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IMPROVING SAFETY ON THE CROSSWALKS WITH THE USE OF FUZZY LOGIC

Summary. The article provides an analysis of the global trends in the field of city transport systems' safety. Currently, the efforts to increase the proportion of trips made by foot or by non-motorized transport are being made. That is why the problem of ensuring safety of the most vulnerable road users is relevant. The statistics of traffic accidents with victims, as well as the factors that cause such accidents, is analysed. Simulation has shown that rational management can reduce the likelihood of road traffic accidents.

1. INTRODUCTION

The world has experienced unprecedented urban growth in recent decades. As the population increases, more people will live in large cities. Many people will live in the growing number of cities with over 10 million inhabitants, known as megacities. In 2008, the world's population was evenly split between urban and rural areas. More developed nations were about 74 percent urban, while 44 percent of residents of less developed countries lived in urban areas. However, urbanization is occurring rapidly in many less developed countries. Mobility is a key dynamic of urbanization, and the associated infrastructure invariably shapes the urban environment – the roads, transport systems, spaces, and architectural solutions. By 2005, approximately 7.5 billion trips were made in cities worldwide each day. In 2050, there may be three to four times as many passenger-kilometers travelled as in the year 2000 [1]. Freight movement could also rise more than threefold during the same period [2].

In some cities, the physical separation of residential areas from places of employment, markets, schools, and health services forces many urban residents to spend increasing amounts of time, and as much as a third of their income, on transportation. In the developing world, and especially in African cities where walking can account up to 70 per cent of all trips, this low-density horizontal urban development causes further exclusion of the urban poor. Due to transport poverty, many residents cannot afford to travel to the city centers or to areas where businesses and institutions are located, depriving them of the full benefits offered by urbanization. The urban space needs to be rethought not only to optimize flow of traffic but also to increase and encourage the use of non-motorized transport, such as pedestrian movement or cycling. Streets need to be adapted, with walkways, crossings, and cycling lanes. Transport junctions need to be established to create connection points between different transport modes, thus facilitating access to and extending the range of a public transport system, on both the macro level – the city, the region, and beyond – and micro level – the neighborhood [3]. Approximately 1.25 million people die every year on the world's roads as a result of road traffic crashes. They are the number one cause of death among young people aged 15–29 years. In addition to the public health impact of road traffic injuries, the disproportionate impact of road traffic crashes on the younger age groups makes them an important development problem: road traffic crashes are

estimated to cost countries approximately 3% of their GDP, with the economic losses in low- and middle-income countries equivalent to 5% of GDP [4].

In addition to disparities in rates, the distribution of road user deaths varies considerably between and within regions. At a global level, about half of all road user deaths (49%) are among vulnerable road users, i.e. pedestrians, cyclists, and motorcyclists. However, this distribution varies considerably by region and by country, revealing common transport modes.

2. THE PROBLEM OF ENSURING PEDESTRIANS' SAFETY AND WAYS OF ITS SOLUTION

2.1. Traffic accident statistics

According to statistics [5], in 2015-2016, less people died in Russia as a result of road traffic crashes than in European countries (Fig. 1). However, it is still one of the main causes of death among young people.

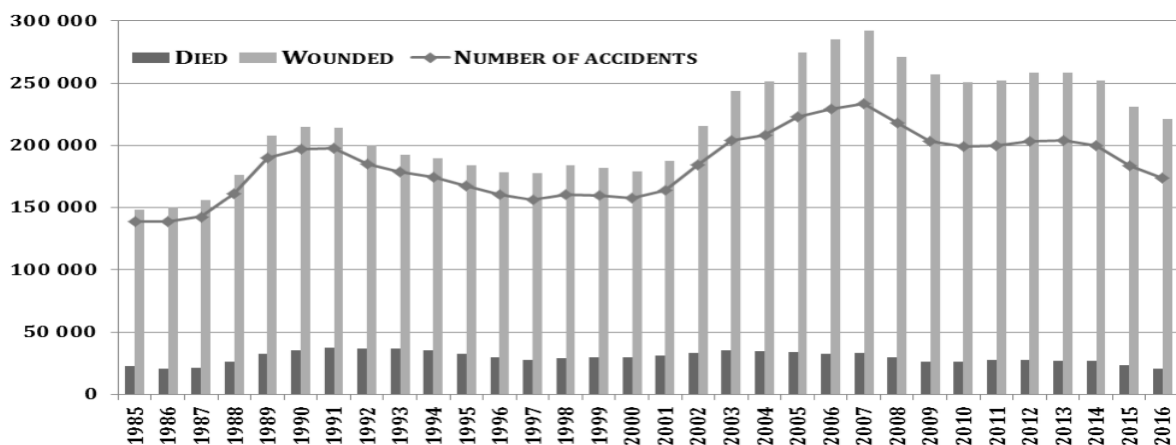


Fig. 1. Dynamics of accidents in Russia

The most common causes of death in road traffic accidents in 2015 were as follows: head-on or lateral collision, with 32 754 people injured in such accidents; poor quality of the road pavement, with 30 667 people injured in such incidents and about 4000 people having died; hitting a pedestrian, with 23 724 cases, including 2731 accidents when people died; vehicle roll-over, with 7906 people injured and 2731 died; faulty state of the vehicle, with 945 cases, including 2731 accidents when people died.

Russia is on the top place of mortality rate on the road among European countries. The main causes of the road traffic accidents are as follows:

1. *Alcoholic intoxication.* According to official data of the traffic police, this causes 40 percent of all road accidents.
2. *Distracting circumstances.* One of the main reasons is making a telephone call. Even if a driver talks on a hands-free cell phone while driving, it increases the probability of an accident 3-6 times.
3. *Foreign objects.* Foreign objects can also cause dispersal of concentration, and as a result, a bad reaction and an inability to make the right decision on the road.
4. *Aggressive driving.* Careless driving greatly increases the risk of a traffic accident up to 40%.
5. *Disregard safety rules.* Many drivers consciously do not want to use the seatbelts and are ready to pay fines. Despite the fact that this is not a direct cause of the accident, it significantly increases the risk of death in the case of emergency. Moreover, many parents neglect the use of the child seats, although it decreases the probability of the children's death by 50-70 percent.
6. *Fatigue of the driver.* This is an insignificant but nevertheless possible cause of accidents. As a result of the long road, a person gets tired, starts to rush, and incorrectly estimates the traffic situation. All of this can lead to the death of the driver, as well as of passengers.

