

# INCORRECT U-TURNING OF VEHICLES AT INTERSECTIONS WITH TRAFFIC LIGHTS

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## Abstract:

The article describes the problem of incorrect U-turns at intersections with traffic lights. Statistical data on road incidents related to U-turns are presented. Then, the international, Polish and foreign regulations concerning u-turning at intersections with traffic lights were analysed. The situations in which U-turns are allowed or prohibited are presented. The differences in design rules for junctions with U-turns in different countries have been taken into account. A literature review was also carried out that outlined various current U-turns around the world, including the design of turning places, the location of turning points, road safety when turning, and the impact of U-turns on traffic conditions.

The further part of the article presents the results of field tests of the U-turn at 6 intersections located in Warsaw. The research was conducted by video observation. The results were broken down by age, gender, place of registration of the vehicle, type of vehicle, and the effect of incorrect turning. Data on road incidents at the examined intersections were also analysed. Data from the database kept by the Police were compared with the measurement data. A regression analysis was performed between the types of recorded incorrect manoeuvres and the number of accidents at the intersection. The results of statistical analysis carried out do not indicate the existence of a relationship between the number of identified incorrect U-turns and the number of road incidents at intersections.

Based on the research, it was found that the phenomenon of incorrect U-turns at intersections with traffic lights is common, and the use of directional (protected) signals does not eliminate this phenomenon. The conclusions indicate practical solutions to reduce the number of illegally U-turning vehicles. The recommended actions are related to the stage of shaping the road network, designing the road geometry and organizing traffic and traffic lights, and auditing road safety, as well as the stage of road operation.

**Keywords:** U-turning, turning back, traffic signals, traffic lights, road safety

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## 1. Introduction

Observations of road traffic on the streets of Warsaw show that despite improvements in traffic organization, modernization of traffic signals at intersections, and improvement in road safety, a large number of traffic accidents and collisions can still be observed, caused by the inappropriate, often illegal behaviour of traffic participants. The issue of road safety is related to many aspects of transport. The topic is important because road accidents not only have a direct impact on their victims but also on the travel times and operating costs of vehicle fleets (Rudyk et al., 2019). In the case of motor vehicle drivers, the problem of illegal U-turning can be observed. Data obtained from the Accident and Collision Recording System show that in 2010-2019, the number of accidents related to illegal turning in Warsaw oscillates around 100 events (SEWIK, 2020). Approximately 20-30% of these accidents occur at intersections with traffic lights operating in the three-colour mode. With non-functioning traffic lights, a maximum of one event per year is recorded. The statistics do not indicate significant changes in the number of accidents from month to month. However, variability within the week is noticeable - the number of accidents on Saturdays is about 1/4 less than on weekdays, and on Sundays, the number of accidents drops by half compared to weekdays.

When analysing the problem of inappropriate vehicle U-turning in prohibited places, the high traffic volume in Warsaw, the lack of places where this manoeuvre can be performed safely, as well as the drivers' lack of respect (and often knowledge) of traffic regulations can be identified as the cause of this problem. The phenomenon of lack of knowledge of the rules or even deliberate violation of them is often overlooked during analyses related to the causes of drivers' behaviour (Muslim et al., 2018). Therefore, the need for empirical research related to drivers' incorrect U-turning was identified.

## 2. Literature review

### 2.1. U-Turning rules in legislation

The current road traffic regulations are contained in (MI, 2002), in (Sejm RP, 2012) and international regulations - (CoRT, 1968) and (CoRSaS, 1968). In turn, (MI, 2003) provides guidelines on the use of appropriate horizontal and vertical signage, types of traffic signals placed at intersections and road traffic safety devices.

The Vienna Convention on Road Traffic (CoRT, 1968) is an international treaty in force in the countries which are its signatories. It defines general rules for the movement of vehicles, their equipment, their interaction with pedestrians and cyclists. U-turning is covered only by one provision, indicating prohibition of this manoeuvre on a motorway. The Vienna Convention on Road Signs and Signals (CoRSaS, 1968) only defines the sign prohibiting a U-turn and does not refer to the admissibility of U-turns at intersections.

In Poland, if there are no signs on the road or intersection, U-turning on the road or intersection is permitted. The manoeuvre of U-turning is not forbidden, also when signs are placed on the intersection: F-10, F-11, even if the possibility of U-turning is not indicated on them (a left turn permit is enough). Horizontal signs allowing to perform a U-turn at the intersection, with general signals at the intersection approach, are signs: P-8b, P-8c, P-8e, P-8g, P-8h, P-8i. U-turning is allowed only from the inner lane unless signs indicate that this manoeuvre may be executed from more than one lane. At intersections controlled by traffic lights, the U-turning manoeuvre is possible when the following signals are present: S-1, S-2, and S-3, but only with the arrow symbol for U-turning or U-turning and turning left (Fig. 1).

