissions of CO, PM_{10}, CO_2 and NO_x respectively by 15.3%, 6.4%, 5% and 4.6%. Unlike Italian research, results of similar measurements conducted in Spain showed that reducing the speed limit from 120km/h or 100km/h to 80 km/h on motorways in Barcelona causes increase in NO*x* and PM10 emission by 1.7–3.2% and 5.3–5.9% respectively. This study also suggest that NO*x* and PM10 pollution can be reduced by 7.7–17.1% and 14.5–17.3% respectively after variable speed policy implementation.

The authors of the studies conducted abroad stress that special attention should be paid to the speed of lorries (trucks). The Dutch study shows that the reducing the speed limit for vans and light trucks to 110 km/h on expressways can lead to a reduction of fuel consumption by 5%. In turn, the reduction of vehicle speed by 2 km/h, 5 km/h and 7 km/h results in the reduction of fuel consumption by 0.5% (7 million litres), 2% (27 million litres) and 3.5% (48 million litres) respectively.

Another factor which can have a significant impact on the reduction of CO_2 emissions is the use of modern technologies, such as ISA (Intelligent Speed Assistance). It is estimated that carbon dioxide emissions from vehicles fitted with ISA may drop by 8% in the UK when compared to other vehicles.

Another study carried in the United Kingdom focused on the impact of speed control on fuel consumption and emissions. It has been shown that speed control on roads where speed is reduced to 110 km/h will increase fuel consumption by 70.6 litres/100 km, and on the road segments with the limit of 80 km/h by 18.8 litres/100 km. In addition, the roads segment with speed limits of 110 km/h reported a decrease in CO_2 emissions by 528 kg/month, and on the road segments where the limit is 80 km/h the decrease was by 1376 kg/month.

4. Polish surveys of the effectiveness of speed management measures

Although most of the speed management measures described in point 2 are implemented in Poland, however, the evaluation of their effectiveness has been the subject of limited research only, conducted primarily on national roads and in the cities (Gaca & Kieć, 2005; Gaca, Jamroz, et al., 2003-2008). The general conclusion from these studies is that the drivers of vehicles commonly exceed the permissible speeds determined by the general or local restrictions. The results described in (Gaca & Kieć, 2005; Gaca, Jamroz, et al., 2003-2008) and other test results clearly indicate the need for additional speed management measures, especially on road segments passing through small and medium-sized towns.

In the case of local roads the typical speed management measures include:

- local speed limits – 36.8%,
- locally applied traffic calming measures – 32.3%,
- complex traffic calming measures (median and refuge islands on roads through built-up areas which cause change of trajectory only for heavy vehicles) – 19.4%,
- speed zones – 6.4%,
- designating road segments with intense speed enforcement (along with speed cameras) – 4.0%,
- measures other than those listed above – 1.1%.

These data were obtained as a result of road administration survey research (Gaca, Kieć, et al., 2016).

Taking into account the above-mentioned frequency of applying the speed management measures on local roads, these measures underwent research intended to precede the development of guidelines for speed management on local roads (Gaca, Kieć, et al., 2016). In subsequent parts of this article, only selected result of speed measurement on 100 road segments and in 24 speed zones were presented.

The basic indicators of the effectiveness of speed management measures are changes in the value of the different criteria of road safety. One can also assess the above-mentioned effectiveness through speed measurements and the evaluation of changes in the driver's behaviour as a response to the applied measure. The expected effect of speed management measures is not only a reduction in the value of average speed, but also a reduction in the share of drivers moving at very high speeds, and the emergence of more uniform behaviour. Therefore, the primary measures of effectiveness are: reduction of average speed, reduction of the value of the 85th percentile speed (V_{85}) and reduction of dispersion in the value of the speed. Their estimation is made by a typical "before and after" or "with and without" studies. The equivalent of "with and without" studies are simultaneous speed measurements conducted on different segments of the road, i.e. in the segment preceding the applied measure, and in the segment where the measure is applied. A group of vehicles in free flow was singled out in the study, which allowed for a better assessment of the driver's reactions to a given measure. A headway greater than 6 sec was assumed as the boundary value for free flow speed. In this case driver has the freedom to make decisions on the selection of speed. As measurement techniques, the following were used: measurements using pneumatic tubes, video technique and measurements using manual devices. The research was carried out in similar weather conditions and during a day. The duration of measurements and the obtained sample sizes met the requirements of mathematical statistics.

