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THE IMPACT OF ADVERSE WEATHER CONDITIONS ON TRAFFIC COSTS, ENVIRONMENTAL POLLUTION AND THE OPERATION OF INTERSECTIONS WITH TRAFFIC SIGNALS

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ABSTRACT: Living in large cities is prone to adverse environmental impacts including air pollution. Increased vehicle traffic generates congestion as some road infrastructure such as intersections, including signalised ones, have limited capacity. When congestion exceeds capacity, vehicle queues occur and their presence increases delays and generates more harmful exhaust fumes. Travel costs also increase. Studies show that adverse weather conditions negatively affect drivers' behaviour, who become more cautious and slower to exit intersections during the green signal. Such behaviour further reduces lane capacity, increasing congestion relative to similar level of demand flow on days with favourable weather (sunny and cloudy days, no rain). The paper will demonstrate the impact of weather conditions on lane capacity and traffic performance on signalised through lanes. Worse traffic performance on days with prolonged rainfall or snowfall contributes to increased travel costs and air pollution, as will also be demonstrated in the paper.

KEYWORDS: traffic signals, capacity, congestion, air pollution, weather conditions, costs

Introduction

Large cities have an extensive street network that is not infrequently surrounded by densely built-up surroundings, often located directly by the road. Cities' road infrastructure was built many years ago to ensure good traffic performance for years to come and to meet the needs of the inhabitants. At present, however, when the population's motorisation rate is very high, it has become apparent that further expansion, i.e. widening of streets' cross-sections is practically impossible. At the same time, public pressure is forcing road managers to take steps to improve traffic performance. The faint possibilities of action, often merely boiling down to changes in the organisation of traffic at intersections, mean that periodic traffic congestion, i.e. situations where there are queues of vehicles which are not tolerated by the majority of drivers, is already factored into the equation even at the stage of designing or updating control programs. For these very reasons, numerous street intersections in large cities are congested or operate near capacity, meaning that any increase in the traffic volume above capacity translates into vehicle queues. This often happens during peak traffic hours, which in large cities last longer than in smaller ones. Under such conditions, i.e. at times of saturation states, modern control systems with advanced traffic detection prove inadequate. Saturation states at the entry to intersections mean that, in congestion, as a matter of principle even the most advanced traffic signal controller begins to operate as the simplest fixed-time one, i.e. on the basis of programs with the maximum green signal duration. The image of congested urban streets during peak hours has become commonplace, and their impact on air pollution and travel costs has come to be downplayed.

In cities, signalised intersections are decisive points for the efficiency of the road network. It can often be seen that in urban arterials, which are often operating near capacity, rain or snowfall during rush hours further exacerbates traffic problems. This is often attributed to the increased need to use vehicles during precipitation, but this is a claim which is not confirmed by studies (Chodur et al., 2011).

This paper will address the issue of a failure to take into account adverse weather conditions in traffic signal design and traffic management (Chodur et al., 2004). It is particularly relevant in large cities, where intersections operate near capacity, and its deterioration in adverse weather conditions results in significantly longer vehicle queues and duration of traffic congestion. Congestion increases air pollution and has an adverse effect on the environment and travel costs. This paper will present the results of a study of the variability of saturation flow and the capacity of selected through traffic under different weather conditions, illustrating the adverse impact of the weather on traffic performance, air pollution and travel costs. Current capacity analysis methods do not take into account the variability of saturation flow under adverse weather conditions. Saturation flow variability directly translates into variability of capacity, which is a fundamental characteristic used in the design of geometry, traffic organisation, control parameters and in the estimation of performance measures (Chodur & Ostrowski, 2006, 2016; Ostrowski & Tracz, 2019). Lack of data on the capacity variability of a lane or group of lanes results in hard to explain congestion at entries to signalised intersections and in increased pollution.

An overview of the literature

One of the most important factors determining the quality and duration of human life is the state of the environment in which people live. The quality of the air we breathe is particularly important (Burchard-Dziubińska, 2019).

Air pollution comes from various emission sources, both natural and anthropogenic, with the latter having become globally dominant since the beginning of industrialisation. It has now become a local, European and global issue. Air pollution is the most harmful and dangerous of all types of contamination because pollutants are airborne and can adversely affect environmental components over large areas. Sources of air pollution include mainly anthropogenic emissions from the municipal, residential, transport and industrial sectors (Skoczko & Szatyłowicz, 2018).

Sources of outdoor combustion include land, air and water transport; industry and power generation; biomass burning, including controlled and uncontrolled forest and savannah fires as well as

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agricultural waste burning and waste burning in urban areas. Other sources and processes contributing to outdoor pollution include surface dust suspensions and construction activities. The long-haul movement of pollutants from distant sources in the atmosphere contributes to local pollution, particularly urban air pollution. Some pollution originates directly from combustion sources as primary pollutants (carbon being the main component of PM particles) and some is formed in the air as secondary pollutants (such as nitrates, sulphates and organic carbon) due to complex physicochemical processes involving gaseous precursors from combustion sources, agriculture (ammonia), other anthropogenic processes and natural processes such as biogenic emissions (WHO, 2021).

Today, air pollution is deemed to pose a serious health risk. Exposure to air pollution, both in the environment and in the home, increases the risk of diseases such as lung cancer, stroke, heart disease and chronic bronchitis. According to the latest available estimates, in 2013, 5.5 million premature deaths worldwide, or 1 in 10 deaths overall, were caused by air pollution. Air pollution has been a major health risk factor since the early 1990s, the earliest period for which global estimates of exposure and health effects are available. Air pollution is particularly grave in some of the world's fastest growing urban regions, where increased economic activity contributes to higher levels of pollution and greater exposure. By causing disease and premature death, air pollution reduces quality of life (The World Bank & Institute for Health Metrics and Evaluation, 2016).

The WHO estimates the number of premature deaths in Europe attributed to air pollution at over 500 000 (WHO Europe, 2018), with 400 000 premature deaths in the EU28. Other studies argue that the WHO figures underestimate that number and that the actual number of excess mortality is even higher (Lelieveld et al., 2019). Globally, air pollution is considered the fourth most common cause of death among all health risks, second only to high blood pressure, diet and smoking (HEI, 2018; The World Bank & Institute for Health Metrics and Evaluation, 2016). Outdoor air quality exceeds WHO air quality guidelines in many European cities, and public health and environmental groups, citizens and politicians have all called for stricter air quality standards and policies to reduce emissions, especially from street traffic. An earlier study by CE Delft (CE Delft, 2018) estimated that the total societal cost of traffic-related air pollution in the EU28 in 2016 totaled €67-80 billion, depending on the sources of emission, with diesel vehicles accounting for 83% of these costs (CE Delft, 2018). Cities are of particular interest from a policy perspective for improving air quality. By planning, organising and regulating different modes of transport, city authorities can have a decisive impact on air quality (Bruyn & Vries, 2020).