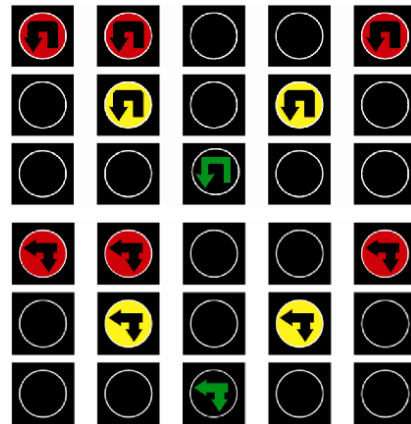


Fig. 1. S-3 turn signals, own elaboration based on (MI, 2003)

The prohibition of U-turning may be introduced by vertical signs, horizontal signs and traffic lights (MI, 2002, 2003). Vertical signs prohibiting the manoeuvre of U-turning at an intersection are prohibition

signs: B-21, B-23 and order signs: C-1, C-2, C-3, C-4, C-5, C-6, C-7, C-8. Road surface markings prohibiting U-turning on roads and intersections are: P-2a, P-2b, P-3a, P-3b, P-4. At intersections controlled by traffic lights, the U-turning manoeuvre is not possible when there are S-3 directional signals that do not directly indicate the possibility of U-turning, including signals intended for left-turning drivers (Fig. 2).

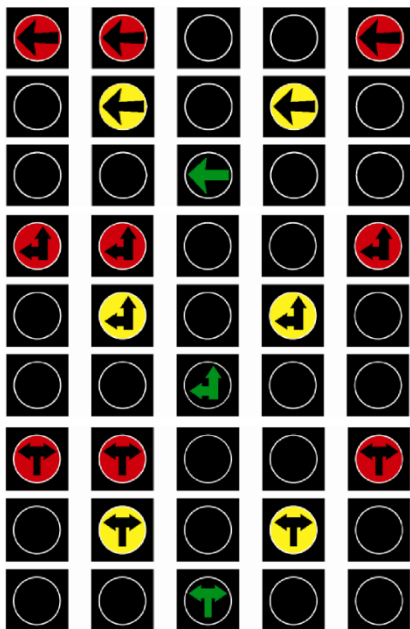


Fig. 2. S-3 directional signal heads prohibiting a U-turn but allowing a left turn, own elaboration based on (MI, 2003)

Particularly little known among drivers is the provision prohibiting U-turning when there is an S-3 signal for left turn only. Drivers often turn in such places without being aware that traffic may be turning simultaneously from the perpendicular approach of the approach they are on.

Foreign regulations contain different provisions for U-turning at intersections with signalling. German regulations (RILSA, 2015) recommend designating turning areas in the lane dividing the carriageways outside intersections to improve the effectiveness of traffic control and specify situations in which traffic lights should be used at such locations. On the other

hand, Russian regulations (NII Avtomobil'nogo Transporta, 2017) allow the existence of conflicting turning vehicles at traffic lights if the traffic volume in the U-turning vehicle stream does not exceed 300 vehicles/hour or the pedestrian traffic volume at the conflicting pedestrian crossing does not exceed 300 persons/hour. In contrast, the Swedish guidelines (Vägar och gators utformning Trafiksignaler, 2012) recommend, to improve the safety of the turning manoeuvre, the use of traffic lights for turning left (which prohibits this manoeuvre in Poland). The use of such traffic lights is mandatory at speeds above 50 km/h. The approach to the problem described in the article is therefore different in different countries.

## 2.2. U-turning literature and research review

The literature on U-turning indicates several directions for current research. The first area of research is the capacity analyses of U-turning places, both traffic signal controlled and unsignalled. These studies are conducted for turning places designated by a dividing lane outside intersections (Ben-Edigbe, 2016), (Mazaheri et al., 2020). They include the dependence of capacity on road geometry, as well as the analysis of gap acceptance. Other studies include the capacity of turning relationships at intersections with traffic lights (Khaled et al., 2017), (Abuhijleh et al., 2020). The results of these studies indicate the saturation flow values used in the capacity calculations or the correction factors for the calculations. Another direction of research is to change intersections where U-turning is performed into intersections where this manoeuvre is forbidden and to ensure that it can be performed outside the intersection. The purpose of such changes is to improve traffic conditions and road safety. Research points to several possibilities of implementing such a solution. One of them is to restrict the possibility of exiting a subdivision road to turning right only while leaving the possibility of turning left from the main road. Such an intersection, called "Restricted Crossing U-Turn Intersection" (RCUT) has been described in (FHWA, 2009), where the reduction of delays and number of collision points have been identified as advantages of this solution. It was indicated that this solution can be used at intersections with roads with lower traffic volumes, and there should be a wide dividing lane on the main road. Detailed design principles for such intersections are described in

(FHWA, 2014). Research (Ulak et al., 2020) indicates that it is possible to model the safety of such intersections and analyse geometric solutions (turning place distance) while still at the design stage. Another direction is the use of an intersection where left-turn relations from the main road and the sub-road are eliminated while leaving the possibility of straight traffic, which is referred to by the term "Median U-Turn Intersection Treatment" (MUTIT) (FHWA, 2007). This is equivalent to the junction known in Poland as a "cigar". When designing such an intersection, it is necessary to analyse geometric alternatives, the location of the intersection, rideability, MOEs, the possible use of traffic lights, road signs (including guide signs) and the impact on road safety. Research in this area focuses on defining criteria for the use of such a solution taking into account its efficiency and geometric parameters (Distefano et al., 2016). There are also studies showing traffic safety at such intersections, using simulation models and the traffic conflict analysis method (Kronprasert, 2020). They show an improvement in traffic safety after using a MUTIT-type intersection, but with an adequate distance between the U-turning places and the intersection with the cross road. Studies on the effectiveness of such intersections equipped with traffic lights (Bared et al., 2002) indicate an overall improvement in traffic conditions, but at the cost of increased delay for U-turning relationships. There has also been researched indicating the feasibility of using non-controlled intersections as U-turning locations and including an evaluation of traffic conditions at such intersections (Fan et al., 2013). The study also showed a solution to improve traffic conditions for turning vehicles by using double U-turning places, separate for light and heavy vehicles. Such a solution can be applied with narrower dividing lanes, but the literature only shows results of simulation studies and no examples of the application of such solutions in practice are known. A review of foreign literature indicates that there is a tendency to move U-turning places outside the intersection area. This improves traffic conditions for vehicles driving straight ahead (especially on the main road) and improves road safety by replacing dangerous left-turning manoeuvres outside the intersection. Also of importance is the fact that in such a case the driver has an easier task as he has to give way to a smaller number of traffic streams, which is a factor that improves safety (Szczuraszek et al.,

