

Article

Estimation of Vehicle Traffic Parameters Using an Optical Distance Sensor for Use in Smart City Road Infrastructure

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Abstract: In recent decades, the dynamics of road vehicle traffic have significantly evolved, compelling traffic engineers to develop innovative traffic monitoring solutions, especially for dense road networks. Traditional methods for measuring traffic volume along road sections may no longer suffice for modern traffic control systems. This is particularly true for induction loops, a widely used method since the last century. In contrast, measuring techniques using microwaves or visible light offer better accuracy but are often hindered by the high cost of sensors. This paper presents new techniques for measuring traffic flow and other parameters that adapt to changing traffic dynamics using low-cost optical distance sensors. Our study demonstrates that the integration of multiple monitoring approaches enhances measurement accuracy, contingent on the dynamics and specific characteristics of the traffic. The results indicate that cheap optical distance sensors are particularly well suited for use in smart city road networks.

Keywords: distance sensor; optical sensor; smart cities; traffic flow; traffic control



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1. Introduction

Vehicle traffic is on the rise within contemporary road networks, including those located in smart cities. This surge is accompanied by a shift in the spatial distribution of traffic flow [1–6]. This effect results from a change in the distribution of traffic generators and absorbers within settlement space. This trend has intensified over the last few decades. For example, 10% of all Polish enterprises are closed and opened each year, with many opening in new locations previously unused [7]. A significant proportion of these enterprises are small- and medium-sized, with numerous small companies being registered on private premises. Consequently, the resultant changes in the spatial distribution of road network access points trigger abrupt shifts in traffic parameters within the respective areas, noticeably impacting traffic dynamics. This phenomenon is compounded by the increasing suburbanization of urban space [8–12].

These factors pose challenges for traffic organizers, who are responsible for tracking changes in traffic dynamics concerning resident mobility, particularly in larger population centers. Both the spatial distribution and the dynamics of the traffic do change over time. This trend is especially pronounced in major urban centers, which produce noticeably different traffic dynamics and driving behaviors compared to smaller towns [13–15]. These changes are illustrated in Figure 1.

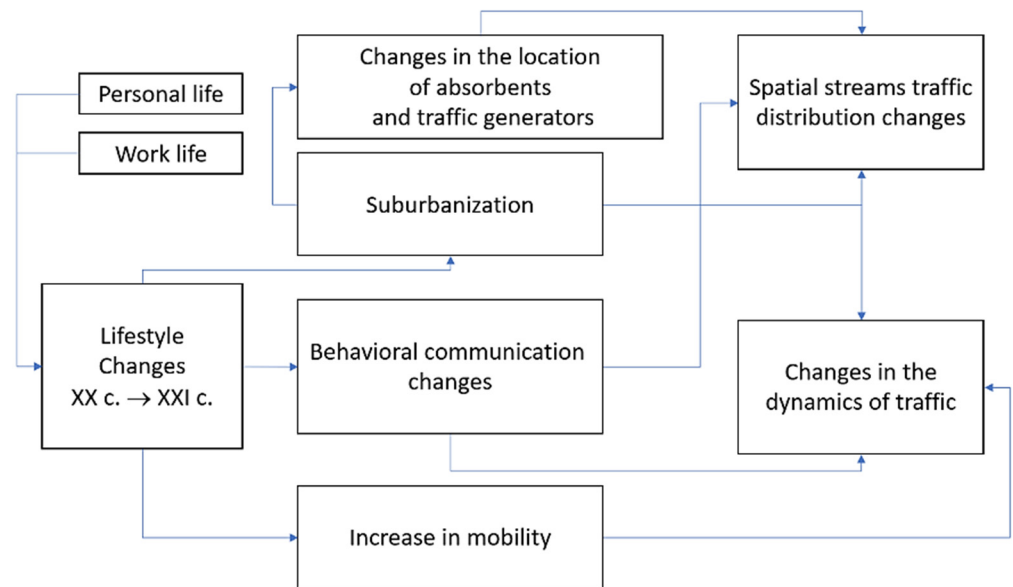


Figure 1. Changes in the dynamics and spatial distribution of traffic within road networks.

For instance, changes in the mobility and communication patterns of city dwellers can lead them to choose different modes of transport. Consequently, this affects both the spatial distribution of the traffic and the traffic dynamics, particularly within smart cities. The traffic share of bicycles and mopeds is increasing, further altering traffic flow dynamics. Similarly, suburbanization contributes to local congestion, reshaping traffic dynamics and transforming roads that previously served primarily transit traffic into roads catering to both the sources and destinations of the traffic infrastructure.