According to World Health Organization (WHO) [4], mortality in road accidents directly depends on the level of development of the country. According to the WHO report, in Europe, the richest countries have the lowest mortality rate in accidents, whereas in Africa for 2015, these indicators are the highest. Regarding some data on mortality in the Third World countries, in Mexico, the chance to get into a fatal accident is 12.3%; in Pakistan, one can die in an accident with a probability of 14.2%; Albania – 15.4%; Afghanistan – 15.5%; China, Tajikistan, and Russia – 18.8%; Armenia – 18.9%; and African countries – 26.6%. The WHO is sure that it is possible to reduce the number of fatal incidents only at the legislative level, as well as by improving the quality and safety of the road infrastructure.

2.2. Mobility of urban residents

The consideration of urban movements for passengers involves their generation, the modes and routes used, and their destination [6]:

1. Trip generation: on average, an urban resident undertakes between 3 and 4 trips per day. Moving in an urban area is usually done to satisfy a purpose such as employment, leisure, or access to goods and services. Each time a purpose is satisfied, a trip is generated. Important temporal variations in the number of trips by purpose are observed, with the most prevalent pattern being commuting.
2. Modal split: it implies the use of a series of transportation mode for urban trips, which is the outcome of a modal choice. This choice depends on a number of factors such as cost, technology, availability, preference, travel time (distance), and income. Therefore, walking, cycling, public transit, the automobile, or even telecommuting is going to be used either as a choice or as a constraint (lack of choice).
3. Trip assignment (routing): it involves which routes will be used for journeys within the city. Passenger trips usually have a stable routing. For instance, a commuter driving a car has most of the time a fixed route between his residence and place of work. This route may be modified if there is congestion or if another activity (such as shopping) is linked with that trip, a practice often known as trip chaining.
4. Trip destination: changes in the spatial distribution of economic activities in urban areas have caused important modifications to the destination of movements, notably those related to work. The central city used to be a major destination for movements, particularly passengers, but its share has substantially declined in most areas, and suburbs now account for the bulk of urban movements.

The share of the automobile in urban trips varies in relation to location, social status, income, quality of public transit, and parking availability. There are important variations in mobility according to age, income, gender, and disability. In some instances, modal choice is more a modal constraint linked to economic opportunities. The main feature of large cities and metropolises is the need to travel long distances both in regular and in one-time trips. Besides, safety and complexity of the route are the determining factors for certain categories of population. The public transport plays a leading role to promote sustainable urban development in the transport systems. Modern transport policies of large cities are based on the postulate to limit gradually the car usage.

Sustainability of the city transport system usually means the effective organization that is characterized by the following: a) transport infrastructure provides safe and comfortable travel to all road users. i.e., to the drivers of private vehicles, to the passengers of public transport, to cyclists, and to pedestrians, regardless of their physical disabilities; b) public transport provides affordable (financially and physically) services to all citizens, and it is an acceptable alternative to private vehicles when their using leads to overloading of the road network; and c) the way of traffic organization ensures the most efficient use of the existing road network, reduction of traffic jams, and negative transport-related impact on the environment [7].

Already, there is discernible movement toward new “multimodal” services — those that facilitate journeys combining walking, cars, buses, bikes, and trains – as well as shared transportation services. Multimodal transportation involves using two or more modes of transportation in a trip. In an efficient public transportation network, the passenger can combine a smaller number of fast, technologically advanced transportation systems (e.g. underground railway) with a larger number of slower modes of transportation that cover the area in a denser fashion (buses and walking). A major goal of modern

multimodal passenger transportation (from an environmental aspect, but also to reduce traffic jams) is to incentivize using public transport as opposed to using automobiles.

There are a variety of options for connecting with high-speed rail, including walking, bicycle, pedicab, streetcar, light rail, metro, car rental, etc. Ideally, the high-speed rail station is located in the middle of downtown where many destinations are within a short walk or bike ride away. The Last Mile Problem (LMP) refers to the provision of transportation's service from the nearest public transportation node to a home or office [8, 9]. Bicycle sharing systems have frequently been qualified as a way to solve the "last mile" problem and connect users to public transit networks [10].

If we consider the security problems of a mixed movement, then at risk are mostly older adults, children, drivers, and pedestrians who are alcohol-impaired. Additionally, higher vehicle speeds increase both the likelihood of a pedestrian being struck by a car and the severity of injury. Most pedestrian deaths occur in urban areas, non-intersection locations, and at night [11]. Pedestrians of all ages are at risk of injury or death from traffic crashes, but some people are at higher risk.

- Male pedestrians are more likely to die or be injured in a motor vehicle crash than females [12].
- Teen and young adult (ages 15-29 years) pedestrians are more likely to be treated in emergency departments for crash-related injuries compared with any other age group.
- The rate of pedestrian death generally increases with age.
- In 2013, 34% of all pedestrians killed in traffic crashes had a blood alcohol concentration of greater than or equal to 0.08 grams per deciliter.

As pedestrians, children are at even greater risk of injury or death from traffic crashes due to their small size, inability to judge distances and speeds, and lack of experience with traffic rules. One in five traffic deaths among children ages 14 and under is pedestrian deaths [13]. The capacity to respond to pedestrian safety is an important component of efforts to prevent road traffic injuries. Pedestrian collisions, like other road traffic crashes, should not be accepted as inevitable because they are both predictable and preventable. The key risks to pedestrians are well documented, and they include issues related to a broad range of factors: driver behavior particularly in terms of speeding and drinking and driving; infrastructure in terms of a lack of dedicated facilities for pedestrians such as sidewalks, raised crosswalks, and medians; and vehicle design in terms of solid vehicle fronts which are not forgiving to pedestrians should they be struck. Poor trauma care services in many countries also thwart efforts to provide the urgent treatment needed to save pedestrian lives.

The American Automobile Association's (AAA) annual study "Your Driving Costs" [14] showed in 2013 that based on driving 15,000 miles per year, depending on vehicle type, owning and operating a vehicle can cost an average of 60.8 cents per mile or \$9,722 per year. However, for city regular trips, safe non-motorized transportation options, combined with access to public transportation, are critical components of a transportation network that connects people – especially low-income households – with jobs, education, and essential services, providing "ladders of opportunity".