2008). The disadvantages of such solutions include poorer legibility of the junction, which requires the use of appropriate guide signs, and increased delays by vehicles performing manoeuvres at the junction. This limits the use of such intersections to situations where roads of clearly different significance in the traffic system intersect.

In Poland, there are few roads with a wide dividing lane. Therefore, the possibility of using MUTIT and RCUT type crossings is limited. There are only a few turning places designated outside intersections. In most cases, these are used to improve the efficiency of traffic control and are placed before the approaches of controlled intersections. For this reason, most U-turning manoeuvres take place at intersections. Intersections in cities were often established as uncontrolled intersections, with the increase in traffic using traffic lights with general signals, and later using directional signals and dedicated phases for left turns.

Traffic safety analyses of U-turning movements are hampered by the fact that accident databases only include accidents at which the police were present. And even for these accidents, the information is often incomplete and does not allow the exact cause of the accident to be determined (Żukowska, 2015). For this reason, indirect measures of road safety - e.g. the number of violations of a given type of regulation or the number of violations causing traffic disruption - can be used for analyses. At the same time, it should be noted that, according to research (Cieśla et al., 2020), the most important determinant of mode choice is travel time, while travel safety is only given sixth place, after the cost or comfort of travel.

Traffic analyses often omit U-turning vehicles because their number at many intersections is small, so turning does not have a very significant impact on intersection traffic - it is omitted from analyses of, for example, pedestrian behaviour (Thakur et al., 2019), cyclists (Cieśla et al., 2018) or left-turning vehicles (Yao et al., 2020). Similarly, studies on traffic control solutions are more general. Studies on timing displays (Sobota et al., 2018) do not often distinguish a separate evaluation of left-turning and turning signal groups, although they tend to have shorter green signal durations and longer waiting times for drivers to wait for the green signal, which may result in different behaviours from those of drivers going straight ahead. Also, among the factors

affecting traffic safety at intersections, no separate factors related to U-turning are identified (Wojtal et al., 2017). Studies on traffic safety refer to RCUT intersections, practically unheard of in Poland (Olearte et al., 2011). Similarly, the impact on traffic safety of removing a controlled intersection and replacing it with a Median U-Turn (MUT) intersection was analysed (Azizi et al., 2013).

### 3. Research fields

Intersections located at various locations in the city of Warsaw, Poland, were taken into consideration to evaluate the U-turning manoeuvre. All intersections used S-3 left-turn signals during the study period, which prohibit turning according to regulations (MI, 2002). Intersections with different geometric layouts and fairly high traffic volumes were selected for the study. Seven intersections were evaluated. The research was conducted in September, October and November 2017.

Intersection No. 1 - the intersection of Przczołkowa Street with Wilanowska Avenue. The analyzed lane is located on the southern approach of the intersection. There are two lanes designated for left turns, each 3.5 m wide. During the measurements, a fixed-time control was in operation at the intersection.

During the measurements, the conflicting turning traffic was moving from the lane marked with A-7 and P-13 signs. As a result of the non-adjustment of the intersection road signs to the regulations in force at the time (MI, 2003, 2015) and the lack of signalization in the entire area of the intersection, vehicles turning left and illegally U-turning from Przczołkowa Street were moving simultaneously with vehicles turning right from Wilanowska Avenue. This is a dangerous situation that endangers the safety of road users.

In the period after the measurements were conducted, the traffic lights were modernized and the colliding right-turn relation was controlled with directional signalling devices. In the initial period of operation of this solution, a very high number of conflicts between vehicles illegally U-turning and those turning right were observed. This was also caused by the routing of routes with a turning relationship by the navigation systems. After notifications to the navigation system operator, made among others by one of the authors of the article, routes including turning at this intersection were no longer determined.

Intersection No. 2 - Czerniakowska Street intersection with Gagarina Street and Nehru Street. Czerniakowska Street is a dual carriageway road with four lanes in each direction. The analysed road section is located on the northern approach of the intersection. The width of the traffic lane for turning left is 3.5 m. Vehicles turning left and illegally U-turning from Czerniakowska Street receive the green signal simultaneously with vehicles from this intersection driving straight ahead. Illegal U-turning is made difficult due to the queues of vehicles behind the intersection in the northbound direction. Due to the queues in front of the pedestrian crossing, drivers performing a turning manoeuvre stop in the middle of the intersection, impeding the movement of other vehicles, mainly those coming straight from Nehru Street. After the measurements were conducted, the traffic organization and the method of signal system control were changed at the intersection in connection with the construction of Polski Walczącej Avenue.