In Poland, the effectiveness of local speed limits on lower classes roads is relatively not very well identified. The following describes the selected results of the speed measurements on the segments of roads with local speed limits of 40, 50, 60 and 70 km/h. Pooled results of speed measurement are provided in Table 5.

By analysing a group of vehicles in free flow in road segments with local speed limits, it was found that:

- a very large group of vehicles were moving at a speed greater than the limit. The share of drivers who do not comply with applicable restrictions ranged from 43% in the case of a 70 km/h limit, up to 89% for a 40 km/h limit;
- the introduction of the local speed limit changes the value of the average speed and V85 on average by 4.4 ÷ 11.9 km/h and 5.8 ÷ 16.3 km/h respectively, depending on the value of the limit. This means a change in the average speed and V85 respectively by 6.8 ÷ 14.4% and 7.7 ÷ 16.8%;
- having regard to the results of the measurements in particular road segments, wide variations in reactions of drivers to the introduced restrictions

Table 5. Results of the speed test on road segments with local speed limits (Gaca, S., Kieć, M., Jamroz, K., et al., 2016)

		Section without a speed limit				**Section with a speed limit**				**Difference**		
No. of segments	**Speed limit [km/h]**	**Mean speed**	**85th percentile speed**	**Coefficient of speed dispersion**	**Share of drivers exceeding speed limit**	**Mean speed**	**85th percentile speed**	**Coefficient of speed dispersion**	**Share of drivers exceeding speed limit**	**Mean speed**	**85th percentile speed**	**Coefficient of speed dispersion**
		[km/h]	**[km/h]**	**-**	**[%]**	**[km/h]**	**[km/h]**	**-**	**[%]**	**[km/h] [%]**	**[km/h] [%]**	**- [%]**
8	40	64.4	75.5	0.185	45	60.0	69.7	0.173	89	4.4 6.8%	5.8 7.7%	0.011 6.2%
4	50	69.9	82.1	0.185	47	60.8	70.7	0.179	77	9.1 13.0%	11.4 13.9%	0.005 2.9%
4	60	82.3	97.0	0.174	24	70.4	80.7	0.152	81	11.9 14.4%	16.3 16.8%	0.022 12.5%
9	70	79.9	93.2	0.170	19	70.6	83.3	0.194	43	9.3 11.6%	9.9 10.6%	-0.024 -14%

were found. Depending on the value of speed limits, the average speed on the various segments changed from -5.6 km/h (average speed increase) to 24.7 km/h in relation to the segment without speed restrictions. This means the presence of a strong influence of local factors on the level of tolerance of local speed limits. It is planned to extend the scope of the research to build regression models quantifying the effect of these factors;
- the value of speed V_{85} was higher than the average speed by 11.1 ÷ 14.7 km/h on average in the control section and by 9.7 ÷ 12.7 km/h in the section with speed limits;
- the research recorded a change in the value of the variation coefficient in the road segments with a speed limit in relation to the control sections. The change equalled up to 0.02. In the case of a 70 km/h speed limit, there has been a 0.02 increase in the coefficient of variation in the road segments with this measure, indicating the occurrence of an unexpected effect of the increasing heterogeneity of traffic.

One of the measures of enforcing speed limits are traffic calming measures and the intensive speed enforcement measures. In the case of physical traffic calming measures, among those tested there were complex measures implemented along road segments passing through small localities. Usually, these are “mild” measures designed in a way that allows drivers to pass with the maximum speed of ca. 70 ÷ 80 km/h. Therefore, their effect in urban areas mainly consists of both their psychological impact (drawing attention to the need to reduce speed) and the physical speed reduction for a group of very fast driving vehicles.