Although road traffic injuries have been a leading cause of death and injury globally for many years, most road traffic crashes are both predictable and preventable. There is considerable evidence on interventions that are effective at making roads safer: countries that have implemented these interventions have seen corresponding reductions in road traffic deaths. The most successful examples of where sustained reductions in the numbers and rates of road traffic deaths have been achieved are where a "safe systems approach" has been implemented. This approach provides the set of additional actions aimed at creating safer roads, safer vehicles, safer speeds, and safer behavior of road users. Adopting a safe systems' approach requires the involvement and the close collaboration of many sectors including transport, health, police, industry, and civil society.

2.3. Features of pedestrian movement in Europe and Russia

By definition, a pedestrian crossing is a special area on the roadway that is allocated for pedestrians to cross the street or road or an artificial structure above or below the roadway for the same purposes.

In Russia, there are currently no mandatory documents that would regulate speed limits on unregulated pedestrian crossings (this also applies to country roads). As a result, we get pedestrian crossings marked only by marking on the road (Zebra) and signs on four-lane highways, over which

the driver accelerates in 80% of cases to 80 km / h or more. When assessing the impact on the driver of many factors, it is difficult to convict him that he did not notice the pedestrian. When you are in the second or third lane, it is very hard to see a pedestrian, particularly because of parked vehicles. To stick to speed limits on such a street is also very difficult in view of the instigating highway geometry. In addition, the viewing angle decreases on high speed. At the same time, safety island for pedestrian can be provided only if there are four or more lanes on the road.

In Russia, a pedestrian crossing is precisely a designated place for passage, and safety islands can be located only at a pedestrian crossing. In Germany, both pedestrian crossings and safety islands refer to so-called supportive elements for crossing the roadway, which can be installed together or separately.

According to the statistics of accidents involving pedestrians [15], Germany is 10 times more successful than Russia (Fig. 2). That is, German strategy of assisting the pedestrian is much more beneficial than the Russian strategy of prohibiting crossing the road.

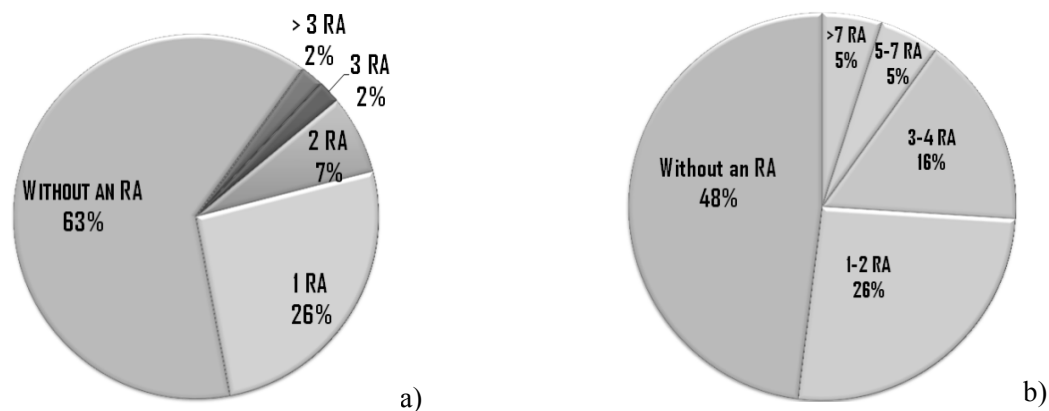


Fig. 2. Statistics of accidents on non-signalized crosswalks (RA – Road Accident) a) Germany and b) Russia

In Great Britain, pedestrian crossings are safe places for pedestrians to cross the road and where they are given priority. There are various types of pedestrian crossings, these include Zebra, Pelican, Puffin, Toucan, and Pegasus (also known as Equestrian crossings) [16, 17].

As it is revealed in the research [18], almost 30% of pedestrian injuries occur at non-signalized crosswalks. Factors of fatality risks were used to model a binary logistic regression which treated the statistical information provided by the police. Many countries apply signalized pedestrian crossings granting pedestrians the minimal waiting time and allowing the vehicular traffic to continue uninterrupted if there are no pedestrians in view. The main advantage of signalized pedestrian crossings consists in providing both motorists and pedestrians with a clear perception of the situation at intersection. Instead of solving of a complex logical-physical task, they are offered to primitively react to a light signal with a conditioned reflex. In Europe, where priority is given to pedestrians, there are numerous signalized crosswalks and practically no non-signalized ones across busy four-, and more, lane roads [19].

2.4. Factors affecting the safety of pedestrian crossings

Statistics of accidents in Russia and in the world indicate that despite the efforts made, pedestrians remain the most vulnerable road users, with road accidents taking place through the fault of both drivers and pedestrians (Fig. 3). Since in Russia a significant part of pedestrian crossings is non-signalized, the number of accidents on them, including accidents where people died, is much higher. At the same time, people die as a result of road traffic crashes outside the city almost 20 times less than in the cities themselves. This is due to the ratio of the intensity of pedestrian and traffic flows.

It is reported in a study [20] that the major reasons for pedestrian noncompliance with traffic signals are the low-quality traffic management, traffic volume, and long waiting time. In the research

[21], it is shown that designing of a signal should take into account the use of neighboring land and the results of traffic survey. Another factor of risk is the conflict between the vehicular and pedestrian flows at left-hand corners [22, 23]. Different models have been proposed for risk assessing and working out of measures to improve the pedestrian safety. Thus, the model proposed in the research [24] allows to measure the impact of potential risk factors on pedestrians' intended waiting times during the red-man phase of the traffic lights. In a later research, the author proposes a multivariant method of risk analysis consisting of two hierarchically generalized linear models, characterizing two different facets of unsafe crossing behavior, and uses a Bayesian approach with the data augmentation method to draw statistical inference for the parameters associated with risk exposure. Dependence severity of accidents by vehicle speed is explored in the research [25]. The authors took into account age group of pedestrians and vehicle type (sedans and light passenger cars). The authors determined that elderly age group (60 years old and over) faces higher risks of serious injury and fatality than both the child age group (12 years old and under) and the mid-age group (13–59 years old). The authors suppose that the findings should be included in designing specifications of the pedestrian detection system in the near future.