Understanding the traffic dynamics serves as a key consideration for the design of traffic light control algorithms and the organization of traffic. If these dynamics are not taken into account in the control algorithms will cause formation of traffic queues during each signaling cycle. Even minor queues propagate exponentially, particularly in large metropolitan areas leading to congestion, which may extend beyond the immediate intersections or even further. This phenomenon resembles a single queue crossing successive nodes of the traffic network. Unlike aviation systems, most detection and monitoring systems struggle to accurately recognize the dynamics of such processes.

Many different vehicle detection systems exist nowadays. Ensuring accuracy in traffic data detection is important for valid operations and the planning of the transportation infrastructure. Therefore, it is essential to carefully select the appropriate system. To achieve this, it is necessary to define the major selection criteria and rank them in the order of importance. Considerations should encompass the lane volume, speed, classification, lane-by-lane volume, trajectories, product maturity, cost, reliability, installation conditions, susceptibility to interference, vehicle stop identification, data transmission conditions, power supply, environmental conditions, and much more [16–20]. Each individual location may influence the selection of factors, and any random event may negate this selection. The main goal is traffic flow optimization and other traffic engineering challenges, a topic extensively covered in the literature [20–23]. This issue is still pertinent, especially in the economic field [24].

Modern systems commonly use induction loops, which are installed in strictly defined cross-sections of the road network, and are operationally cumbersome. The second most prevalent approach involves basic vision systems that lack the capacity to record movement dynamics, but operate using basic detection fields. These solutions tend to be expensive and require complex detection and analysis algorithms in addition to appropriate equipment with highly specific requirements [16–18]. The use of aerial drones for this purpose remains constrained by their maximum operating duration.

For the survey of the currently available traffic counting products in terms of functional capabilities, the reader can refer to the study [20]. The research indicates that only radar and vision techniques offer advantages that outweigh their disadvantages. Furthermore, the authors emphasize that price should also be taken into account due to the mass nature of modern monitoring [25]. The cost factor in the widespread adoption of radar and camera-based solutions has a negative impact on their implementation. The authors also possess expertise in the calibration of radar devices and cameras in commercial applications [26,27]. However, the market offers numerous solutions with better capabilities such as computer vision, radar, microwave, on-pavement loop detectors, traffic tubes, and pucks. Their deployment should always be preceded by BCA (benefit–cost analysis) analyses, taking into account all critical factors on location, such as data transmission parameters and especially the implementation price. The integration of fog computing with computer vision will increase the expenses of using cameras but improve costs and transmission parameters in other aspects.

However, critical issues arise with the proposed optical sensor. Which are limited in scope of usability in traffic data collection compared to computer vision-based methods with cheap HD cameras and open-source algorithms. This is happening because cameras can not only gather all traffic data but also provide classifications and trajectories. Nevertheless, as demonstrated in this article, this sensor can also be adapted to address these concerns.

Quantum localization in the field of road networks is rarely discussed [25]. A significant obstacle is the current state of this technology, which currently makes it impractical to calculate road traffic characteristics. It mainly concerns the size and cost of devices used in this technology. However, this is an example of a technology that, upon wider adoption, may revolutionize sensor networks and telemetry in general in road networks, especially in combination with C-ITS systems. One such transformative technology is satellite imaging using satellite technology and UAV vehicles [26–28]. These aerial technologies offer better capabilities compared to traditional methods such as computer vision systems, radar, microwave, on-pavement loop detectors, traffic tubes, pucks, and any ground measurement stations. Techniques for monitoring traffic from the air provide a global picture of traffic (on both macro and micro scales) and allow for better conditioning of modern road networks

The paper outlines several significant findings and contributions:

- The paper presents experiments demonstrating the efficacy of employing simple optical sensors for the measurement of road traffic flow and the results indicate sufficient accuracy for basic applications in traffic engineering;
- This research delves into the extended capabilities of optical sensors beyond traffic flow measurement, highlighting their potential in gauging other essential parameters of road traffic;
- The paper scrutinizes various factors that impact the accuracy of optical sensor measurements;
- The presentation of the examples of research with the application of optical sensor networks and the combined networks of such sensors with extended possibilities and potential areas of application;
- This paper includes a financial analysis of the developed solution and discusses the possibilities of the miniaturization of measuring devices in order to integrate them with the road traffic infrastructure in a dense sensor network.

