# PREREQUISITE FOR ACCIDENT-FREE TRAFFIC AT SIGNAL-CONTROLLED INTERSECTIONS

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**Abstract**
**Introduction:** Improving intersection capacity will not be possible without accounting for traffic safety. **Purpose of the study:** We aim to determine the prerequisite for accident-free traffic at signal-controlled intersections with turning traffic flows. **Methods:** In our study, we used the methods of observation, comparison, and mathematical analysis. **Results:** We have carried out a field observation of traffic intensity at signal-controlled intersections in the city of Yekaterinburg, focusing on vehicles that moved when the green light was on. We have also analyzed traffic flow moving in three directions in the same lanes. We have discovered that traffic accident likelihood is the highest (54%) at four-way intersections. Three-way intersections account for 44% of traffic accidents, while the remaining 2% of accidents occur at multi-way intersections. Furthermore, we have determined the additional factors that impact safety in turning traffic flows at intersections. Our study demonstrates that in order to ensure maximum intersection capacity, the duration of the traffic signal cycle must be adjusted with the minimum safe distance between vehicles in mind.

**Keywords**
Traffic safety, traffic signal cycle duration, signal-controlled intersection.

## Introduction

The rise in the number of vehicles within the street and road network over the recent years has made it necessary to adjust the assessment of traffic signal cycles, and justify this adjustment through research. Today, large cities experience major fluctuations in the excess duration of the traffic signal cycle, which can reach 150 seconds, 180 seconds, 200 seconds, or even more. Therefore, the number of traffic accidents at intersections remains high, especially at intersections with turning traffic flows. This means that the current methods of setting up traffic signal modes need to be changed.

An analysis of studies by different authors from various countries shows that traffic safety at intersections largely depends on intersection traffic management; notably, ensuring safety is reduced to calculating the duration of the traffic signal cycle.

This prompts a conclusion that one of the main problems of traffic management lies in determining the appropriate duration of the traffic signal cycles that would simultaneously ensure maximum capacity and traffic safety at signal-controlled intersections. The current methods of assessing traffic signal cycles are centered around the key concept of saturation flow. But none of these methods account for the changes in traffic speed rate at intersections with turning traffic flows. When making a turn, vehicles tend to change speed due to a number of factors, such as situations when the vehicle in front slows down abruptly either before the turn or directly after the turn, as well as the sudden emergence of road obstacles (pedestrians), bumps on the traffic lane, etc. In light of the above, the goal of this study is to find the prerequisite for accident-free traffic at signal-controlled intersections with turning flows, by using the methods of observation, comparison, and mathematical analysis. This prerequisite is essential for determining the duration of the traffic signal cycle.

## Methods

The observation methods used in our study have shown that the concept of «saturation flow» has completed a lengthy development process, sufficient for its efficient application to traffic management at signal-controlled intersections.

The need for traffic management arises when the road users' paths intersect on the same plane. If traffic intensity is low, traffic is managed through priority traffic signs. As traffic intensity rises, especially if traffic was already intense along the main road, minor road traffic becomes reduced or almost impossible. At the same time, the number of accidents at such intersections also tends to rise. This creates a need for signal control.

It is a known fact that about 40% of all RTAs occur at intersection conflict points. A look at accident statistics in cities reveals that the number of RTAs at intersection conflict points is even higher there. Simultaneously, this reduces intersections' traffic capacity. According to Gorev (2013), the common intersection classification includes the following types:

– three-way intersections (intersections where three approach routes join together);
– four-way intersections (the most widespread type, where four approach routes join at different angles);
– multi-way intersections (uncommon intersections with five or more approach routes).

Analysis of the number of RTAs allows us to conclude that almost all of them occur at the intersection of traffic lanes with moving vehicles when the vehicles' trajectories overlap. These include places when the traffic flow merges or splits. RTA observation practice shows that traffic flows overlap, merge, and split most commonly at intersections where traffic moves in different directions (Gorev, 2013). The analysis of RTAs in different regions allows us to conclude that, despite the significant difference in traffic conditions, the overall distribution of accident locations reaffirms the conclusion above.

Figure 1 illustrates the possible configurations of intersections according to Matson et al. (1960), which still exist today.