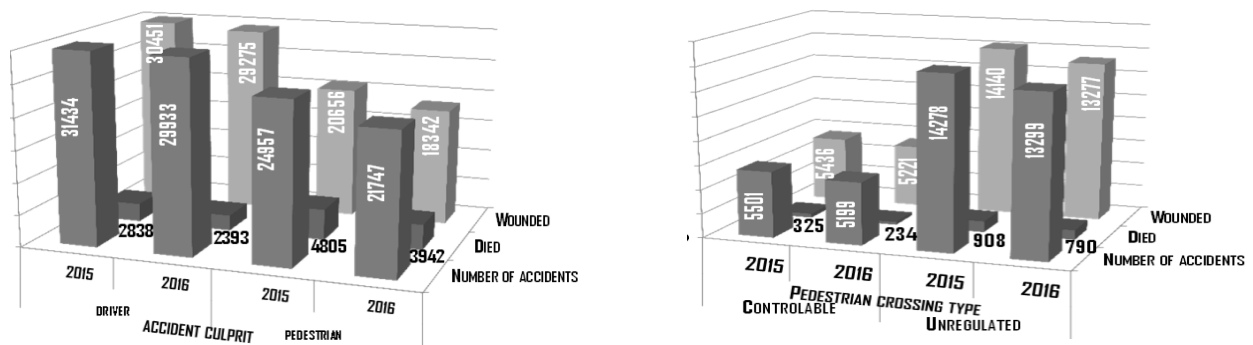


Fig. 3. Dynamics of road accidents in Russia depending on the culprit and the place of occurrence

The behavior of pedestrians is still, in a certain sense, the most common and dangerous type of road behavior. The peculiarity of the behavior of pedestrians depends on their natural data, in which their difference from all other road users is expressed. Thus, pedestrians have different abilities in movement, initial speed, the least inertia, and the maximum mobility in a choice of a direction of movement. These natural features make pedestrian behavior the least predictable for others. On the other hand, pedestrians have the least restrictions in the current traffic rules [26]. Accidents with pedestrians at the highest frequency are divided into two age groups: children under 15 years and persons over 65 years. The results of numerous studies allow us to generalize the difficulties of behavior specific to these age groups [27].

- *Difficulty in understanding of the situation.* Restricted visibility in a difficult traffic situation; difficulty in crossing the road (reorientation in the middle of the roadway); and collision with other pedestrians on the crossing.
- *Narrowing of attention.* Tracking traffic light signals at the expense of monitoring vehicles and do not pay attention to turning vehicles.
- *Lack of information.* Ignorance of the behavior of the surrounding road users.
- *Uncertainty or indecisiveness.* Ambiguous behavior on the pedestrian crossing type “zebra” and forward and backward movement (slow transition completion at the moment of switching yellow to red light).
- *Difficulties in understanding* with other road users [28].

In most countries of the world, children as road users are relatively more likely to get into an accident than adults. The peak age of children involving into road accidents falls under 7-9 years (Fig. 4). The most common individuals involved in the road accident are pedestrian children, while crossing the roadway without sufficient account of the transport situation in conditions of poor

visibility, and children-cyclists in case of non-compliance with the rules of preferential travel and incorrect performance of the left turn [29].

As studies on traffic accident statistics show, among the best solutions for urban conditions with uneven traffic and pedestrian flows, the most effective method of organizing pedestrian traffic is the use of push-button traffic lights. This will minimize the influence of psychological factors on the probability of an accident; at the same time, the synchronization of the work of a calling traffic light object with traffic lights at adjacent intersections will allow to reduce the intensity of the traffic flow during periods of peak load.

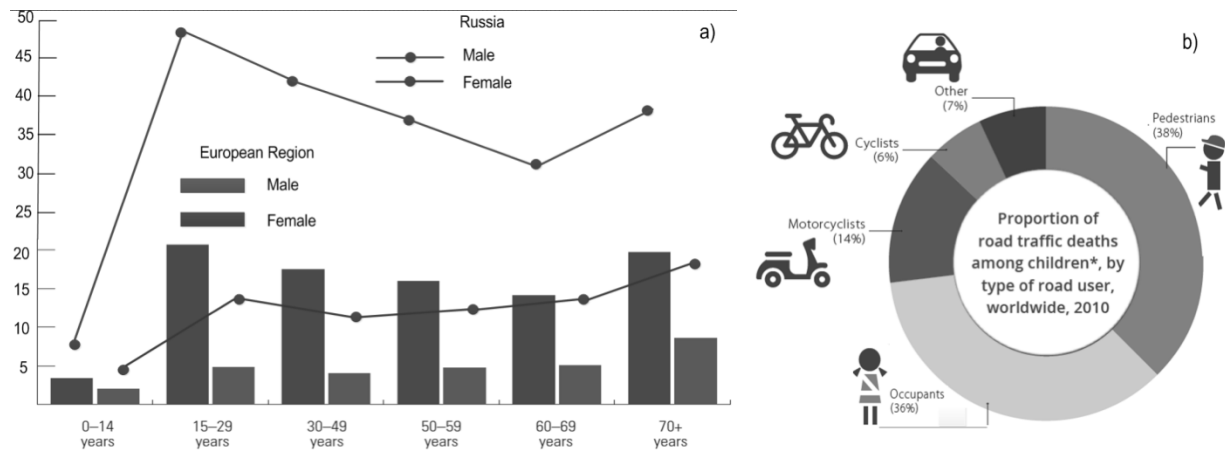


Fig. 4. a) Mortality rates in the WHO European Region and Russia from the road traffic injuries per 100 000 population by age and gender, 2012; b) statistics of road accidents with victims among children

3. RESULTS AND DISCUSSION

3.1. The use of fuzzy logic to control the traffic lights in the organization of traffic

The methods of rigid regulation of transport and pedestrian flows, providing for a fixed duration of traffic signals calculated with a certain margin in the case of increasing traffic intensity, less and less satisfy the requirements for optimal control under conditions of variable intensity traffic. This approach increases the likelihood of congestions during peak hours on street-road networks.

To reduce transport delays on multilane highways of the city with pedestrian flows of variable intensity, the organization of pedestrian crossings outside the intersections is carried out with the help of traffic light push button [30]. Traffic lights equipped with push button are usually installed in places designed for a small amount of pedestrians. In this case, the waiting time for the pedestrian phase, as a rule, is not calculated for the peak traffic intensity in this place. As a rule, such pedestrian traffic lights have a constant control cycle, in which the pedestrian phase time-out is used, which has a constant value, which is inefficient under conditions of intensive traffic, since the traffic light starts to work as a regular one at a certain traffic intensity of pedestrians. Under conditions of a significant increase in the pedestrian flow, this leads to the vehicles' queuing.