Intersection No. 3 - the intersection of Rolna Street with Niedźwiedzia Street. The analysed lane is located at the southern approach of the intersection. The lane width for the left turn is 3.5 m. Actuated control operates at the intersection. Vehicles turning left and illegally turning from Rolna Street have the green signal simultaneously with vehicles from the same approach going straight ahead. It has been observed that during one traffic light cycle, approximately three cars may turn left. During the tests, there was a large queue of vehicles, which caused many cars to pass on the yellow and red signal.

Intersection No. 4 - the intersection of Wolska Street with Sowińskiego Street. The intersection is four-leg. Wolska Street is a dual carriageway road with three traffic lanes in each direction, separated by a narrow dividing lane. In the area of the intersection, an additional lane for turning left has been introduced. The width of the traffic lane for turning left is 2.75 m.

Actuated control is used at the junction. Vehicles turning left and illegally U-turning from Wolska Street have the green signal simultaneously with vehicles from the same approach which are driving straight ahead and with vehicles from Sowińskiego Street, which have the signal for turning right displayed at that time. At the analysed intersection, vehicles were observed turning right from the southern

approach on a displayed yellow signal and in the initial seconds of a red signal. This situation may lead to traffic accidents with vehicles illegally U-turning from the north-eastern approach.

Intersection No. 5 - the intersection of Gandhi Street with KEN Avenue. The analysed lane is located on the south-western approach of the intersection. The lane width for turning left is 2.75 m. Actuated control operates at the intersection, adjusting the length of displayed signals for given groups depending on traffic conditions. Vehicles turning left and illegally U-turning from Gandhi Street have the green signal simultaneously with vehicles from the same street from the opposite approach turning left. After the measurements were made, the traffic lights were upgraded and an S-3 directional signal allowing left turns and U-turns were installed on the approach covered by the measurements.

Intersection No. 6 - The intersection of Wilanowska Avenue with Rolna Street and Bukowińska Street. The analyzed lane is located on the south-east approach of the intersection. The width of the traffic lane for left turns is 3 meters. Actuated control operates at the intersection. Vehicles turning left and illegally turning from Wilanowska Avenue receive the green signal simultaneously with vehicles from Rolna Street, which receive the displayed signal for turning right.

Intersection No. 7 - The intersection of Żwirki i Wigury Street with Pruszkowska Street. The analyzed lane is located on the southern approach of the intersection. The width of the lane for turning left is 3 m. Actuated control is used at the intersection. Vehicles turning left and illegally turning back receive the signal simultaneously with vehicles from the same approach going straight ahead and vehicles from Pruszkowska Street, which at the time display the signal for turning right.

#### 4. Research method

The research was carried out using a Panasonic Lumix camera. From the observation point, the drivers' behaviour at the observed intersection was recorded. The recordings from the camera allowed for a more in-depth analysis of the method and consequences of turning. The measurements were made in a way that was unnoticeable for the road users. This allowed eliminating the behaviour of drivers, whose actions could be changed during the observation.

The tests were carried out at different times and on different days of the week. The minimum sample size for which conclusions could be drawn was set as 25 turning vehicles for one measuring point. To obtain as many turning drivers as possible, measurements were made for 1.5 hours at each intersection. According to research (Hadi et al., 1995), 45% of traffic accidents at urban intersections were caused by heavy traffic. For this reason, the surveys were usually carried out during the morning or afternoon rush hours. The measurements were carried out during rain-free days in September, October and November 2017.

Driving behaviour is influenced by many factors, related to the current traffic situation and directly to the driver, including the driver's gender, age, familiarity with the infrastructure they are on and the purpose of driving, the need to hurry, habits (Fuller et al., 2002). During the measurements taken, the turning drivers were classified into different categories such as the type of vehicle, the place of registration of the vehicle they were driving, the gender and age of the driver and the presence of a passenger.

In the category of the type of vehicle driven, a distinction was made between passenger cars, heavy vehicles (vans, trucks, buses) and single-track vehicles. Based on the number plates, vehicles were divided into three categories: registered in Warsaw, registered up to 30 km from Warsaw, and registered more than 30 km from Warsaw.

The surveyed drivers were also divided into men and women. In the driver age category, three age ranges have been established, based on estimations only. These are 18-30 year-olds, 31-50 year-olds and 51+ year-olds.

## 5. Research findings

### 5.1. Results of fieldwork

Surveys were conducted and observation sheets completed for all locations. Overall, the number of incorrect U-turns during the 1.5 hours of observation at each location is shown in Table 1.

Table 1. Number of illegal U-turners at intersections

Intersection	1	2	3	4	5	6	7
Number of illegal U-turns	79	61	25	94	46	53	47

The behaviour of drivers U-turning inappropriately at individual intersections was analysed in depth.

The paper presents a comparative analysis of the results of measurements at individual intersections. Summary results of measurements at all intersections are presented in Table 2. Abbreviations used in Table 2 mean: RP - vehicle type (SO - a passenger car, PC - heavy vehicle, PJ - single-track vehicle); MRP - a place of vehicle registration (1- registration in Warsaw, 2 - registration up to 30 km from Warsaw, 3 - registration over 30 km from Warsaw); PK - gender of the driver (K - women, M - men); WK - age of the driver (1 - 18-30 years, 2 - 31-50 years, 3 - over 51 years).