Intersections with differing geometrical features have a great impact on determining the duration of the traffic signal cycle. Restriction of traffic flows at intersections when not of all the intersection's reserve capacity has been used up is caused by irrational traffic signal operation and the increasing number of RTAs. This creates long lines of vehicles at the approaches to the intersection. The conditions at one intersection may spread to other intersections, which will render traffic management on the relevant road segment impossible (Tsarikov, 2010).

The emergence of traffic signals as a tool for managing traffic and pedestrian flows led to new types of tasks, as the duration of traffic flow movements in different directions now needed to be regulated without involving a traffic controller. This prompted an assumption that traffic signals would help improve the traffic capacity of signal-controlled intersections. The common belief when determining the green light duration is that all vehicles are moving regularly and simultaneously. But field observations of actual vehicles on the road disprove this belief. The largest deviations in irregular traffic flow occur in that segment of the flow that includes several vehicles that both start and stop moving at a green light.

Such random timing of vehicle start-up has been known for a long time. But still, all calculations keep being built on the assumption that it is possible to determine the number of vehicles by referencing

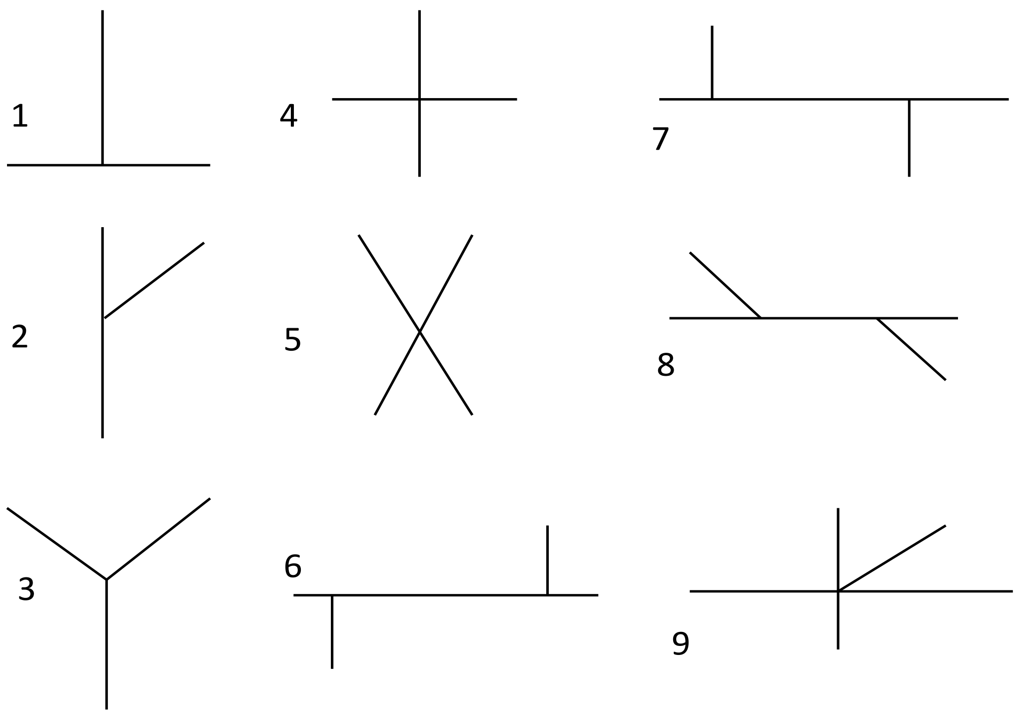


Figure 1. Types of intersections: 1, 2, 3 — three-way intersection; 4, 5, 6, 7, 8 — four-way intersection; 9 — multi-way intersection

DOI: 10.23968/2500-0055-2021-6-1-73-80

traffic flow segments with stable parameters.

Therefore, introducing the concept of «saturation flow» has become necessary for properly assessing the duration of traffic signal cycles. In fact, this concept now lies at the core of assessing traffic signal cycle duration. An analysis of studies by different authors from various countries shows that the definition of what we call saturation flow is based on a number of assumptions, all of which, in turn, stem from empiric observations. For instance, Wodrop (1952) defines saturation flow as traffic flow that occurs when vehicles are following one another at minimum achievable headway. During each phase, vehicles arrive in traffic flow q, with the appropriate subscript being added; the interval, therefore, equals *1/q*. Some vehicles stop for the duration of the red light, which equals r. When the light goes green, the first vehicle in line dashes ahead; but this happens due to acceleration, rather than lost time a. The vehicles that follow move at equal intervals without waiting. During this time period, when vehicles move one after the other at minimum achievable headway, traffic flow p becomes the «saturation flow». For the remaining green light duration, vehicles arrive and leave at intervals of *1/q* without delay.