The problem of pollution in cities was studied by ICCT (2019), which estimated the global burden of disease from transport-related emissions. Some studies presented a monetisation of the impact of pollution on air quality. For example, there was an in-depth quantitative assessment of the costs of air pollution in London (King's College London, 2015), Thessaloniki (Vlachokostas et al., 2012) or Skopje (Martinez et al., 2018).

Road infrastructure costs can be divided into the following categories: vehicle operating costs, road infrastructure user time, road accidents and casualties related to air pollutant emissions, climate change and noise. The first two categories constitute direct effects resulting from the volume of traffic, while the other categories are external costs, representing the negative effect of the impact of road transport on the environment and on the life and health of road users (JASPERS, 2023).

Outdoor air pollution kills more than three million people worldwide each year and causes various health problems, from asthma to heart disease. It costs OECD countries, as well as the People's Republic of China and India, an estimated $3.5 trillion a year in terms of the value of lives lost and ill health, and the trend is on the rise. In OECD countries, road transport is estimated to likely account for about half of the total, or $1.7 trillion.

Economic growth brings with it an increase in the number of vehicles owned and kilometers travelled. It also brings with it societal demand for stricter pollution controls, in particular for increasingly stringent regulatory standards of vehicle emissions. One would therefore expect that, over time in each country, the tightening of vehicle standards will eventually outpace the increase in kilometers travelled. One would also expect that, over time, this downward trend would be further reinforced by a steadying of, or indeed a reduction in, kilometers travelled, particularly where there is a preference for cycling, walking and collective public transport (OECD, 2014).

Despite some improvement in recent years, global air quality is still far from levels that do not pose a threat to human health or to the environment. Nitrogen oxides (NOx), along with particulate

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matter, ozone (O3) and ammonia (NH3) are among the most problematic air pollutants (Abera et al., 2021; Cohen et al., 2017; Burnett et al., 2018). At the same time, concentrations of greenhouse gases such as CO2 are steadily increasing in the atmosphere. Road transport is not only one of the main causes of NOx and CO2 emissions, but is also a major factor in logistics costs (Deschle et al., 2022).

The rapid development of urban areas has increased fuel consumption and vehicle emissions in transport networks (Wei et al., 2003). As an essential component of the urban transport network, signalised intersections are one of those locations where congestion and delays occur in the road network (Zhao et al., 2016). In urban traffic, the fuel consumption of vehicles passing through an intersection accounts for more than half of the fuel consumed during the total travel distance (Wu, 2016).

Studies such as Nocera et al. (2018), Mensink and Cosemans (2008), Ropkins et al. (2009), Pathak et al. (2016) are examples of research which takes transport emissions into account through modelling approaches. On the local scale, traffic network models can provide planners with information about the impact of infrastructure decisions on emissions by predicting traffic flows.

Some of the research (Bell, 2006; Małecki et al., 2014) has shown that the implementation of ITS applications, such as advanced traffic management systems, advanced travel information systems and advanced vehicle control systems, is one of the potential outcomes aimed at minimising negative impacts on traffic, including congestion, and reducing fuel consumption and road emissions. Several mathematical and simulation methods were developed to optimise the cycle length of signalised intersections. Traffic-related emissions are influenced by numerous factors. These include traffic volume, road capacity, vehicle operating conditions and technical specifications, as well as external environmental conditions. Traffic emissions from streets in urban areas depend primarily on the geometric characteristics and capacity of signalised intersections (Kutlimuratov et al., 2021).

As intersections are high fuel consumption and high emission areas, by making certain assumptions, researchers using different methods calculated fuel consumption and emissions at them. Combining traffic models with vehicle emissions models for the analysis of optimisation measures, a study Liao and Machemehl (1998) analysed the changes in vehicle speed at different locations, such as entry to the intersection, the intersection itself and the intersection exit. In line with the energy consumption rates at the indicated locations, a cumulative energy consumption model for the vehicle at the intersection was proposed and the influence of signaling parameters on vehicle energy consumption was modelled. Considering the effect of random flow on vehicle fuel consumption, the optimal cycle duration and arrangement of signaling phases with minimum fuel consumption were derived (Liao, 2013).

Based on the vehicle fuel consumption rate under different operating conditions (Li et al., 2019), the authors proposed a method to calculate the vehicle fuel consumption at intersections when the vehicle accelerates, decelerates and idles. A multi-criteria optimisation model for intersection operation was established, which takes into account vehicle deceleration, fuel consumption and emissions and selection of optimal green signal duration. Liao and Machemehl (1998) and Li et al. (2019) modelled the fuel consumption and vehicle emissions generated at a signalised intersection. Lv et al. (2013) combined a traffic model and vehicle fuel consumption, as well as emission models, to analyse vehicle fuel consumption and emissions at signalised intersections. They used a combination of VISSIM and MOVES models as part of their study and demonstrated the effect of coordinating adjacent intersections on vehicle emissions.

Lv et al. (2013) developed a model for traffic signal control parameters optimisation at an intersection with a view to reducing total emissions. Gao and Hu (2015) applied VISSIM to simulate traffic flow characteristics at signalised intersections and obtained real-time vehicle data such as location, time, vehicle type, vehicle speed and acceleration/deceleration at the intersection. Zhang et al. (2009) combined the VISSIM simulation data with an emissions modelling method based on vehicle specific power and created a microscopic emissions simulation platform. Through a case study simulation, they evaluated the exhaust emissions at an intersection in two traffic control strategies, different signal cycle durations and different traffic flows.

Tang et al. (2017) simulated vehicle trajectory by combining the car following model with a VT-Micro model and analysed the effect of signal cycle duration on fuel consumption and vehicle emissions at signalised intersections. They only analysed the effect of signal cycle duration on fuel consumption and vehicle emissions at signalised intersections, ignoring other factors such as vehicle

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arrival speed, traffic disruptions and speed on a given road section. Therefore, there still exist numerous limitations in the study of emissions at signalised intersections. Conclusions drawn in studies are often based on overly ideal assumptions or traffic simulation models, and their applicability to real traffic control situations needs further analysis (Zhao et al., 2019).

In a study Coensel et al. (2012), a model was built by simulating different scenarios to investigate the impact of traffic volumes, signal coordination patterns and signal parameters on emissions of noise, carbon dioxide, nitrogen oxides and particulate matter along a main road with a series of traffic lights. It was found that the introduction of a green wave could potentially reduce emissions of the air pollutants under consideration by 10% to 40% under the most favorable conditions, depending on traffic flow and traffic control timing settings. Demand flow and signal phase settings were found to have the greatest impact on emissions, while cycle duration had no significant effect on emissions.

Traffic in cities is impacted by numerous external factors. A lot of research work has been carried out to analyse the influence of external factors on traffic flow parameters.