Table 2. Aggregate results of measurements at all intersections

Intersection	Intersection Results by category in [%]											
	RP			MRP			PK		WK			
	SO	PC	PJ	1	2	3	K	M	1	2	3	
1	99	1	0	72	11	17	39	61	27	61	12	
2	89	3	8	77	8	15	27	73	34	41	25	
3	92	8	0	84	4	12	32	68	20	44	36	
4	96	2	2	63	17	20	30	70	31	57	12	
5	100	0	0	76	15	9	41	59	37	41	22	
6	89	9	2	78	9	13	34	66	28	58	14	
7	85	11	4	68	19	13	34	66	19	51	30	

The table shows that the most common vehicle was a passenger car. It was noted that those turning with a heavy vehicle would have difficulty manoeuvring due to the geometry of the intersection. This could be due to the large dimensions, large turning radius and low dynamic capabilities of the car.

When analysing the percentage share of turning drivers in relation to the place of vehicle registration, the highest number of recorded vehicles was registered in Warsaw.

At each studied intersection, the percentage share of women was significantly lower than that of men. At each intersection, the most numerous age group was between 31 and 50 years old.

When measurements were made at different intersections, different effects of turning were detailed. To obtain a comparative analysis of the intersections, Table 3 shows the effects of turning at unauthorised places for each intersection.

The effects of turning were defined as follows: A - passing safely without forcing priority on another traffic participant, B - forcing another driver to reduce speed slightly, C - forcing another driver to reduce speed significantly, D - forcing another driver to stop at the intersection, E - running into the kerb.

Table 3. The effects of U-turning at intersections

Intersection	Effects of U-turning [%]				
	A	B	C	D	E
1	91	4	1	4	0
2	94	4	0	2	0
3	64	4	12	0	20
4	81	4	11	4	0
5	76	10	14	0	0
6	70	18	10	2	0
7	69	23	6	2	0

Based on Table 3, graphs were created (Figure 3 and Figure 4), taking into account only the negative effects caused by illegal U-turning. Based on the data from the graphs, it is possible to identify the locations where drivers most frequently disrupted the flow of traffic. Intersection 3 recorded the highest proportion of negative impacts of illegal U-turning. Drivers were mainly entered on the kerb and forcing other road users to significantly reduce their speed. The reason for such a bad result may be the prohibition of turning at 1.7 km before the intersection and the geometry of the intersection, mainly the radius and width of the island dividing the carriageways. Intersection No. 7 had the highest percentage of people who forced another traffic user to slightly reduce speed. Among the observed intersections, the largest number of people forced a significant change in speed at intersection No. 5. The main reason for this phenomenon was that they performed the turning manoeuvre too slowly.

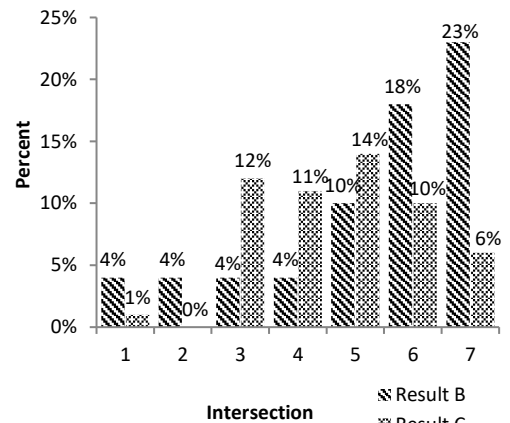


Fig. 3. The percentage share of U-turners according to the effect of turning back depending on the crossroads part 1

Intersections No. 1 and No. 4 had the highest number of people who forced other drivers to stop their vehicle completely. In the first location, this was due to a lack of awareness of the priority at the given intersection. At the second one, it was due to waiting too long before carrying out the turning manoeuvre, which resulted in the signal being changed to prohibit entering the intersection. It can be deduced from the observations that there is a variation in the effects of the U-turning manoeuvre at different intersections.

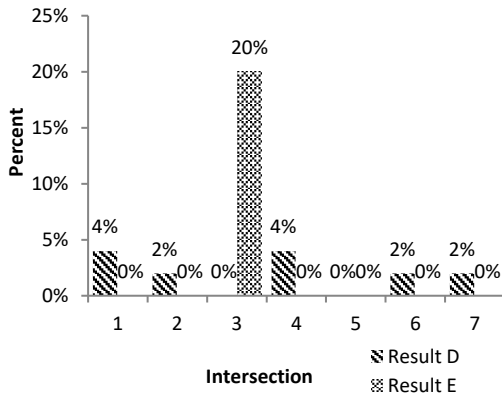


Fig. 4. The percentage share of U-turners according to the effect of turning back depending on the crossroads part 2

For all measurement points, a summary of the occurring effects of U-turning (A - safe passage, B - disruption of traffic flow) depending on the gender of the driver was created (Table 4).

Table 4. Percentage of U-turners according to the sex of the driver and the effect of U-turning at intersections

Intersection	Number of U-turners according to the sex of the driver and the effect of the crossing [%]			
	Female		Male	
	A	B	A	B
1	87	13	94	6
2	94	6	95	5
3	75	25	59	41
4	83	17	78	22
5	88	13	70	30
6	61	39	74	26
7	81	19	61	39

Based on Table 4, graphs were created (Fig. 5, Fig. 6), depicting the percentage of female and male U-turners depending on the intersection.