Yu. A. Kremenets (Kremenets and Pechersky, 1977) believes that saturation flow exists in situations when vehicles move most actively at a green light in a dense traffic flow.

The Guidelines on Traffic Management in Cities define saturation flow as the highest intensity of traffic moving at a green light, measured in vehicles per hour. It is recommended to measure the saturation flow during field observations, provided that the number of vehicles in the traffic flow before the intersection meets the requirements (Ministry of Internal Affairs of the USSR, Ministry of Housing and Utilities of the RSFSR, 1974).

The Guidelines on Designing Urban Streets and Roads interpret saturation flow as the highest number of vehicles moving in a traffic lane at a speed of 15 km per hour when the traffic flow is uninterrupted (Central Research and Design Institute for Urban Development of the National Committee for Civil Engineering and Architecture, 1980).

Yu.A. Vrubel notes that saturation flow occurs when there is a certain average value that characterizes the departure of vehicles from the stop line at the intersection at a green light (Vrubel, 1988).

Further attempts to give saturation flow a more accurate definition were also made by authors specializing in traffic management, who presented the following interpretations of the saturation flow concept:

- for example, saturation flow could be interpreted as the number of vehicles that pass through an intersection over a given period of time, namely when the green light is on (Canada) (Teply et al., 1995);
- another example is the number of vehicles that pass through an intersection over a certain period of time under base conditions. Base conditions are conditions when the green signal is available and no lost times are experienced (USA) (Transportation Research Board, 2000);
- the next example is the highest number of vehicles that pass through an intersection over a certain period of time and are capable of leaving the intersection while the green light is still on (Germany) (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2001).

As noted by A. G. Levashev in his study, a possible way to improve the results of design operations in traffic management at signal-controlled intersections would be to improve the accuracy of describing traffic flow characteristics, as well as propose new study methods or adjust the current methods for actual real-life traffic (Levashev, 2004). A. G. Levashev himself proposes a method for calculating the ideal saturation flow at signal-controlled intersections. This method requires designing a regression model that would help pinpoint the moment when the vehicle's position in the «queue» and the time frame (for a passenger car) get balanced. A. G. Levashev believes that the viability of this model is reaffirmed by traffic observation statistics.

As we summarize the proposals for defining the ideal saturation flow, we note the following: all authors agree that this requires describing the various characteristics of the traffic flow that moves through an intersection at a green light; notably, the traffic flow in this context only includes passenger cars. Aside from the above, there also are a number of factors that are necessary to ensure that the saturation flow is ideal: the lane should be 3.6 m wide; the slope inclination at the approach to the intersection should be 0%; the road surface should be dry; there should be no interference on the part of parking cars and public transport stops; there should be no conflicting pedestrian, bicycle, or vehicle flows, or any trucks or buses in the traffic flow (Transportation Research Board, 2000).

We carried out our field observations of traffic flows moving in three directions along the same lanes between 2010 and 2019. The study involved almost 500 intersections. For our analysis, we selected intersections with high traffic intensity and turning flows. To reaffirm the results of our analysis, we contrasted reference data against the traffic conditions at real-life intersections with the highest number of RTAs per year. Our analysis of the intersections in question shows that 72% of them are signal-controlled, while 28% are not controlled (Fig. 2).

By using the comparison method, we were able to contrast the actual number of vehicles passing through the intersection against the reference number. Our field observations showed that during the green interval, braking tends to occur in a part