Adverse weather conditions, such as rain, snow and fog, can significantly reduce visibility or alter adhesion properties of the wheel, and thus affect drivers' sense of safety, comfort and response to changing driving conditions, resulting e.g. in lower speeds and a bigger headway between successive vehicles. The altered behavior of individual drivers affects both traffic flow characteristics, i.e. average speed and headway between vehicles, as well as parameters related to motorway performance, such as free-flow speed and capacity (Romanowska & Budzynski, 2022). Research (Chodur et al., 2011) indicates that the occurrence of unfavorable weather conditions for traffic (prolonged rainfall, snowfall, or fog) should be taken into account in the calculation of capacity and traffic performance, as well as in traffic control and congestion management, as they markedly reduce the comfort of intersection crossing and its reliability (Ostrowski, 2014; Ostrowski & Chodur, 2015; Ostrowski & Tracz, 2019; Maślak & Ostrowski, 2018).

Research (Romanowska et al., 2018) indicated that the average speed in winter conditions (snowfall, slippery surface) declines by about 15% compared to other seasons.

Weather conditions are among many factors that have a major impact on urban traffic. Due to such external factors, traffic performance will vary due to drivers' decisions, the choice of means of transport and travel duration. Hence, on rainy or snowy days, there will be a significant change in the urban scenarios reflecting the changing share of trips by public vs individual transport.

Traffic data from the German city of Duisburg was used to calibrate and test the Neural Prophet time series forecasting model. The results of this research demonstrated the effectiveness of traffic estimation incorporating weather data. Such predictive processes can be used in driving simulators to analyse vehicle dynamics depending on the road surface condition (wet/dry) caused by rainy/snowy weather. Predictions can also be used in real-time traffic management systems to simulate urban traffic (Pragalathan & Schramm, 2024).

In addition, meteorological factors such as temperature, precipitation, wind speed, relative humidity and atmospheric pressure significantly affect the dispersion and accumulation of particulate matter of under 2.5 micrometers in diameter (PM2.5) (Ma et al., 2021). An example of research integrating weather conditions with pollution intensity can be found in work carried out in Norway (Cao, 2024). Monitoring sites for traffic and urban air pollution were selected. Weather variables were then matched with the selected sites, resulting in a dataset covering the period 2009-2018. Included in the study were key pollutants such as NO, NO2, NOx, PM2.5 and PM10.

Research methods

To demonstrate the negative impact of signalised intersections operation in adverse weather conditions on the costs of emissions and climate change, an attempt was made to estimate capacity and performance measures (delay, queues) under different weather conditions. To this end, empirical studies were carried out at selected signalised intersections. Field measurements consisted of recording on the stop line, the headways between the rear bumpers of successively passing vehicles during the red with yellow signals, green and yellow signals in the lanes for through traffic. In addition, departures at the red signal were recorded. The study took into account vehicle types, distinguishing between passenger vehicles, delivery vehicles, trucks and buses and trucks with trailers.

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Tablets for direct recording of test results were used in the process (Figure 1). In addition, during the red signal, the number of vehicles remaining in the lane after the end of the green signal (residual queue) was recorded in the test forms. The values obtained from the measurements were used to build a database for the analyses of the basic variability values of demand flow, capacity and performance, by group of weather conditions.

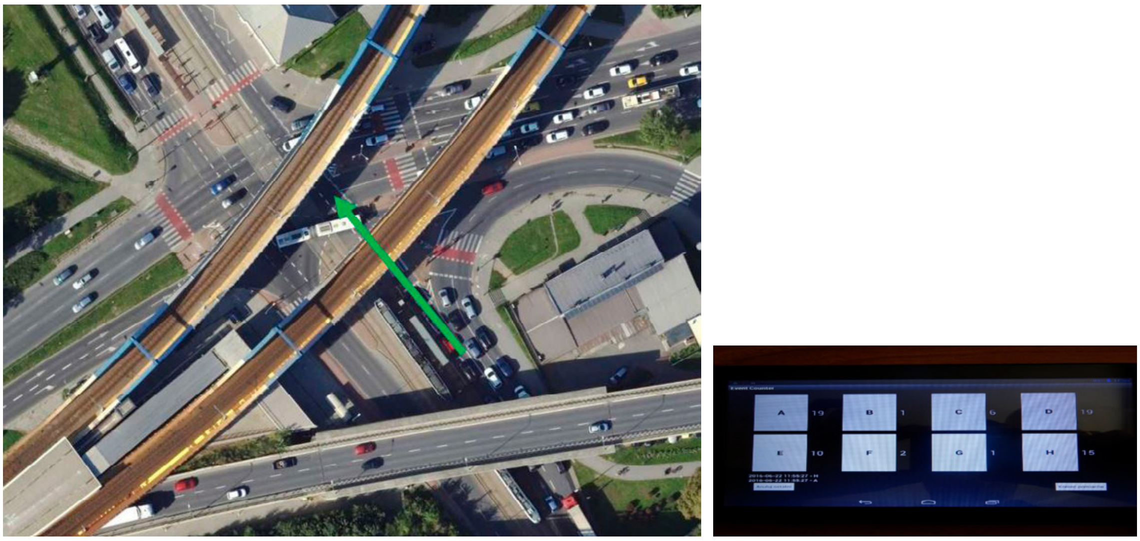

Figure 1. Selected research site, tablet and Event Counter app

Source: authors' work based on Geoportal (n.d.).

The empirical tests were carried out at selected intersections with traffic lights in groups with a dedicated single lane for the through traffic, during the morning and afternoon peaks. The tests were carried out for each lane (test site) separately and in different groups of weather conditions. They were carried out in Cracow.

Assumptions Underlying the Selection of Test Sites

To carry out the empirical study, test sites were selected so that the geometric and traffic characteristics of the analysed entries corresponded approximately to the basic conditions used to determine the basic saturation flow value, according to which is the basis for capacity calculations (Chodur et al., 2004).

A selection of the most important assumptions describing the initial conditions is presented below:

- Full saturation during the green signal, which translates into the occurrence of queues remaining for a minimum of 40 signal cycles during the measurement period,
- traffic and the intersection are not blocked, which means that the queue from the previous intersection does not impact on vehicles leaving the studied entry,
- the queue of turning vehicles fits into the turn lane and does not block through traffic,
- the number of lanes of the analysed direction on the intersection entry is the same as in the section preceding the intersection,
- low longitudinal gradient of the entry (i±1.5%), typical lane widths (approximately 3.5 m), good technical condition of the street surface, including, possibly, of the tramway track, curvature of the travel path with a large radius and a small angle of turn (R>100, γ<10º). These factors do not affect drivers' behaviour or traffic dynamics,
- bus stops located in bus bays separated from the carriageway or in a lane designated for public transport.

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As a result of the field tests carried out at 8 intersections with a single lane for through traffic in Cracow, a database was built up containing measured values of the headways between vehicles and the lengths of residual queues. As a result, large databases with a sample size of more than 10 000 events were obtained.