If the peak hours of the pedestrian and transport flows fall in the same time interval, this causes the queue of the vehicles before the pedestrian crossing that does not have time to depart during the vehicle phase. As a result, there is a snowballing growth of queue and forming of such a congestion that is not possible to disperse if the waiting time for the pedestrian phase is constant and is usually less than 30 seconds. A common trend in solving this problem is the use of traffic light regulation with a flexible change in the duration of the phases [31].

The existing fuzzy algorithm for the regulation of pedestrian crossing [32] supposes the decisions on termination or extension of the authorizing vehicle signal as a response variable. In this case, the input variables are the total waiting time of pedestrians, the number of vehicles between two detectors

at a distance of 60 m, and the average distance between the vehicles following one after another. When developing this fuzzy algorithm for controlling the pedestrian crossing signal, it was found that it increases performance compared to using a fixed signal. In this algorithm, 18 fuzzy rules are used.

The waiting time for the pedestrian crossing signal must be regulated by the densities of the pedestrian and transport flows. If the time has elapsed for pedestrians, and the size of the vehicle queue is long, it is necessary to increase the waiting time for the pedestrian phase to increase the possibility of shortening the transport queue. The waiting time for pedestrians is reduced if there are few vehicles, and a lot of time has elapsed since the authorizing pedestrian signal. In this case, each combination of time values from the last transition and the size of the queue should be associated with a certain waiting time for the next pedestrian phase.

The size of the vehicle queue can be determined using transport detectors, for example, based on use of video cameras, and also by calculations based on the synchronization algorithm and the specified mathematical model. Evaluation of the time elapsed since the last pedestrian phase, and the size of the accumulated transport before the crosswalk, as well as making the decision on the waiting time for the pedestrian phase, can be carried out using a mathematical tool of fuzzy logic [33]. Such an approach to managing pedestrian flows during the peak hours will reduce the possibility of congestions, and if it occurs, to normalize the situation within a few control cycles. On the basis of the cycle (Fig. 5), we propose the algorithm for operation of the pedestrian traffic light with the fuzzy control equipped by push button (Fig. 6).

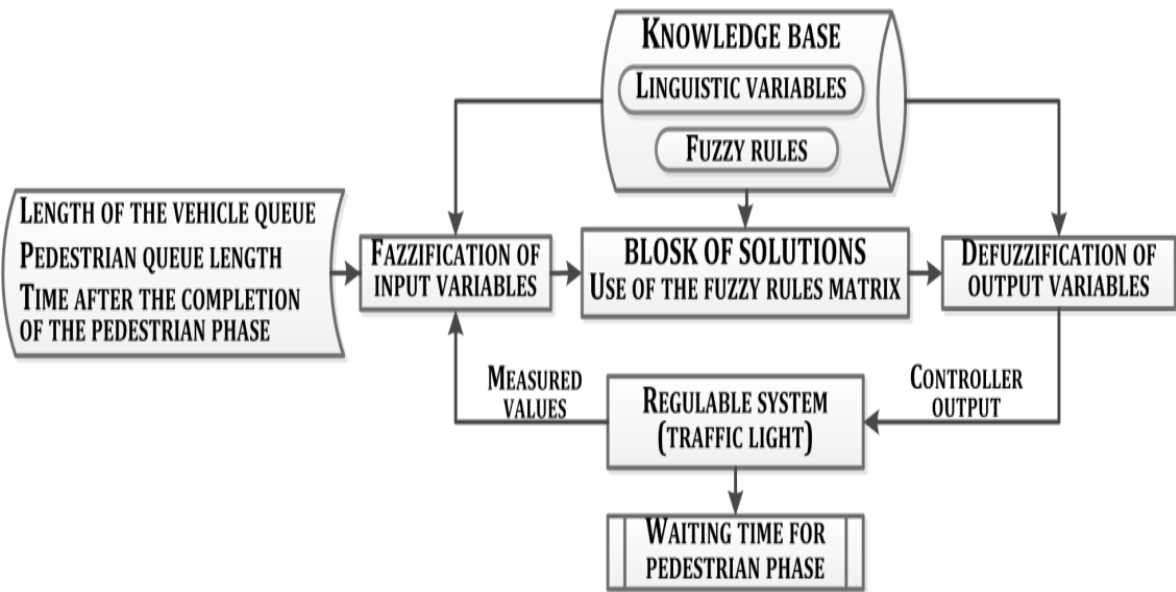


Fig. 5. The control cycle of the pedestrian

To check the effectiveness of this managerial method, the section of Moskovskiy av. in Naberezhnye Chelny city was selected. This is an avenue with three lanes in each direction. There is a signalized intersection with Avtozavodskiy av., which has a two-lane traffic in each direction. Since Avtozavodskiy av. connects the industrial and residential areas of the city, during peak hours the traffic intensity on Moskovskiy av. is high and non-signalized pedestrian crosswalk causes congestions. This is the main reason of accidents on this section, including automobile-pedestrian accidents. The original model was built in AnyLogic (Fig. 7) The input data of the traffic light object are shown in the Tab. 1. In this section, the peak loads of pedestrian and transport flows practically fall in the same time interval. Since the use of a traffic light equipped with a push button with a constant delay time is ineffective, we investigated the application of adaptive regulation of the authorizing phase of the traffic light using fuzzy logic.

Input fuzzy variables include the time T_p elapsed since the last pedestrian phase and the length N_q of the queue of vehicles accumulated before the pedestrian crossing during the previous pedestrian

phase. The distance from the nearest signalized intersection is significantly less than the distance to the next one, and in addition, there are two turns and an exit road on this site. That is why, to create more favorable conditions for vehicles during the red pedestrian phase, it is desirable to synchronize these two traffic lights with the use of fuzzy logic. Since the time of traffic light at the signalized intersection is constant, it is possible to use a timer in the model that will help to determine the phase that falls in the time of pushing the button. The output of the fuzzy variable is the waiting time of the pedestrian phase W . Term-sets of input variables were set taking into account the experience of organization of traffic signal regulation of similar crosswalks for this category of roads.