Based on tests carried out on 23 road segments passing through localities with complex traffic calming measures, it was found that (Gaca, Kieć, et al., 2016):
- the average speed in free flow in control sections, i.e. before the road segments featuring traffic calming measures, oscillated between 42.8 km/h and 75.4 km/h. In road segments with a 60 km/h speed limit and complex traffic calming measures, this speed ranged from 44.0 km/h to 65.8 km/h;
- the value of speed V_{85} was higher than the average speed by 10.0 km/h on average in the control section and by 8.3 km/h in the section with traffic calming measures;
- the majority of analysed segments with traffic calming measures saw a decrease in average speed and V85 in relation to the control section by 0.1 ÷ 18.1 km/h and 0.6 ÷ 20.8 km/h respectively. For some segments, however, the values of average speed and V85 increased. In total, the tested road segments showed an average decrease in average speed and V85 in free flow by 2.8 km/h and 4.7 km/h respectively;
- complex traffic calming measures on road segments passing through localities have a positive impact on the improvement of traffic homogeneity: the value of the averaged coefficient of speed dispersion in free flow decreased by 0.02 when compared to control segments;
- the share of drivers going over the speed limit in the section with traffic calming measures was 68% and was 11% lower than in the control section.

Preliminary research into the effectiveness of physical traffic calming means in street segments have confirmed the impact of these measures on the reduction of vehicle speeds. Single speed bumps and raised intersections caused a local decrease in speed by 15.7-27.0 km/h. When it came to speed bumps placed consecutively one after another, the object of the study was the average speed in that street segment, which was compared with the speed in the same segment but without speed bumps. The presence of speed bumps resulted in a reduction of the average speed by 20-23 km/h. In the qualitative sense, the quoted examples of random test results fall in line with the results of research by other authors, and they confirm the high efficiency of the physical traffic calming measures.

The above-mentioned examples of studies of the impact of speed management measures on the reduction of the different characteristics of speed indicate a high potential of such management as a means of improving road safety. Although the averaged values of speed reduction of ca. 3 ÷ 15 km/h may seem relatively small, their importance in relation to the improvement of road safety, assessed on the basis of the model described in section 3, is very high. Figure 2 shows the extent to which the change in average speed in a given segment of the road, respectively by 3, 6, 9, 12 or 15 km/h, will affect the reduction (expressed in percent) in the number of accidents with fatalities and serious injured depending on the level of speed before the change.

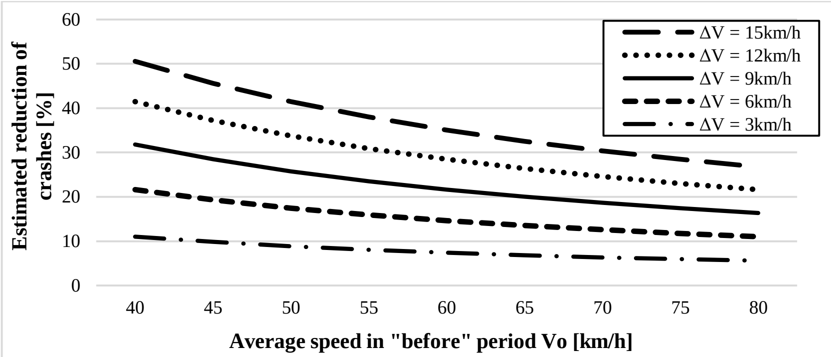
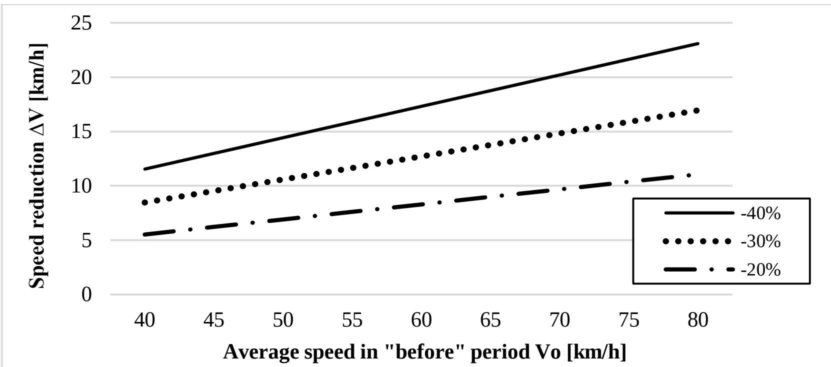
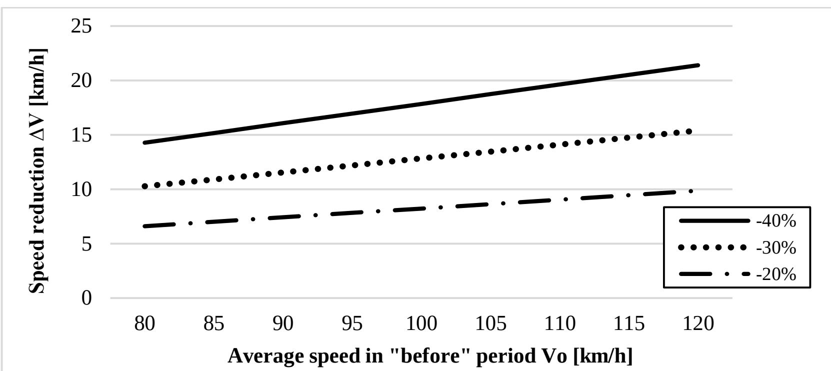