Factors Impacting Saturation Flow and Capacity

By conducting the study under conditions similar to the basic conditions (Chodur et al., 2004), the influence of certain factors including: smaller lane widths, significant longitudinal gradients at the entries, the presence of bus stops without bays, the presence of a short lane at the entry were all avoided. The detailed nature of the analyses (cycle by cycle) facilitates the examination of a number of relevant factors that have been partially discussed in national and international literature (ITE Canada, 2008; National Academies of Sciences, Engineering, and Medicine, 2022; HBS, 2015). The identified factors were defined as quantitative and qualitative variables. The variables were then divided into two groups depending on the type of variability identified, i.e. deterministic and random ones.

The paper will show the results of the research targeting the following groups of weather conditions:

- sunny,
- cloudy, dry road surface,
- long- and short-lasting rainfall (long-lasting rainfall is rainfall of varying intensity, usually continuous with possible momentary interruptions, lasting for most of the day, the whole day or several consecutive days. Short-term precipitation is a sudden rainfall of varying intensity, on a day when sunny or cloudy weather prevails and the surface is dry),
- snowfall.

Analyses featuring other independent variables determining, among other things, the drivers' behaviour, extent of the intersection area, lane position in a group of lanes, impact of the structure of vehicle types, type of lighting, proportion of the green signal in the cycle, which are not included in this paper, are presented in the paper (Ostrowski & Chodur, 2015; Chodur et al., 2016).

Method of Analysis

In the analysis, an approach is used based on headways between pairs of passenger vehicles. The intensity of vehicle departures in the middle interval of the green signal during the signal cycle was determined from the quotient $3600/t_{n,s}$, where $t_{n,s}$ is the average headway between passenger vehicle pairs in the saturated state. Figure 2 reveals that the average headway between vehicles varies depending on weather conditions. As the headways in the initial and final intervals of the green signal are different (usually larger), the method was reinforced to include a variable number of rejected f and k headways between vehicles (Table 1) to reflect the recorded weather conditions. The beginning and end of the middle interval were determined by comparative analyses of adjacent intervals for successive vehicles passing over the stop line. The analyses were carried out using the parametric Student's t-test at a significance level of α=0.05 and evaluation of the shape of the moving average for successive headways under different weather conditions (end interval) (Chodur et al., 2011).

The analysis shows that the worse the weather conditions are, the shorter the middle interval of service intensity is (Figure 3). Drivers need less time (smaller delay) to achieve a stable headway between vehicles in the middle interval of the green signal in adverse weather conditions than in sunny or cloudy weather with a dry surface (Figure 2, Table 1). In favourable weather conditions with good visibility, more vehicles are involved in achieving a high departure intensity during the middle interval than in unfavourable weather conditions (lower departure intensity). Vehicles accelerate to higher speeds.

Increased headways between vehicles departing from an intersection during rainy weather can also have the effect of reducing green signal duration when an inappropriate, too short green signal extension time unit is introduced into the control algorithm.

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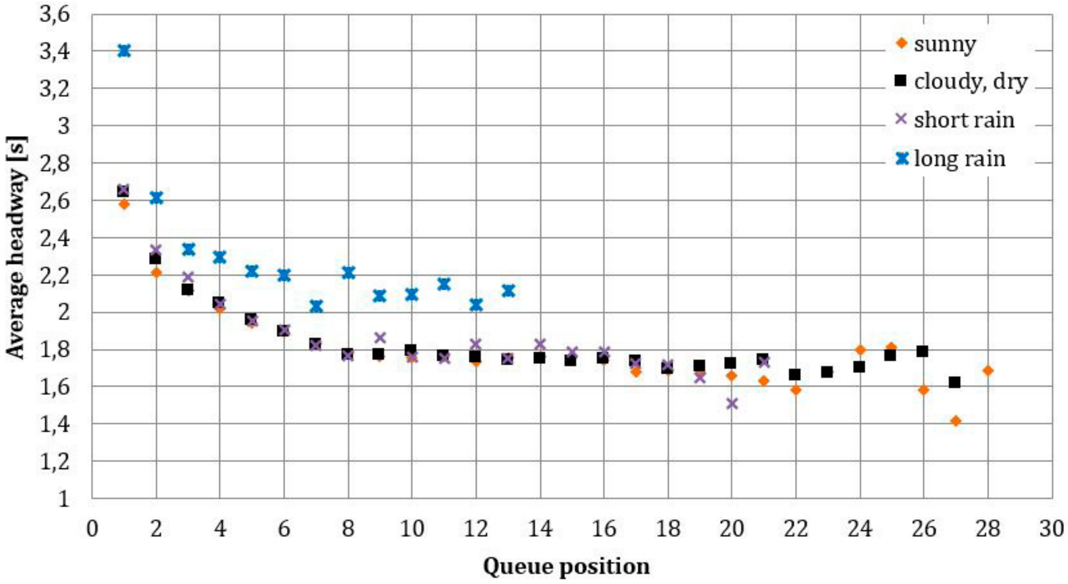

Figure 2. Time intervals of consecutive vehicles departing during the green signal in various weather conditions during the afternoon peak on a single-lane test site. Sample sizes range from 30 to 1249 (for cloudy, wet weather conditions from 7 to 12)

Table 1. Limits of the middle intervals of the green signal to determine the intensity of service in the middle interval

Weather conditions	Single-lane test site
Sunny	From 8 to 23 vehicles
Cloudy, dry	From 7 to 25 vehicles
Rainfall, short duration	From 6 to 19 vehicles
Rainfall, long duration,	From 4 to 12 vehicles
Snowy, long duration	From 4 to 15 vehicles

Source: authors' work based on Chodur et al. (2011).

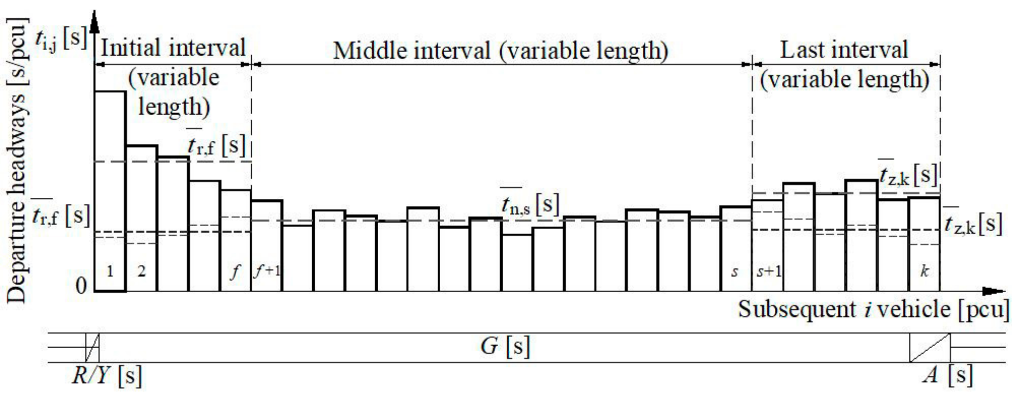

Figure 3. Service process model during a *j*-cycle phase

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Analyses of Variability Distributions of the Basic Value Saturation Flow S_w