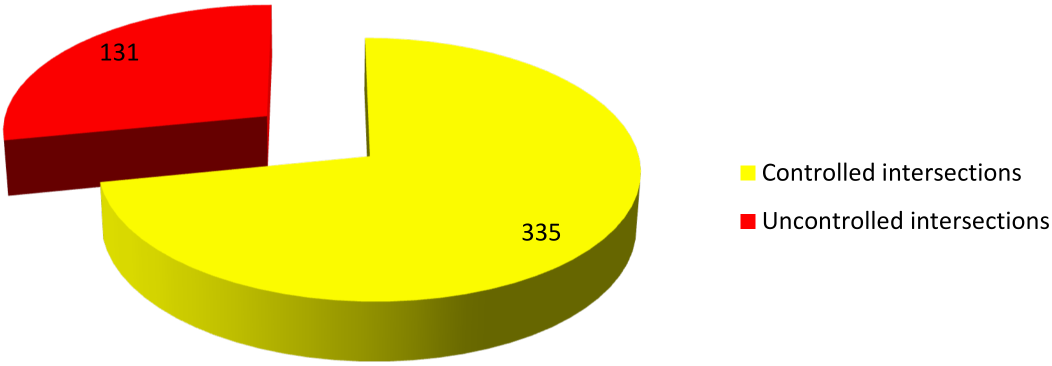


Figure 2. Distribution of accident-prone intersections

of the traffic flow moving through intersections with turning flows, for a variety of reasons, including situations when the vehicle in front slows down abruptly either before the turn or directly after the turn, as well as the sudden emergence of road obstacles (pedestrians), bumps on the traffic lane, and the presence of turning flows. Notably, braking happens from two to five times, depending on the intersection's configuration. For this reason, the actual number of cars that end up passing through the intersection with turning flows is significantly lower than the reference number, determined by applying the current method of assessing the duration of the traffic signal cycle (Webster and Cobbe, 1966). As the vehicle in front abruptly decelerates, this may cause the vehicle behind to crash into it. Therefore, it is necessary to set the minimum value for a safe distance between moving vehicles; this value can later be used for determining the green interval duration. The movement of vehicles at a green light at a minimum safe distance will be the prerequisite for accident-free traffic. The green interval must be adjusted for the minimum safe distance between moving vehicles $S^0_{\min}$ (1) (Gasilova, 2017):

$$S^0_{\min} = \left(V_2^0 t_{2d} - V_1^0 t_{1d}\right) + \frac{2}{3}\left[V_2^0\sqrt{\frac{2V_2^0}{\alpha_2}} - V_1^0\sqrt{\frac{2V_1^0}{\alpha_1}}\right], \quad (1)$$

where $V_1^0$ is the speed of the first vehicle; $V_2^0$ is the speed of the second vehicle; $t_{1r}$ is the response time of the first vehicle's driver; $t_{2r}$ is the response time of the second vehicle's driver; $t_{1rd}$ is the first vehicle's brake drive response delay; $t_{2rd}$ is the second vehicle's brake drive response delay;

$$t_{1d} = t_{1r} + t_{1rd};\ t_{2d} = t_{2r} + t_{2rd};\ \alpha_i = \frac{j_i}{T_i - t_{id}},$$

where $i = 1$ is the first vehicle, $i = 2$ is the second vehicle; $j_1$ is the deceleration of the first vehicle; $j_2$ is the deceleration of the second vehicle; $t_{1db}$ is the first vehicle's deceleration build-up time; $t_{2db}$ is the second vehicle's deceleration build-up time;

$T_1 = t_{1d} + t_{1db}$; $T_2 = t_{2d} + t_{2db}$.

When we use the current method for determining the green interval duration, the resulting value does not account for the impact of the aforementioned factors on the number of vehicles that pass through the intersection. In other words, the current methodology of calculating the duration of the traffic signal cycle needs to be changed in a way that will allow for both determining the green interval duration and accounting for the minimum safe distance.

**Results**

We have obtained our experimental data at a four-way intersection with turning flows in the city of Yekaterinburg. The intersection is signal-controlled, with four phases. The green light duration during the turning flow phase is 57 seconds. The traffic intensity at the right turn is 487 vehicles per hour. We have examined the intersection to determine the distance between vehicles stopping at a red light, the distance between vehicles moving at a green light, and the structure of the traffic flows. We have discovered that when vehicles move straight ahead or turn right at the intersection, while staying in the same lane, the flow slows down between two and five times. Furthermore, this lag tends to affect vehicles in «batches», three cars each. In addition, we have reaffirmed that one of the most important factors that ensure traffic safety is the minimum safe distance between vehicles, which makes it possible to prevent RTAs in any traffic conditions.

We have discovered that traffic accident likelihood is the highest (54%) at four-way intersections. Three-way intersections account for 44% of traffic accidents, while the remaining 2% of accidents occur at multi-way intersections. The share of accident-prone intersections with traffic flows that move in two or three directions along the same lanes is 82%.