Table 1

Input data of the traffic light object

street	Red	Green	Right turn	street	Red	Green	Right turn
Avtozavodskiy	27	25	23	Moskovskiy	25	27	23

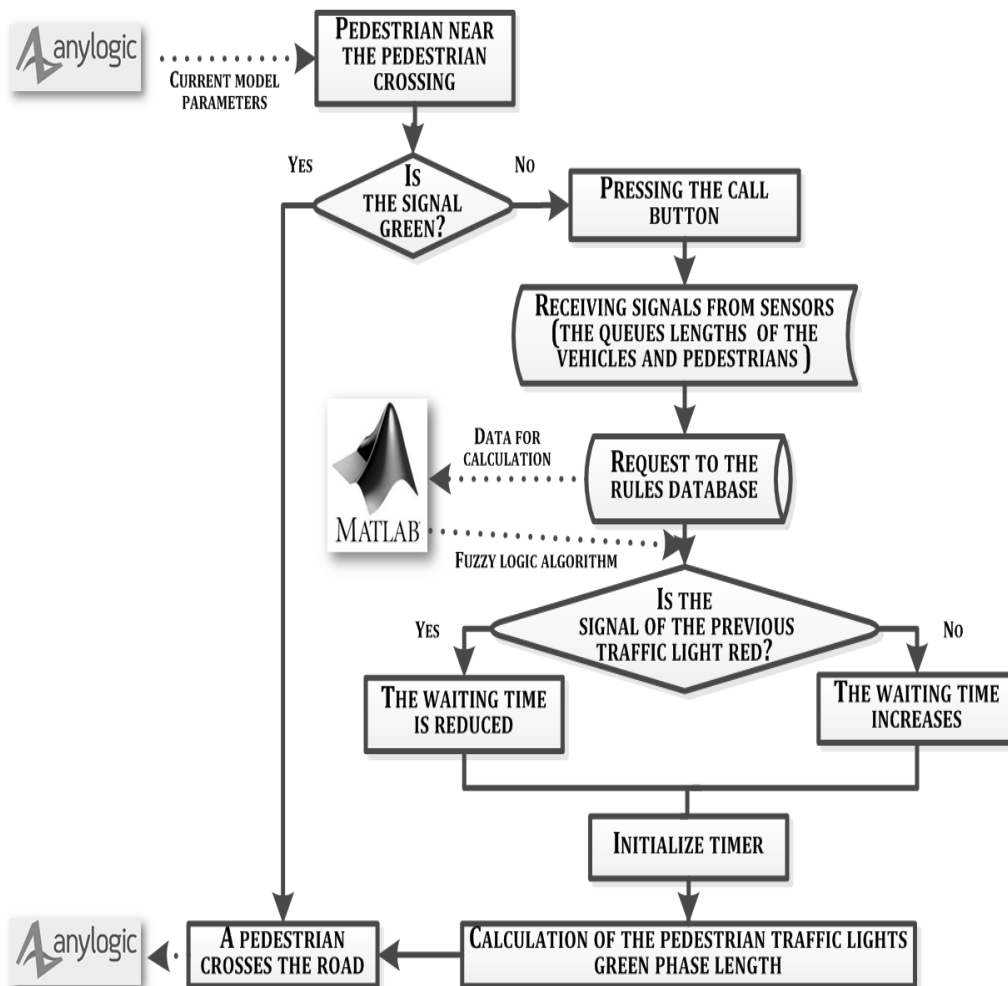


Fig. 6. Algorithm of simulation experiment

Table 2

Membership functions of input variables

Value of the term-set	Small	Average	Large
Number of vehicles N_q , units	0-13	13-27	27-40
Number of waiting pedestrians, people	0-8	8-21	21-30
Time to the beginning of the red phase, T_p , sec.	1-7	7-15	15-60

When specifying the ranges of values of the term-set of the input and output variables, it is advisable to limit to five terms (Tab. 2-3). The values of the fuzzy output value W are determined depending on the combination of N_q and T_p . A list of fuzzy rules was defined to determine the output variables, depending on the membership of the input variables in the sets (Tab. 4).

Simulation of operation of the pedestrian traffic light was performed in Matlab 7.0. Requests for a pedestrian crossing followed regularly, depending on the actual density of the pedestrian flow determined by the field observations in this area. The vehicle flow was also set in accordance with results of the field observations (aut./hour), and the average speed of the road crossing was 1 vehicle/sec. The results of the simulation, shown in the graphs (fig. 8), indicate the effectiveness of the fuzzy approach to the control of the pedestrian traffic signal. This method of traffic regulation reduces the average length of the queue and the possibility of congestion, and if it occurs normalizes the situation within a few operational cycles.