Analytical methods (Chodur et al., 2004; National Academies of Sciences, Engineering, and Medicine, 2022; HBS, 2015) commonly assume that the value of basic saturation flow is constant. An exception is constituted by the Canadian method (ITE Canada, 2008), which gives different (fixed) values of the basic saturation flow S_0 for different cities and activities in the surroundings of the street. The impact of weather conditions on the value of saturation flow and thus on capacity and traffic performance is not included in the calculations and traffic management methods. Nor is this impact analysed in terms of environmental pollution costs. The analysis of the variability of saturation flow presented in this paper will be based on the variability of service intensity in the middle interval of the green signal in the traffic signal cycles under the initial conditions**.** The theoretical distributions were fitted to the empirical data using the Kolmogorov-Smirnov test at a significance level of α = 0.05. The following theoretical distributions were considered: normal, log-normal, Gumbel, gamma and Weibull (Rao, 1992).

Figure 4 shows that the more favourable the weather conditions for the service, the higher the modal values of the basic saturation flow in the fitted theoretical distributions. For the most unfavourable weather conditions, i.e. snowfall, a normal distribution was obtained, while for the other weather conditions, the gamma distribution proved to be the best distribution.

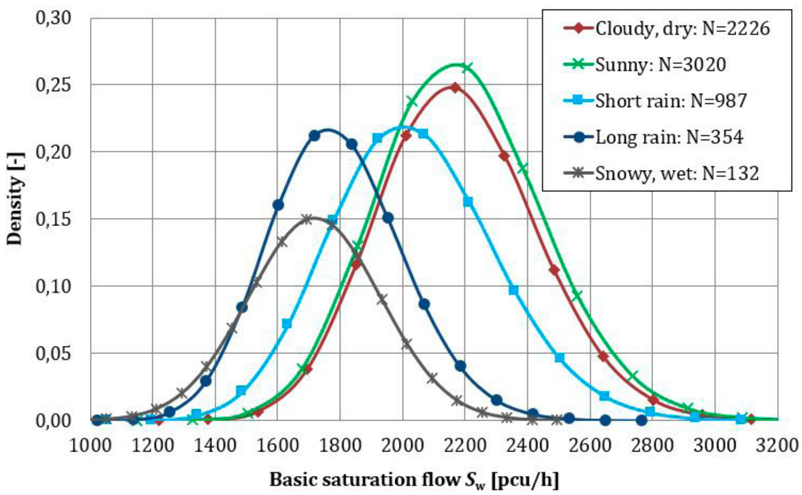

Figure 4. Density functions S_w for aggregated data from single-lane test sites (*N* – sample size)

There are several groups of weather conditions and surface conditions that significantly differentiate S_w saturation flows. These are: a dry surface and sunny or cloudy weather, a wet surface and a short rainfall and a wet surface combined with a prolonged rainfall or snowfall. The differences in modal values of saturation flow S_w between these groups range from 150 to 250 E/h. The spread of saturation flows across the signal cycles in the different weather condition groups is similar at ± 600E/h.

Lane Capacity and Traffic Performance

Analyses of lane performance for through traffic at the entry to a signalised intersection will be carried out using the Polish calculation method (Chodur et al., 2004) for various assumed increments in the demand flow and fixed control parameters in two different groups of weather conditions.

Using the empirical results of headways between vehicles, the variation of capacity across cycles was simulated under different weather conditions (Ostrowski & Tracz, 2019).

The above distributions show the variability of capacity under different weather conditions in terms of average values as well as the size of the standard deviation. It is seen that the longer the green signal, the greater the differences among average values and the greater the spread of capacity values for different weather conditions. In order to show the impact of differences in capacity values, such values of saturation flow and effective green signal (resulting from empirical studies) were introduced in the models of traffic performance included in the (Chodur et al., 2004) method that will give a capacity value close to the average (modal) value shown in Figure 5 for the adapted control parameters: The level of demand flow was selected so as to obtain a similar degree of capacity utilisation in favourable and unfavourable weather conditions.

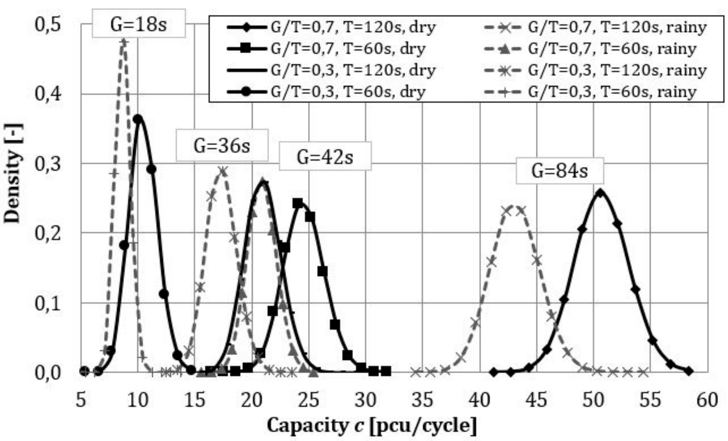

Figure 5. Density functions C [E/cycle] at different λ $(l=G/T)$ and green signal G [s] in different weather conditions

Source: authors' work based on a simulation model (Ostrowski, 2013).

The following data were assumed in the study:

- two outlying groups of control parameters:
  - G_e=18 s and T=60s,
  - G_e=84s and T=120s.
- demand flow ranging from 200 to 1040 E/h for the first group of control parameters and from 200 to 1600 E/h for the second group of control parameters,
- capacity calculated from the formula $C=S*G_e/T$ (Chodur et al., 2004) standing at 450 E/h and 615 E/h for unfavourable and favourable weather conditions respectively for the first group of control parameters and at 1260 E/h and 1540 E/h for the second group of parameters,
- capacity utilisation rate $X=Q/C$, which reaches maximum values of 2.31 and 1.69 for the first group of control parameters in unfavourable and favourable weather conditions respectively, and 1.27 and 1.04 for the second group of control parameters.

Graphs showing selected measures of traffic performance under different weather conditions and the range of variation in the differences of performance between the distinguished outlying groups of weather conditions and control parameters are shown below.