Based on the graphs in Figures 5 and Figure 6, it is possible to compare the effects of U-turning among women and men at different intersections. The greatest discrepancies in negative impacts can be observed at intersections #3 (a greater proportion of negative impacts among males), #5 (a greater proportion of negative impacts among males), #6 (a greater proportion of negative impacts among females), and intersection #7 (a greater proportion of negative impacts among males). At the remaining intersections, the differences are less than 10%.

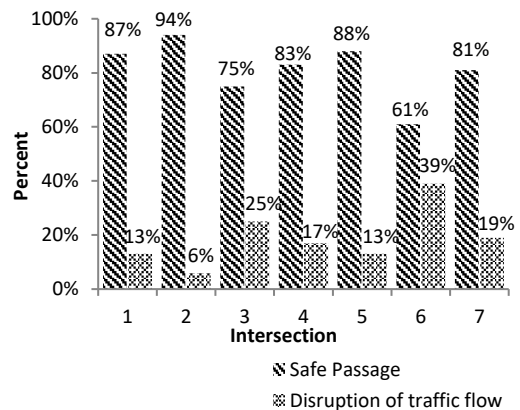


Fig. 5. Percentage of women turning back depending on the intersection

The persons who turned back more often at the selected measurement points were men. Based on the study, it can be concluded that they more often negatively affected the traffic flow while manoeuvring. On this basis, it can be concluded that the driver's gender has an influence on turning in a prohibited place.

Table 5 shows the summary results for the number of turning drivers by age range and the effect of the manoeuvre at the different measurement points (A - safe crossing, B - disruption to traffic flow). Analysis of the data shows that intersection #7 recorded the highest number of negative U-turning impacts for 18 to 30-year-olds. Within this age range, the highest number of turning drivers who safely crossed the intersection was recorded at intersection 2, with all negative impacts involving forcing another road user to slightly change speed.



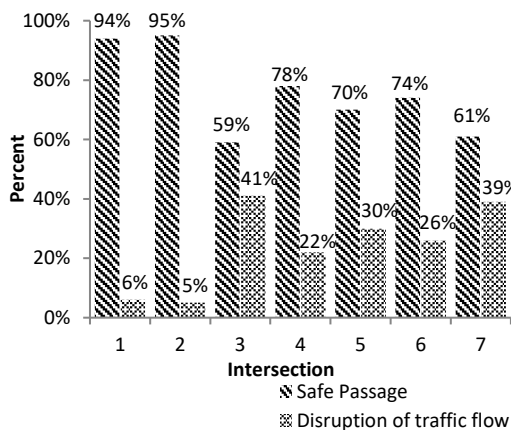


Fig. 6. Percentage of men turning back depending on the intersection

Table 5. Percentage of U-turners according to the age of the driver and the effect of turning back at junctions

Intersection	Number of U-turners according to the age of the driver and the effect of the crossing [%]					
	18-30		31-50		51+	
	A	B	A	B	A	B
1	91	9	89	11	100	0
2	95	5	100	0	87	13
3	80	20	10	0	50	50
4	72	28	85	15	73	27
5	87.5	12.5	75	25	60	40
6	73	27	65	35	86	14
7	56	44	67	33	86	14

Drivers between the ages of 31 and 50 were the most common group among those surveyed. At the two measurement points, 100% of the U-turning drivers passed safely, without obstructing other drivers. The overall share of drivers who more or less disrupted the traffic flow in this age category was 17%. This is the best result among the surveyed age groups.

At intersection No. 3, the highest share of cases of performing a U-turning manoeuvre in a way that impeded the traffic flow of other vehicles was noted. Such behaviour constitutes as much as 50% of all recorded situations. Among all age groups, the overall percentage of negative consequences of turning is the highest for adults over 51 years old.

Based on conducted measurements, it cannot be unambiguously determined which drivers in which age

bracket cause most traffic obstructions at selected intersections. Different percentages of individual consequences of an improper manoeuvre were recorded at the measurement points. Based on the presented data, it may be concluded that the age bracket of drivers does not influence the decision to perform a U-turn.

## 5.2. Analysis of traffic accident data

The analysis of traffic accidents related to wrong U-turning in 2017 in Warsaw showed that 105 accidents took place in this period. Only one location has a significantly higher number of accidents of this type as many as 7. This is Górczewska Street, in the vicinity of the Wola Park Shopping Centre. In this place in that period was introduced temporary traffic organization associated with the construction of the second line of the underground. At the remaining intersections no more than 1 accident caused by an incorrect U-turn was observed. This gives rise to a suspicion that these accidents are qualified as other accidents including side events.

Traffic accident statistics for 2017 were analysed for the intersections included in the analysis. The number of traffic accidents at each intersection is shown in Table 6.

Table 6. Traffic accidents at analysed intersections

Intersection	Number of accidents in 2017	Number of side crashes in 2017
1	9	1
2	18	3
3	2	0
4	7	2
5	0	0
6	7	3
7	1	0

There are numerous rear-end crashes at intersections that are unrelated to U-turning and lateral crashes related to lane changes, which were omitted from the analysis and are not shown in Table 6. The SEWiK database does not contain detailed information on accidents, so it is impossible to link a given accident to an intersection approach, and accidents classified as sideswipe accidents may occur in different situations and locations at the intersection.