Calculations based on field observations have shown that the average speed of vehicles during the 57-second green interval is 4.3 m per second. If we determine vehicle speed without taking into account the deceleration of the traffic flow, then it is going to equal 5.39 m per second. This means that the actual

DOI: 10.23968/2500-0055-2021-6-1-73-80

speed is reduced by approximately 21% compared to the reference value. The practical assessment of the traffic signal cycle duration involves calculations in line with the current methodology, where the given value of the saturation flow does not change over the entire green interval duration. Research shows that vehicle speeds fluctuate greatly at different intersections, depending on visibility conditions, intersection configuration, climate, driver experience, and more. At the same time, in order to ensure traffic safety, it is necessary to be mindful of the minimum safe distance between vehicles, which, if we take vehicle speed at 4 m per second, equals 8.3 m. It is known that, in signal cycle duration calculations that follow the current methodology, the average length of a passenger car is assumed to equal 5 m. Experimental data shows that, when the speed equals 4.3 m per second, cars move at a distance ranging between 5 and 9 m from one another. That means that the sum of the car length and the distance between cars averages at 12.2 m. To ensure that the cars move at a speed of 4 m per second while maintaining the minimum safe distance, as obtained through analysis, this sum should equal 13.3 m.

Therefore, the green interval needs to be prolonged by 5.9 seconds, to allow for the safe passage of vehicles that did not have time to go past the intersection. Depending on the green interval duration in situations at the intersections when vehicles go straight and to the right along the same lane, the interval should be increased by an average of 8–15%, which can be taken into account by introducing an adjustment factor into the existing methods of assessing the signal cycle duration.