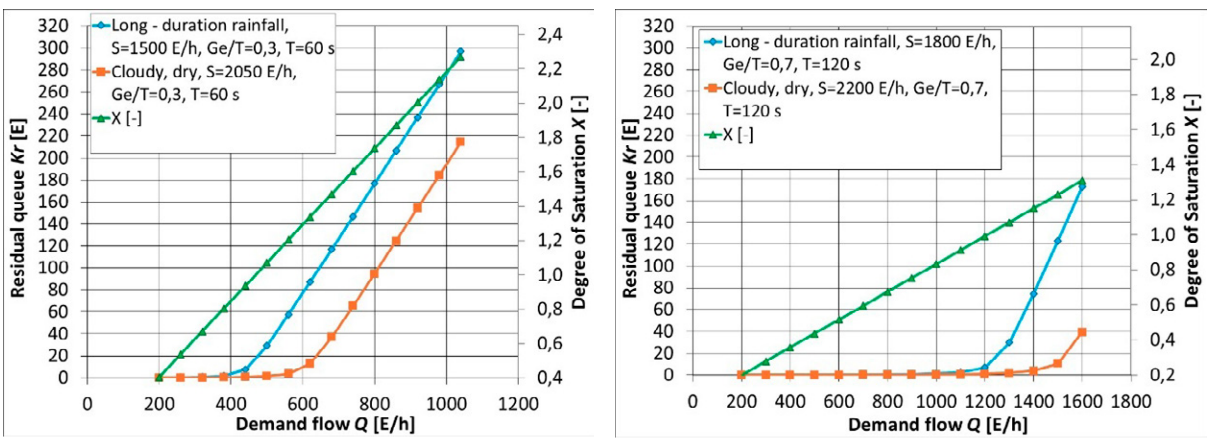

Figure 6. Impact of traffic volume Q on the length of residual queue K_r, under different control parameters and weather conditions

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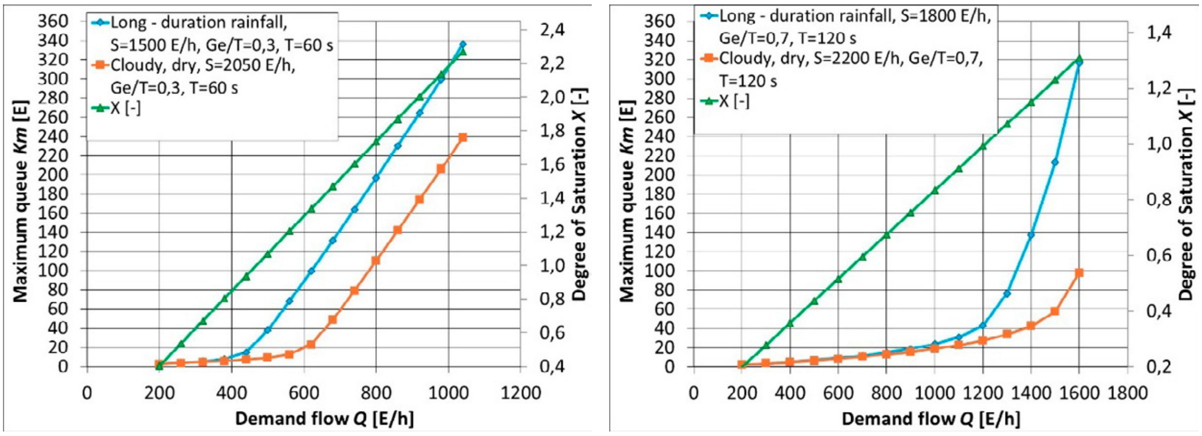

Figure 7. Impact of traffic volume Q on back of queue K_m, for different control parameters and weather conditions

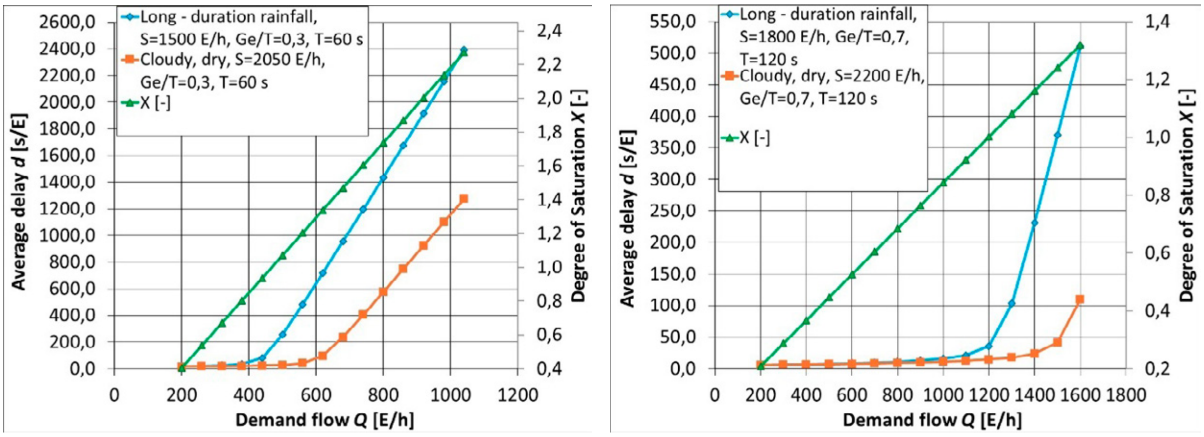

Figure 8. Impact of traffic volume Q on size of delay d, in different control parameters and different weather conditions

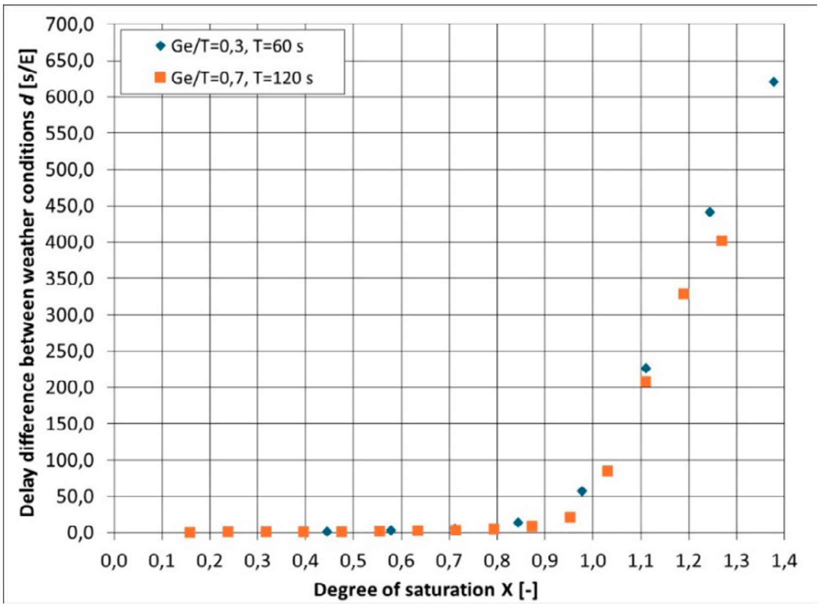

Figure 9. Impact of capacity utilisation rate X on the delay difference d determined between favourable and unfavourable weather conditions, in different control parameters

The following conclusions are drawn from the analyses:

1) It was determined that a relative reduction in the average saturation flow value relative to rain-free weather conditions for the following weather conditions amounts to: long-duration rainfall: between 8.5% and 20.0%, short-duration rainfall: approx. 4% and snowfall (wet carriageway) approx. 10.0%. Reduced saturation flow values reduce lane capacity.
2) Reduced capacity values in adverse weather conditions become most apparent during prolonged rainfall and translate into a deterioration of traffic performance, with the same level of demand flows, as shown in Figures 4–6. The differences in delay between favourable and unfavourable traffic performance increase as capacity level utilisation rises (Figure 9).
3) With shorter green signal durations and signal cycle durations, slightly greater differences in delay are observed between favourable and unfavourable weather conditions.