However, statistical analysis was carried out by determining Pearson and Spearman correlation coefficients between the measured numbers of misbehaviour, speeding violations, stopping violations, total

priority violations and the number of traffic accidents or the number of side crashes. No statistically significant relationship was found in any of the cases. Various regression functions were determined using tools for selecting the best regression function, e.g. linear regression, LOESS regression (Long et

al., 2019). It was found that in each case of regression between the values, the coefficients have a very wide confidence interval at the level of 0.95, practically in the whole length reaching or crossing the horizontal axis. Example plots for the number of events and the number of side crashes versus the number of violations are shown in Figures 7 and 8.

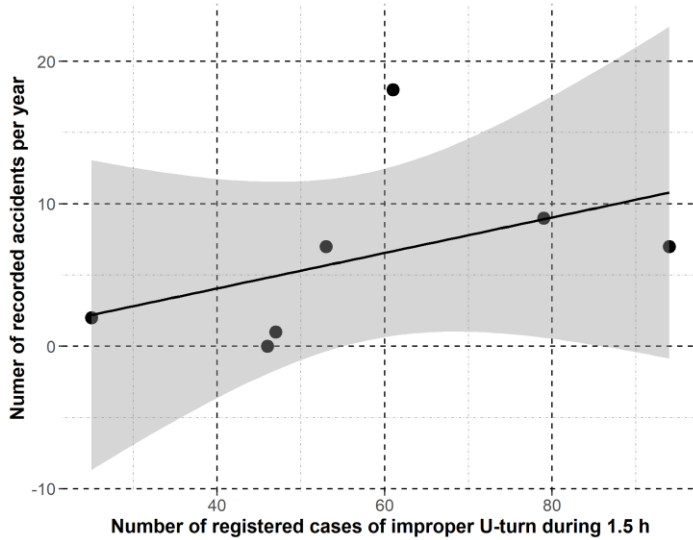


Fig. 7. Number of accidents with 0,95 confidence interval

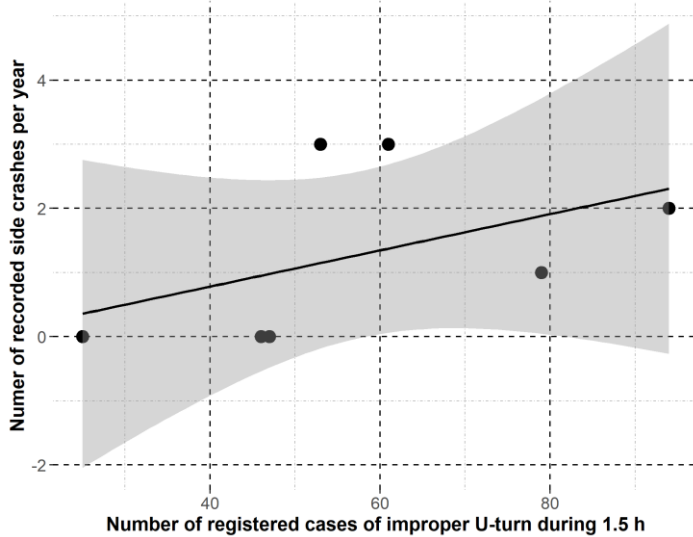


Fig. 8. Number of side crashes with 0,95 confidence interval

For the number of traffic accidents and the number of side crashes, multivariate linear regression was performed between the number of speed reduction enforcements, stopping enforcements and kerb invasions. The results of the analysis are presented in Tables 7 and 8.

The estimated values of all coefficients close to zero, with a very large standard deviation, a high probability Pr and a wide confidence interval, indicating that the model variables do not significantly affect the number of events and the number of side crashes. Analogous conclusions for the whole can be drawn by analysing the R<sup>2</sup> coefficient of 0.5678 for the number of events and 0.2565 for the number of side crashes and the p-value of 0.414 and 0.7973, respectively.

The conducted analysis did not show any relationship between indirect measures of road traffic safety and the number of traffic accidents at the analysed intersections. Therefore, it is not possible to forecast direct measures of road traffic safety based on the results of the conducted measurements. Another problem identified during the analysis is a small number of accidents with police participation in their elimination, and only such accidents are included in the SEWiK database, as well as a small scope of data included in the SEWiK database.

## 6. Summary and conclusions

Based on the conducted measurements, it may be stated that U-turning in prohibited situations is a phenomenon commonly occurring at controlled intersections in Warsaw. On average, 58 drivers U-turned at the analysed intersections during a 1.5-hour observation period. Most cases of illegal turning take place safely, which is due to good visibility and legibility of priority rules and wide exits at most of the analysed intersections. The situation is different in the case of conflicts with vehicles moving on a signal allowing U-turning with the vehicles moving on the right turn on red signal (so-called “green arrow”) from a perpendicular approach - in this case, the visibility is much worse and the priority rules are not clear, as drivers do not know what signal is displayed for the other driver. However, analyses of traffic accidents indicate that the number of recorded traffic accidents at the analysed intersections is not significant and is not statistically significantly related to the recorded irregularities while U-turning. The main conclusion that can be drawn from the research is that the use of an S-3 directional signal allowing only left turns is not an effective means of ensuring the elimination of illegal U-turning at the intersection. The reason for this situation is the widespread lack of knowledge of the provision prohibiting U-turning in such a situation.