It is currently challenging to identify the technologies that will be used to study traffic processes in transport systems in the future. However, it is difficult to agree with sentence that vision and radar techniques will remain dominant. There are many issues beyond road traffic engineering that may influence this state of affairs. For example, the perception of the issue of road traffic measurement may be changed by the concept of 15 min cities. It is unclear where traffic structures will be located in shared urban spaces, with a focus on non-motorized transport. In such cases, technologies such as radar will be ineffective, and the use of vision will be problematic due to occlusion. It is, therefore, reasonable to assume that in future transport systems, a combination of measurement techniques will be used in

a dedicated manner for specific infrastructure solutions. Consequently, the deployment of compact sensors, such as those proposed in this article, will be particularly beneficial.

2. Materials and Methods

This paper describes the measurement of vehicle motion parameters using a low-cost measurement system with a total component price of less than EUR 50. This price does not include the data transmission module. The system is sufficiently robust to be installed directly into the road infrastructure, including superstructure elements such as road posts, street lighting elements, and safety barriers at intersections. As illustrated in Figure 2a,b, the system comprises an ATMEL 328 microcontroller, a Sharp GP2Y0A710K0F optical distance sensor, and an optional DCF77 clock circuit. Sensor used in the research project Sharp GP2Y0A710K0F is a distance measuring sensor unit, composed of an integrated combination of position sensitive detector, infrared emitting diode and signal processing circuit, all in one (Sharp Cp., Sheet No.: E4-A00301EN). This sensor is always the basis for measurement systems made by the authors in various versions (standalone, mobile, elevated structure). The article contains data obtained in the manufacturer's version of the sensor. The project also used standard controller systems ATmega328. Is a single-chip microcontroller created by Atmel (Atmel, 7810D-AVR-01/15). The authors' dedicated software was used here. Time signal receiver module DCF77 clock circuit, also used in the manufacturer's version without modifications (e.g., Micro Analog Systems DAEV6180B1COB.003).

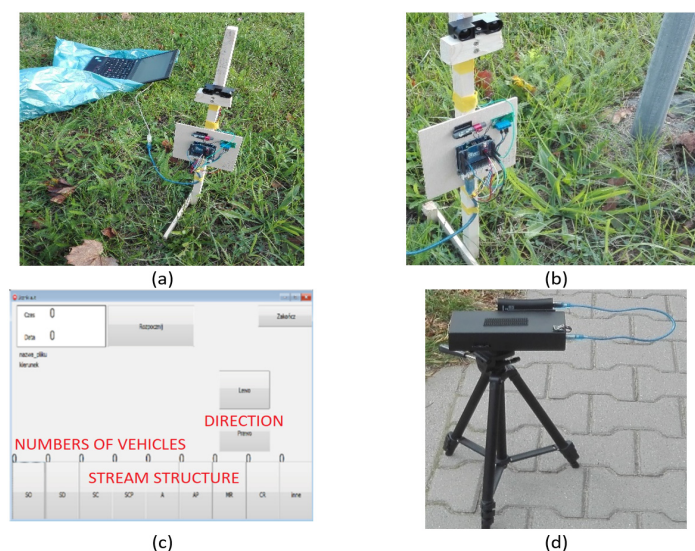


Figure 2. The vehicle motion measurement systems, showing (a) the system and a laptop computer, (b) the system alone, (c) the user interface that allows the manual recording of traffic intensity on a tablet computer, and (d) the fully autonomous version two of the measurement system.

The time can also be obtained using the data transmission system or the GPS system. In the latter case, the cost of the system increases to approximately EUR 100 (retail price of the sensor for June 2024 is 20 euros). The low price of the system renders it an optimal choice for the development of smart cities. The integrated version of the system will be correspondingly cheaper.

Research on the use of this sensor presupposes simultaneous research in many aspects of the road network (not only counting vehicles). According to the authors, the collected data can be used within the framework of a functioning smart city. That is, the sensor forms part of a distributed measurement system composed of multiple types of complementary data. Therefore, the measurement system should be inexpensive, reliable, and widely available. The use of a presence sensor to detect vehicles is somewhat straightforward, with only the size of the measurement error an area of concern. However, the transmission of the captured data, which may pertain to multiple parameters, to intelligent networks within a

smart city requires the solution of many technical issues, such as data structure, message size in bytes, and data connection method. The measuring system is undergoing continuous development—Figure 2d shows a fully autonomous version with a GPS antenna and a wireless communication system. The measurement height is variable depending on the tripod or monopod used, with a maximum value of 3.5 m.