Longer queues, increased delays at entries to signalised intersections occurring on days with a prolonged rainfall at traffic volumes similar to those on days with favourable weather conditions have an adverse effect on the environment, increasing air pollution through increased exhaust emissions, increased traffic costs and thus adversely effect climate change. The relevant calculations showing these impacts are presented below.

Emissions Cost. Air Pollution Costs

Air pollution costs are the total costs generated by all vehicles travelling on roads covered by cost analysis. Air pollution costs include costs related to the environmental impacts of transport, including: negative impacts on human health (cardiovascular and respiratory diseases), crop losses, negative impacts on agricultural crops leading to lower yields, material losses (damage to buildings and facilities), environmental damage (negative impacts on biodiversity and ecosystems).

The most significant transport-related air pollutants are particulate matter (PM10, PM2.5), nitrogen oxides (NOx), sulphur dioxide (SO2), non-methane volatile organic compounds (NMVOCs). The calculation of air pollution costs is based on the unit economic costs of air pollution. These costs are directly related to vehicle use (of mainly internal combustion vehicles) and depend on the types of vehicles, road conditions, longitudinal gradient of the road and its location (urban or suburban road). They are subject to indexation. The economic costs of air pollution are calculated per vehicle type, separately for each variant and each year of the economic analysis in line with traffic forecasts for all categories of economic impacts. (JASPERS, 2023).

As part of the research on the impact of weather conditions on traffic performance, their impact on the social costs of pollutant emissions and the social costs of climate change was also estimated. Results from the surveyed test sites were used for the analysis.

Since the current JASPERS methodology does not determine the impact of speed on emission costs, it is not possible use the method to calculate emission costs at intersections simply because consideration of the vehicle speed factor is missing in the formula. To estimate the emission costs for the environment, relying on the results of studies (Metcalfe, 2023), indicator wv reflecting the vehicle speed at the intersection was assumed.

$$K_{zp} = 365 * \sum_{j=1}^{2} k_{zpj}(T,S) * w_v * W_j, \tag{1}$$

where:

K_{zp} – annual emission costs, in PLN,
j – number of vehicle types (light – LV and heavy – HGV),
$k_{zpj}(T, S)$ – unit climate change costs for vehicle type 'j' as a function of the terrain T and the technical condition of the surface S, in PLN/vehicle-km,
SDR_j – average annual daily demand flow for vehicle type „j”, in vehicles/day,
L – road section's length, in km,
W_j – vehicle kilometres travelled VKM for vehicle type „j” depending on road section's length in vehicle-kilometres/day, $W_j = L * SDR_j$,
w_v – coefficient of speed change at intersection.

A section of 0.65 km (access to the intersection), an average vehicle traffic volume of 1,000 vehicles per hour at the intersection, and a crossing speed range of 15 to 50 km/h were assumed for the analysis. Unit costs for light vehicles were assumed at 0.0561 PLN/vehkm and for heavy vehicles at 0.7588 PLN/vehkm.

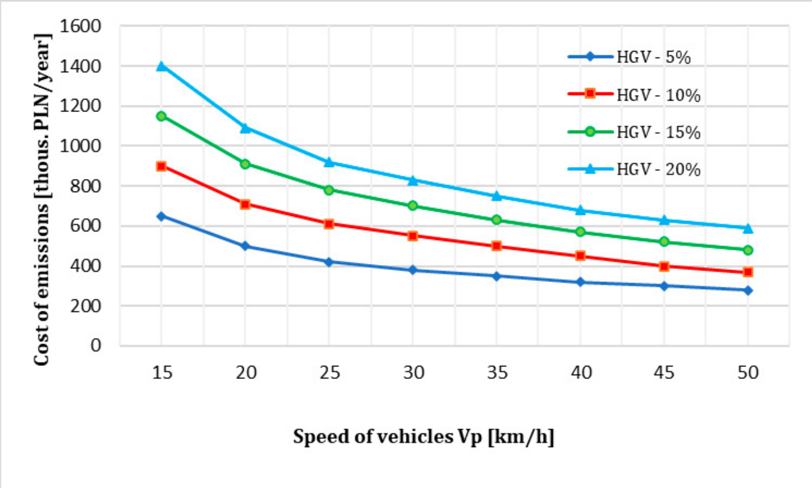

Figure 10. Variation of the social cost of pollutant emissions as a function of vehicle speed and share of heavy traffic

The following conclusions can be drawn from Figure 10:

1) At a speed of approx. 15 km/h, the emission cost is about three times higher than for a smooth crossing at a speed of approx. 50 km/h.
2) The traffic performance at the intersection resulting from the control mode and the weather conditions has a highly significant impact on the speed of passage and therefore on the volume and cost of air pollutant emissions.

Emissions Cost. Climate Change Costs

The costs of climate change, the impact of greenhouse gas (GHG) emissions, are the total costs generated by all users travelling on the transport networks under study. The climate change costs (expressed as CO2 equivalents) consist of the total CO2 equivalent emissions multiplied by the unit cost. The proposed methodology is in line with the EIB's Project Carbon Footprint Calculation Methodology, version 11.1, July 2020, which assesses the impact of GHG emissions from road infrastructure projects resulting mainly from the operational phase of the project (vehicle traffic on different road and rail networks). For calculation purposes, the GHG emission coefficients can be considered as relating to CO2. The estimation of GHG emissions for projects according to the methodology requires the assessment and presentation of information on: absolute emissions: total emissions in a typical year of operation (tCO2e); relative emissions: given in incremental terms (increases/decreases). The estimation of annual relative emissions will depend on the emissions produced by the users of different vehicles (and means of transport) on the network. In this case, reference is made to 'greenhouse gas emission coefficients, which are multiplied by the relevant vehicle kilometres travelled, VKM. Emission coefficients depend on users' vehicles (and means of transport), in terms of fuel/energy consumption. For road vehicles, fuel consumption depends primarily on speed, vehicle type, as well as road surface condition and geometry (JASPERS, 2023). Climate change costs are calculated according to the following formula:

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$$K_{zk} = 365 * \sum_{j=1}^{2} k_{zk,j}(V_{p,j}, T, S) * W_j. \qquad (2)$$

where:
K_{zk} – annual climate change costs, in PLN,
j – number of vehicle types,
$k_{zkj}(V_p, T, S)$ – unit climate change costs for vehicle type *'j'* as a function of travel speed $V_{pdrt,j}$, the terrain *T* and the technical condition of the surface *S*, in PLN/vehicle-km,
SDR_j – average annual daily demand flow for vehicle type „*j*", in vehicles/day,
L – road section's length, in km,
W_j – vehicle kilometres travelled *VKM* for vehicle type „*j*" depending on road section's length in vehicle-kilometretrs/day, $W_{kmj} = L * SDR_j$.