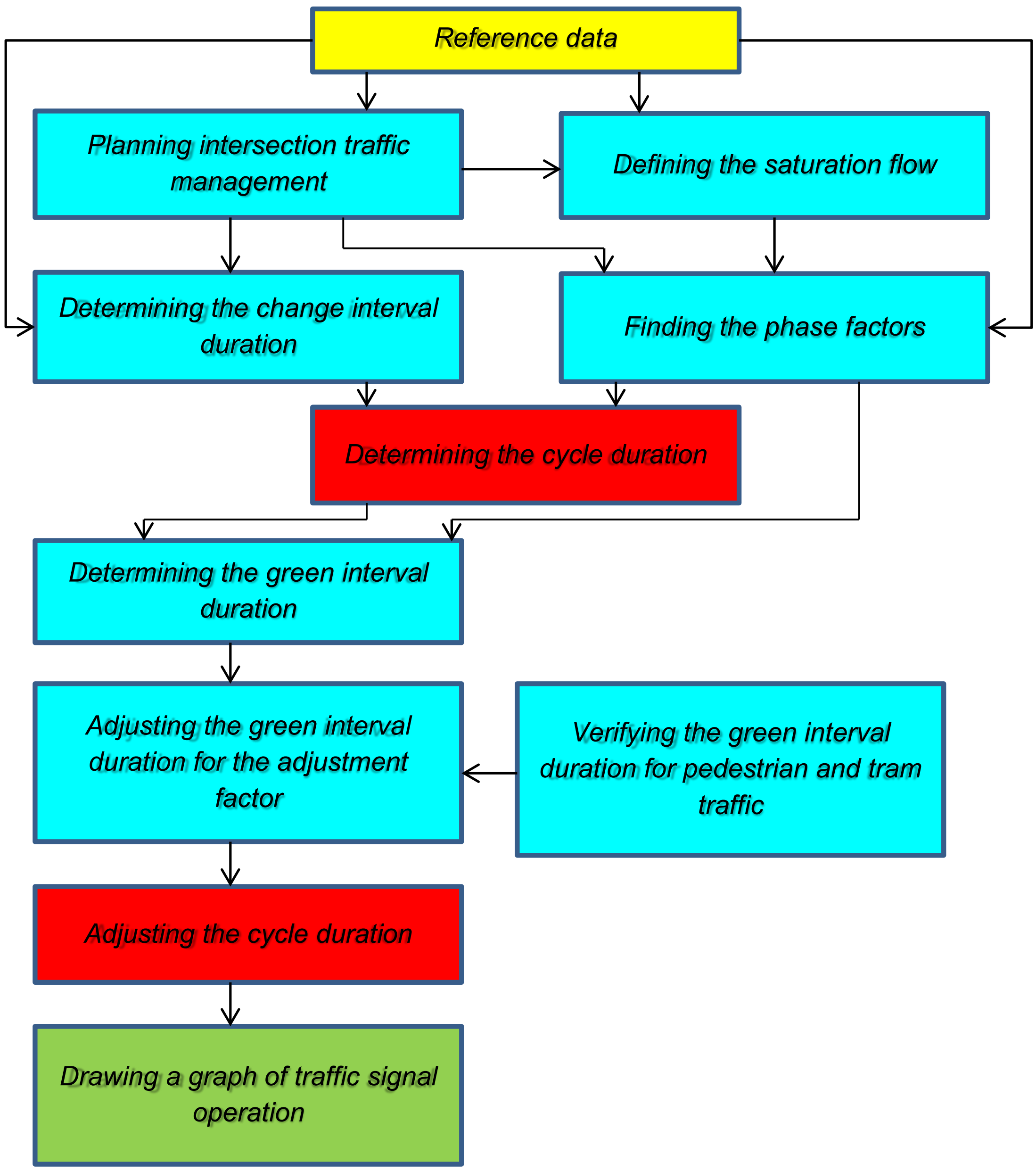


Figure 3. Proposed procedure for determining the duration of the cycle and its elements

The adjustment factor value $k_a$ will range as follows: $k_a$ = 0.08–0.15. After adjusting the duration of the green interval along the relevant traffic directions, it is necessary to adjust the duration of the signal cycle at the intersection with turning flows. A rough diagram of the process of assessing the traffic signal cycle duration after the aforementioned adjustment will look as follows (Fig. 3).

**Discussion**

As we contrasted the results of our field observations, aimed at determining the actual capacity of intersections with turning flows, against theoretical insights obtained through modern methods, we discovered that they differ greatly. This, along with the high accident rates at intersections, called for an explanation. The analysis of the situation has reaffirmed that the existing methods do not account for the most important traffic safety prerequisite: the movement of vehicles at a green light while maintaining the minimum safe distance.

**Conclusion**

Our research has allowed us to conclude that the prerequisite for traffic safety at signal-controlled intersections with turning flows is the movement of vehicles during the green interval, which should be measured with the minimum safe distance in mind. This will make it possible to adjust the existing methods of assessing the signal cycle duration while accounting for the minimum safe distance between cars.

**Acknowledgment**

The research team would like to thank Colonel Aleksey Sultanovich Gabdorakhmanov, deputy head of the State Road Traffic Safety Authority at the Sverdlovsk Region office of the Russian Ministry of Internal Affairs, for his help with our field observations of traffic at intersections in the city of Yekaterinburg.

DOI: 10.23968/2500-0055-2021-6-1-73-80

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# УСЛОВИЕ БЕЗАВАРИЙНОГО ДВИЖЕНИЯ АВТОМОБИЛЕЙ НА РЕГУЛИРУЕМЫХ ПЕРЕСЕЧЕНИЯХ

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**Аннотация**

Повышение пропускной способности пересечений невозможно без учета необходимости обеспечения безопасности дорожного движения. **Целью исследования** явилось определение условия безаварийного движения транспортных средств на регулируемых пересечениях при наличии поворотных потоков. Для выполнения исследования использовались **методы** наблюдения, сравнения и математического анализа. **Результаты:** Проведено натурное исследование интенсивности движения транспортных средств на перекрестках со светофорным регулированием г. Екатеринбурга, движущихся на разрешающий сигнал светофора. Выполнен анализ транспортных потоков, движущихся в трех направлениях по одним и тем же полосам движения. Установлено, что наиболее аварийными являются четырехсторонние пересечения (54 %). На трехсторонние пересечения приходится (44 %) ДТП, остальная часть (2 %) это многосторонние пересечения. Определены дополнительные факторы, влияющие на безопасность дорожного движения на пересечениях при наличии поворотных потоков. Показано, что для обеспечения максимальной пропускной способности длительность цикла светофорного регулирования должна определяться с учетом минимально безопасного расстояния между транспортными средствами.

**Ключевые слова**

Безопасность дорожного движения, длительность цикла светофорного регулирования, регулируемое пересечение.