Table 7. Regression model analysis for the number of road accidents

Variable	Estimate	Std. Error	t value	Pr(> t )	Confidence interval of the regression coefficient	
					2,5%	97,5%
Number of speed reduction forces	-0.78693	0.50373	-1.562	0.216	-2.39002	0.81616
Number of Forces to Stop	0.33841	1.89268	0.179	0.869	-5.68495	6.36176
Number of curbs hits	-0.01379	0.37197	-0.037	0.973	-1.19757	1.16999

Table 8. Regression model analysis for the number of side crashes

Variable	Estimate	Std. Error	t value	Pr(> t )	Confidence interval of the regression coefficient	
					2,5%	97,5%
Number of speed reduction forces	-0.03984	0.14681	-0.271	0.804	-5.29283	7.91056
Number of Forces to Stop	0.20143	0.55163	0.365	0.739	-1.55409	1.95695
Number of curbs hits	-0.04154	0.10841	-0.383	0.727	-0.38656	0.30348

It would be advisable to apply supplementary driver education aimed at maintaining and enriching knowledge of traffic regulations (Szczuraszek, 2008).

Other conclusions concerning particular categories of traffic participants indicate that, although the problem concerns the whole cross-section of the driving population, educational activities should be directed in particular to older male drivers.

The conclusions of the research should also be used at the various stages of the life cycle of road infrastructure. At the stage of traffic planning and forecasting, proper planning of the road network is essential, including the designation of U-turning places. Such places should result from traffic measurements and, in the case of a newly designed road, from traffic forecasts. The possibility of U-turn should not be eliminated at the initial stage of making traffic forecasts to identify places where it is necessary. This, therefore, requires an update of the macroscopic traffic models used to perform forecasts.

At the stage of road design, it is necessary to design the possibility of U-turning at junctions where the traffic of U-turning vehicles is forecast. The surroundings of the road and the possibility of access to facilities located on the road should be analysed. The U-turning should provide adequate rideability. Solutions presented in foreign literature for the design of U-turning places allow the elimination of the phenomenon described in the article. However, these solutions can only be applied at selected intersections, and Polish roads, with narrow dividing lanes, do not allow their widespread use. Nevertheless, during the design of new roads and a thorough reconstruction of existing roads, such a solution may be considered. One of the methods of eliminating U-turning at unauthorised places is to provide an opportunity to safely perform this manoeuvre at designated places. Often U-turning at unauthorised places is caused by the lack of possibility to perform this manoeuvre on a long section before and after an intersection.

During road operation, U-turning at forbidden places can be eliminated by proper drafting of maps used in car navigation systems - it is necessary to eliminate in these maps the relation of U-turning at a place, where it is forbidden in the current traffic organization, although in reality this activity is not performed. U-turns in prohibited locations may be

caused by the navigation system's designation of such a route and the driver's reluctance to take a route with a longer travel time. This phenomenon increases especially during periods of congestion on the road network (Juhász et al., 2017).

In cases where illegal turning is the cause of repeated traffic accidents at the operational stage, other traffic organisation measures should be applied, e.g. additional B-23 "No U-turning" signs. Although their use is not formally necessary when an S-3 traffic signal is used for vehicles turning left, it unambiguously prohibits drivers from U-turning at a given place.

It should be noted that even the Road Safety Audit Manual (Podręcznik audytu BRD, 2019) does not provide guidance for evaluating a road for the placement of U-turning areas. In the opinion of the authors, this manual should be supplemented with issues related to U-turning, at each stage of the road safety audit. In particular, the need to pay attention to considering the location of U-turning places in conjunction with the development of the road environment should be emphasised. If on the section between intersections on a dual carriageway there are sources or destinations (including individual exits), there will be the phenomenon of U-turning connected with servicing those facilities, even not complying with the regulations. As such, provision must be made at the design stage for legal U-turning to and from these facilities. The importance of this issue increases as the road safety audit procedure is being extended to non-TEN-T roads in 2021 (Directive (EU) 2019/1936, 2019).

The problem with implementing a U-turn is often the width of the dividing lane (e.g. intersection No. 3), which does not make it possible to ensure passage for all vehicles. In such cases, a solution applied by, among others, the Mobility and Transport Policy Office of the Municipal Office of the Capital City of Warsaw and the General Directorate for National Roads and Motorways (GDDKiA) in Warsaw is the use of the S-3 directional signal device permitting a U-turn and the placement of the B-23 "No U-turn" sign with a label reading "Not for passenger cars and single-track vehicles". It is also possible to additionally widen the road shoulder to ensure passability for long vehicles.

These proposals apply to all types of traffic lights. The issues related to the proper handling of turning movements are dealt with in the earlier design

stages, before the development of the traffic control algorithm. Therefore, once the presented conclusions are taken into account, any control algorithm can be used e.g. (Sathiyaraj et al., 2020), (Zhao et al., 2018), (Lin et al., 2020).

During the operational stage of the road, more frequent traffic police checks are also recommended at intersections where the problem of improper U-turning has been diagnosed. Consistency and punishment of traffic violators should effectively improve road safety. In countries with strict penalties for non-compliance with traffic regulations, drivers are less likely to break them. The best examples of such countries are the USA and Sweden (Szczuraszek, 2008).

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