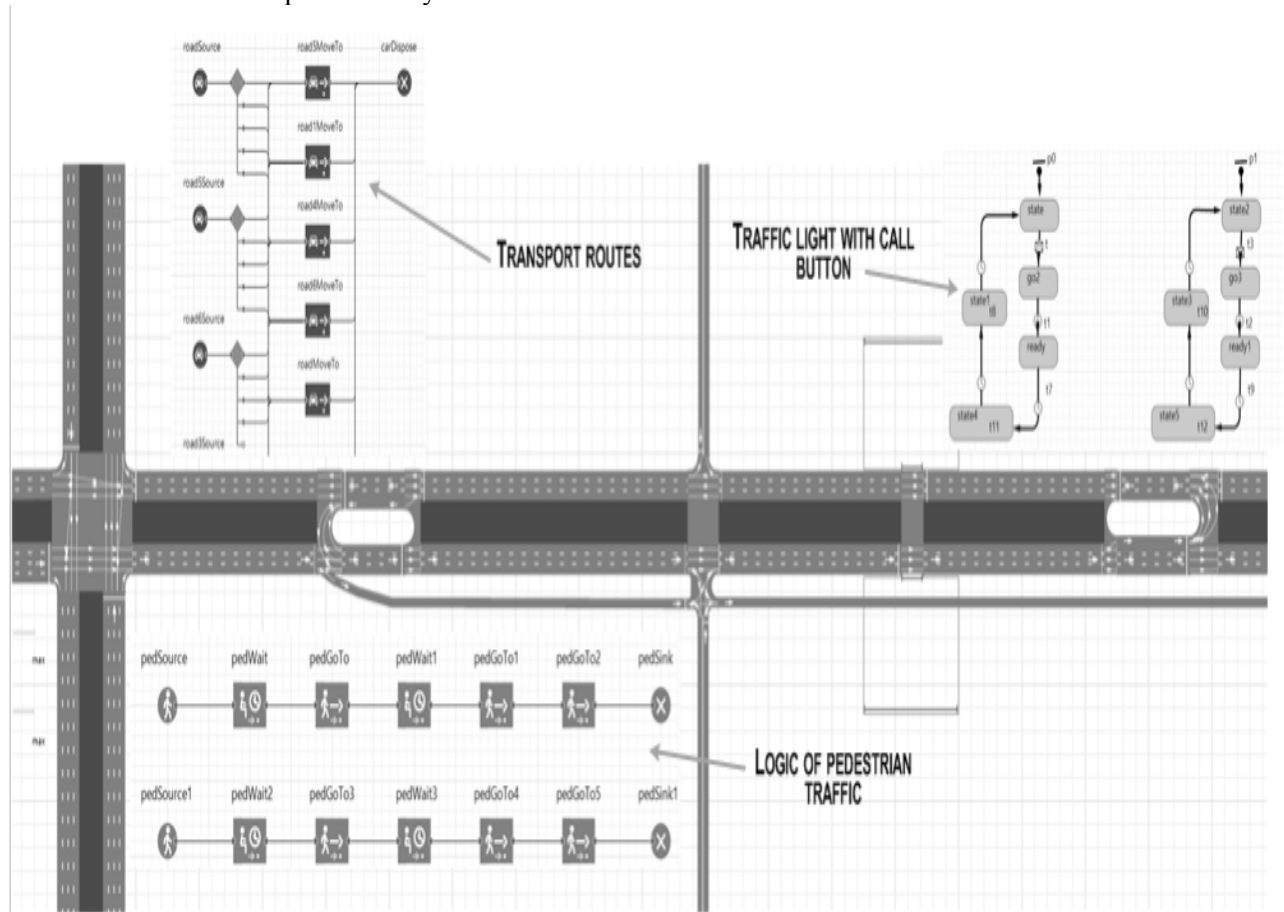


Fig. 7. Simulation model realized in AnyLogic

Table 3

A membership function of an output variable

Value of the term-set	Small	Average	Large
Waiting time for the pedestrian phase, sec.	0-20	20-40	40-60
Road crossing time, sec.	0-20	20-40	40-60

4. CONCLUSION

Despite the implemented interventions to improve road safety all over the world, there are still a lot of accidents with victims, especially among the most vulnerable road users. According to researches,

non-signalized pedestrian crosswalks are the most dangerous. The main argument against the use of pedestrian traffic lights equipped with push button on the intersections with irregular pedestrian and traffic flows, with peak hours falling in the same time interval, is that under certain traffic parameters such traffic light start operating in a way of regular traffic light, and this causes congestions. The use of fuzzy logic for synchronization of the traffic lights phases on the intersections with pedestrian traffic lights equipped with push button allows normalizing traffic parameters. As the next step, we plan to conduct simulation experiments under different traffic conditions (including when a road accident occurs) with the use of theory of fuzzy cellular automata.

Table 4

A list of fuzzy rules

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
D	S	S	S	S	S	S	S	S	S	S	A	A	A	A	A	A	A	A	L	L	L	L	L	L	L	L	L
L	S	S	S	L	L	L	A	A	A	S	S	S	L	L	L	A	A	A	S	S	S	L	L	L	A	A	A
C	S	A	L	S	A	L	S	A	L	S	A	L	S	A	L	S	A	L	S	A	L	S	A	L	S	A	L
W	S	S	S	S	S	S	S	S	S	S	A	A	A	L	L	L	A	A	A	S	S	S	L	L	L	L	A

Input data: Density: Density of the transport flow (D); LightState: time before the red traffic light at the crossroads (L); PedCount: number of waiting pedestrians (C). Output variables: PedWait: waiting time for pedestrians (W)

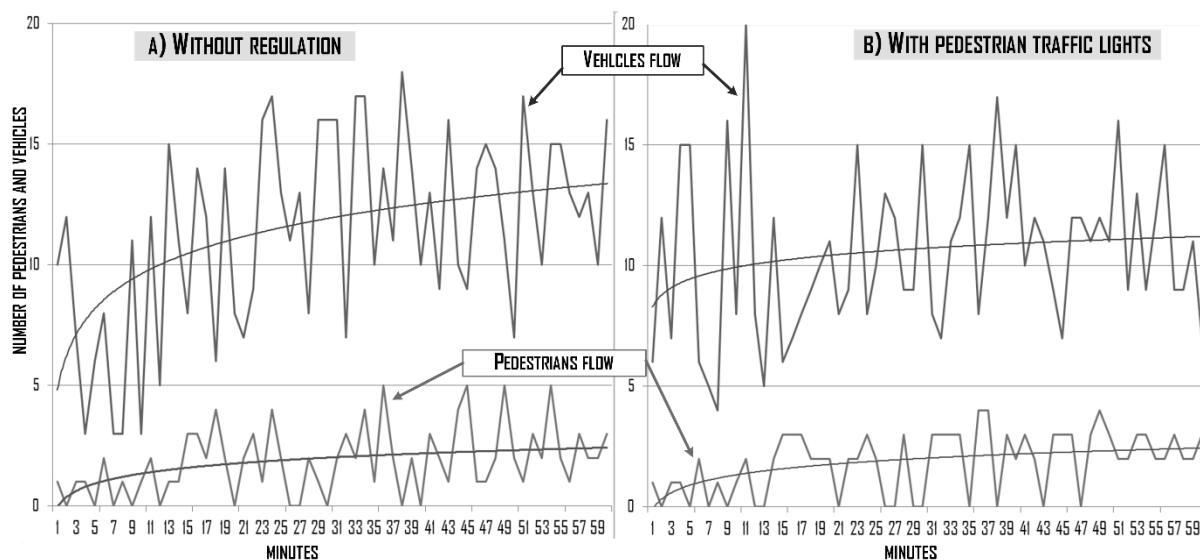


Fig. 8. Results of the simulation experiment

References

1. Pourbaix J. Towards a smart future for cities'. *Journeys*. Available at: http://ltaacademy.gov.sg/doc/J12%20May-p07Jerome_Towards%20a%20Smart%20Future%20for%20Cities.pdf
2. Transport Outlook: Meeting the Needs of 9 Billion People, Organization for Economic Development. *International Transport Forum*. Paris. Available at: <http://www.internationaltransportforum.org/Pub/pdf/11Outlook.pdf>
3. Transforming our world: the 2030 Agenda for Sustainable Development. *Resolution adopted by the General Assembly on 25 September 2015*. Available at: http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E
4. *Global status report on road safety 2015*. World Health Organization. 16 p.
5. *Госавтоинспекция* [In Russian: *State Autoinspection*]. Available at: <https://www.gibdd.ru/>
6. World Health Organization. *Global status report on road safety 2015*.