A section of 0.65 km (access to the junction), an average vehicle traffic volume of 1,000 vehicles/h, and a crossing speed range of 15 to 50 km/h were assumed for the analysis. Unit costs were also assumed for light vehicles (from 0.3578 PLN/vehkm for V=15 km/h to 0.1899 PLN/vehkm for V=50 km/h) and for heavy vehicles (from 0.8143 PLN/km for V=15 km/h to 0.1899 PLN/km for V=50 km/h).

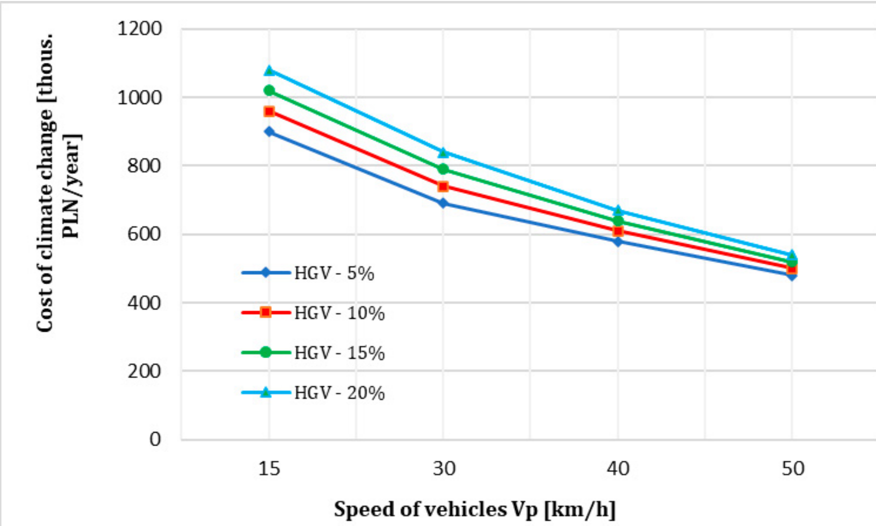

Figure 11. Change in the social costs of climate change as a function of vehicle speed and share of heavy traffic

The following conclusions can be drawn from Figure 11:
1) At a speed of about 15 km/h, the emission cost is almost twice as high as for a smooth crossing at a speed of about 50 km/h.
2) The traffic performance at the intersection resulting from the way it is controlled and the weather conditions have a very significant impact on the speed of passage and therefore on the magnitude and cost of climate change, expressed in terms of CO2 emissions.

Conclusions and future research

The following conclusions are drawn from the analyses of capacity and traffic performance and the costs of air pollution and climate change:
1) The empirical traffic studies show a relative reduction in the average saturation flow value in adverse weather conditions compared to days without precipitation at 8.5% to 20.0% for prolonged rain, approx. 4% for short rainfall and approx. 10.0% for snowfall (wet carriageway). The reduced saturation flow leads to reduced lane capacity.

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2) Reduced capacity values in adverse weather conditions are particularly evident during prolonged rainfall (also snowfall) and translate into worse traffic performance for the same level of demand flow as usual. The differences in delay and queue lengths between favourable and unfavourable traffic conditions increase with higher capacity utilisation, i.e. the closer the demand flow is to capacity (or when it exceeds it) the worse the traffic performance (bigger delays and longer queues).
3) With shorter green signal durations and signal cycle durations, slightly greater differences in delays between favourable and unfavourable weather conditions have been ascertained.
4) Bigger delays translate into slower speeds, deviating from a smooth passage through the intersection during the green signal, which increases harmful emissions and their cost. At a speed of around 15 km/h, the emission cost is almost double that of a smooth crossing at around 50 km/h. The analysis also revealed an adverse effect of traffic performance on the cost of climate change in terms of CO2 emissions.
5) Methods for calculating capacity and traffic performance measures should be augmented with saturation flow data in adverse weather conditions, which would allow it to predict the occurrence of adverse traffic conditions in both favourable and adverse weather conditions at the design stage. A more detailed design approach would facilitate designing control parameters (signal programmes) targeted at days with prolonged rain or snowfall. Retrofitting traffic lights with weather stations would allow control parameters to be altered automatically when unfavourable weather conditions are automatically recorded and identified.

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The contribution of the authors

Conceptualisation, K.O.; literature review, M.B. and K.O.; methodology, K.O. and M.B.; formal analysis, K.O. and M.B..; conclusions and discussion, M.B.

The authors have read and agreed to the published version of the manuscript.

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WPŁYW NIEKORZYSTNYCH WARUNKÓW ATMOSFERYCZNYCH NA KOSZTY RUCHU, ZANIECZYSZCZENIE ŚRODOWISKA ORAZ FUNKCJONOWANIE SKRZYŻOWAŃ Z SYGNALIZACJĄ ŚWIETLNĄ

STRESZCZENIE: Życie w dużych miastach narażone jest na niekorzystne oddziaływania środowiskowe w tym zanieczyszczenie powietrza. Wzmożony ruch pojazdów generuje stany zatłoczenia, gdyż niektóre elementy infrastruktury drogowej takie jak skrzyżowania w tym z sygnalizacją świetlną mają ograniczoną przepustowość. Gdy natężenie przekracza przepustowość pojawiają się kolejki pojazdów, a ich obecność zwiększa straty czasu i generuje zwiększone wydzielanie się spalin, które są szkodliwe dla zdrowia. Rosną również koszty podróży. Badania wykazują, że wpływ niekorzystnych warunków pogodowych wpływa negatywnie na zachowania kierujących pojazdami, którzy ostrożniej i wolniej zjeżdżają ze skrzyżowania w czasie trwania sygnału zielonego. Takie zachowania dodatkowo zmniejszają przepustowości pasów ruchu, a tym samym zwiększają zjawisko kongestii przy podobnym poziomie natężenia dopływającego obecnego w dniach ze sprzyjającą pogodą (dni słoneczne i pochmurne, bez opadów). W artykule ukazany zostanie wpływ warunków pogodowych na przepustowość pasów ruchu oraz warunki ruchu pojazdów na pasach z relacją na wprost sterowanych sygnalizacją świetlną. Gorsze warunki ruchu w dni z długotrwałymi opadami deszczu (albo śniegu) przyczyniają się do wzrostu kosztów podróży oraz zanieczyszczeń powietrza, co zostanie wykazane w artykule.

SŁOWA KLUCZOWE: sygnalizacja świetlna, przepustowość, zatory drogowe, warunki pogodowe, zanieczyszczenia powietrza, koszty