Fig. 2. Estimation of the possible reduction in accidents with fatalities and serious injured depending on the average speed in "before" period and the speed reduction value ΔV, based on the formula (4) (own work).



a)Segments in urban areas



b) Segments in rural areas

Fig. 3. Estimation of the possible reduction in accidents with fatalities and serious injured depending on theaverage speed in "before" period and the speed reduction value ΔV, based on the formula (4) (own work).

The relation shown in Figure 2 indicates a connection between the effect of a potential reduction in the number of accidents and the value of speed "before" the implementation of a specific speed management measure. In addition, this effect is illustrated in Figure 3 which shows the desired speed reduction values in order to obtain the intended value of the reduction in the number of accidents with fatalities and serious injured.

The results of the analyses provided above indicate the need to implement more restrictive speed management measures at side with higher recorded speeds.

5. Discussing the results and the summary

The presented research, in conjunction with other Polish publications, confirm the low level of tolerance of general and local speed limits in Poland. In the case of general speed limits, the share of drivers not adhering to these limitations is significantly larger than in other countries of the European Union (Gaca & Kieć, 2005 Jamroz, Gaca, et al., 2013).

Respecting local speed limits are mainly influenced by the principles of their imposition. If they are not understandable for drivers, then a large role is played by using supervision and additional measures aimed at enforcing the desired behaviour. The general cultural and sociological circumstances, which may vary depending on the region, are also of importance. These circumstances limit the possibility of direct comparison of national research results with the results of research carried out abroad.

The view that the local speed limits are not effective and therefore do not contribute to the improvement of road safety, is quite common. In order to verify this thesis, the research was undertaken. This research found that the reduction in average speed in an area with local speed limits was, on average, 4.4 ÷ 11.9 km/h (6.8% ÷ 13.0%), depending on the value of the limit. These values are lower than expected, but they can potentially cause a reduction in the number of accidents with fatalities and serious injured by ca. 10 ÷ 20%. This is sufficient proof for the legitimacy of the use of local speed limits in areas of increased accident risk. Of course one should aim to improve the degree of compliance with local speed limits, which requires the implementation of more effective speed management measures. Their correct choice requires a better understanding of the determinants of drivers speed choice in conjunction with local circumstances. The results of the presented research clearly indicate the presence of a strong influence of local factors on the level of acceptance of local speed limits.

Research of speed on roads with "mild" traffic calming measures confirmed their low effectiveness, which points to the need for verification of both these solutions and the ways of their implementation. A high effectiveness was, in turn, confirmed, when it comes to physical speed reduction measures in the form of speed bumps and raised intersections. It must be stressed, however, that these measures usually cause only a local decrease in speed.

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