7. Rodrigue J.P. & Comtois C. & Slack B. *The Geography of Transport Systems*. Routledge. 2017. 440 P. Available at: <https://people.hofstra.edu/geotrans/index.html>
8. *Sustainable Transportation*. Available at: <http://www.nrel.gov/docs/fy15osti/63161.pdf>
9. Zhili Liu et. al. Solving the Last Mile Problem: Ensure the Success of Public Bicycle System in Beijing. *Procedia - Social and Behavioral Sciences. 8th International Conference on Traffic and Transportation Studies (ICTTS 2012)*. Vol. 43. 2012. P. 73-78.
10. Maria Bordagaray et.al. Modeling User Perception of Public Bicycle Services. *Procedia - Social and Behavioral Sciences. Proceedings of EWGT2012 - 15th Meeting of the EURO Working Group on Transportation. Paris. 2012*. Vol. 54. P. 1308-1316.
11. Jenn-Rong Lin et.al. A hub location inventory model for bicycle sharing system design: Formulation and solution. *Comp. & Industrial. Engineering Intelligent Manufacturing Systems*. 2013. Vol. 65. No. 1. P. 77-86.
12. National Highway Traffic Safety Administration. *Traffic Safety Facts 2013. Data - Pedestrians. Washington, DC: US Department of Transportation, National Highway Traffic Safety Administration*. 2015. Available at: <http://www-nrd.nhtsa.dot.gov/Pubs/812124.pdf>
13. Centers for Disease Control and Prevention, National Center for Injury Prevention and Control. *Web-based Injury Statistics Query and Reporting System (WISQARS)*. Available at <https://www.cdc.gov/injury/wisqars/>
14. Department of Transportation (US), National Highway Traffic Safety Administration (NHTSA). *Traffic Safety Facts 2013: Pedestrians*. Available at: <https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811888>
15. *Пешеходные переходы. Часть 3. Оценка безопасности нерегулируемого пешеходного перехода* [In Russian: *The crosswalks. Part 3. Assessment of the safety of unregulated crosswalks*]. Available at: <http://transspot.ru/2014/04/14/peshexodnye-perexody-chast-3-ocenka-bezopasnosti-nereguliruemogo-peshexodnogo-perexoda/>
16. *Your Driving Costs. How Much Does it Cost to Drive?* 2016. Available at: <http://exchange.aaa.com/wp-content/uploads/2015/04/Your-Driving-Costs-2015.pdf>
17. *Pedestrian crossings*. Available at: <http://www.driving-school-beckenham.co.uk/pedestriancrossings.html>
18. *Your guide to pedestrian crossings*. Available at: <https://www.trafford.gov.uk/residents/leisure-and-lifestyle/sport-and-leisure/walking/docs/a-guide-to-pedestrian-crossings.pdf>
19. Olszewski, P. et al. Pedestrian fatality risk in accidents at unsignalized zebra crosswalks in Poland. *Accident Analysis and Prevention*. 2015. Vol. 84. P. 83-91.
20. Duduta, N. *Understanding how intersection and signal design impact pedestrian behavior*. 2014. Available at: <http://thecityfix.com/blog/understanding-intersection-signal-design-impact-pedestrian-behavior-cross-on-red-safety-nicolae-duduta-coby-joseph/>
21. Brosseau, M. et al. The impact of waiting time and other factors on dangerous pedestrian crossings and violations at signalized intersections: A case study in Montreal. *Transportation Research Part F*. 2013. Vol. 21. P. 159-172.
22. Di Stasi, L.L. et al. The Influence of Traffic Signal Solutions on Self-Reported Road-Crossing Behavior. *Spanish Journal of Psychology*. 2014. Vol. 17(103). P. 1-7.
23. Alhajyaseen, W.K.M. & Asano, M. & Nakamura, H. Estimation of left-turning vehicle maneuvers for the assessment of pedestrian safety at intersections. *IATSS Research*. 2012. Vol. 36. P. 66-74.
24. Quistberg, D.A. et al. Multilevel models for evaluating the risk of pedestrian-motor vehicle collisions at intersections and mid-blocks. *Accid Anal Prev*. 2015. Vol. 84. P. 99-111.
25. Baibing, Li. A model of pedestrians' intended waiting times for street crossings at signalized intersections. *Transportation Research Part B*. 2013. Vol. 51. P. 17-28.
26. Oikawa, S. et al. Relation between vehicle travel velocity and pedestrian injury risk in different age groups for the design of a pedestrian detection system. *Safety Science*. 2016. Vol. 82. P. 361-367.
27. Kadali, R. Evaluation of pedestrian mid-block road crossing behavior using artificial neural network. *Journal of Traffic and Transportation Engineering (English Edition)*. 2014. Vol. 1(2). P. 111-119.

28. María Ángeles Onieva-García et al. Gender and age differences in components of traffic-related pedestrian death rates: exposure, risk of crash and fatality rate. *Inj Epidemiol.* 2016 Dec. Vol. 3(1). P. 14.
29. Zhu M.Inj et al. Why more male pedestrians die in vehicle-pedestrian collisions than female pedestrians: a decompositional analysis. *Prev.* 2013 Aug. Vol. 19(4). P. 27-31.
30. *Facts and Stats.* Available at: <http://mdot.ms.gov/safetyeducation/parents/facts-and-stats/>
31. Tom de Castella Does pressing the pedestrian crossing button actually do anything? *BBC News Magazine.* 4 September 2013.
32. Junchen Jin An intelligent control system for traffic lights with simulation-based evaluation. *Control Engineering Practice.* 2017. Vol. 58. P. 24-33.
33. Araghi, S. et al. A review on computational intelligence methods for controlling traffic signal timing. *Expert Systems with Applications.* 2015. Vol. 42. P. 1538-1550.
34. Collotta, M. et al. A novel approach for dynamic traffic lights management based on Wireless Sensor Networks and multiple fuzzy logic controllers. *Expert Systems with Applications.* 2015. Vol. 42. P. 5403-5415.

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