The calibration of the SHARP sensor is performed via the software main window (Figure 2c). This setup is necessary for the counting and classification of vehicles according to their type using an operator equipped with a tablet and a handheld vehicle recorder. For this purpose, the infrared data are transmitted to the main microcontroller (with NEC protocol). This solution allows for the comparison of sensor data with the data measured by the system operator. The connection of the sensor microcontroller system to the mobile computer is solely for control purposes and is related to the data calibration procedure. Ultimately, the system functions within a network of sensors on Bluetooth Low Energy (BLE).

The measurement systems of networked distance sensors should be supplemented with a sensor communication system that operates in the radio band (e.g., 433 MHz). Such a system has a low cost of just several Euros. The authors of this study previously developed several different intelligent sensors that were connected with external systems using LoRa communication [29–31]. These systems required that measurement data was superimposed onto the appropriate data structures before being sent to the smart city network while accounting for the bandwidth limitations in the selected tele-transmission band.

This study addressed two fundamental research problems:

- The measurement of traffic flow parameters using the developed sensor;
- The selection of an appropriate data representation for the transmission of data within an urban smart city network.

Additional minor research problems are described in the Discussion and Conclusion Sections.

The measuring system was connected to a personal computer via a serial port in order to obtain the measurement results. For control purposes, the movement of vehicles was measured using a tactile vehicle recorder program running on a tablet computer. As illustrated in Figure 2c, the program interface allows the manual recording of traffic. The interface allows the user to register traffic measurements by selecting the appropriate icon, which specifies the type of vehicle. This data can then be used to calibrate and validate the data obtained by the distance sensor. Figure 3 provides an overview of the measurement system.

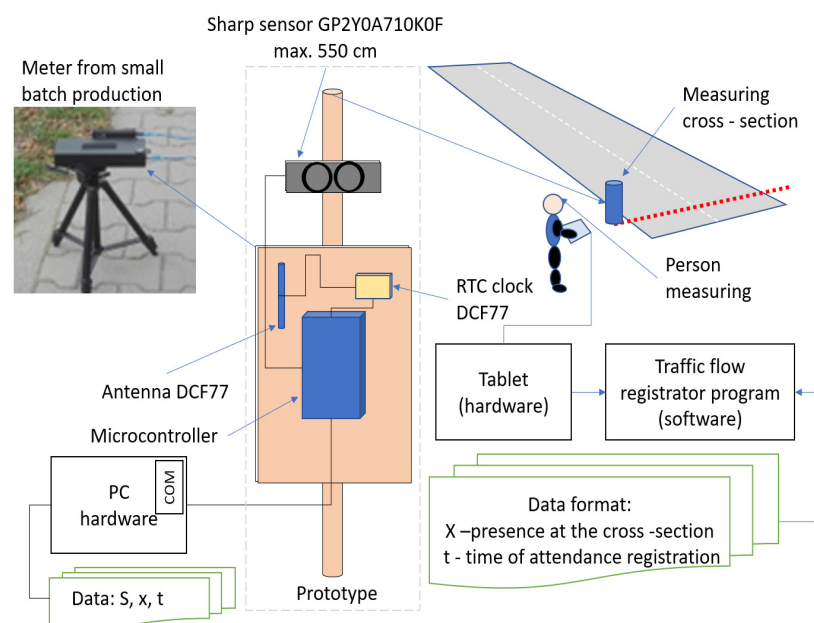


Figure 3. Overview of the measurement system.

The Sharp GP2Y0A710K0F optical distance sensor is employed to ascertain the distance of an object (in this case, a road vehicle) from the sensor face. The sensor manufacturers recommend a detection distance between 100 cm and 550 cm. However, during testing, considerably longer and shorter detection distances were recorded, accompanied by a corresponding reduction in accuracy.

Figure 4a illustrates the characteristic voltage response of the sensor. The sensor exhibits a high degree of nonlinearity within the range of approximately 0–90 cm. A data filter was employed to map the recorded sensor voltage onto a corresponding distance value. The filter was utilized in accordance with the appropriate documentation of the programming library, version 1.6.0 [32]. Thereafter, the sensor and sensor software were subjected to laboratory tests utilizing objects of varying shapes and conditions at known distances under laboratory conditions, with consistent lighting conditions. Following the completion of the testing phase, minor adjustments were made to the calibration coefficient in accordance with the recommendations set forth in the documentation [32].

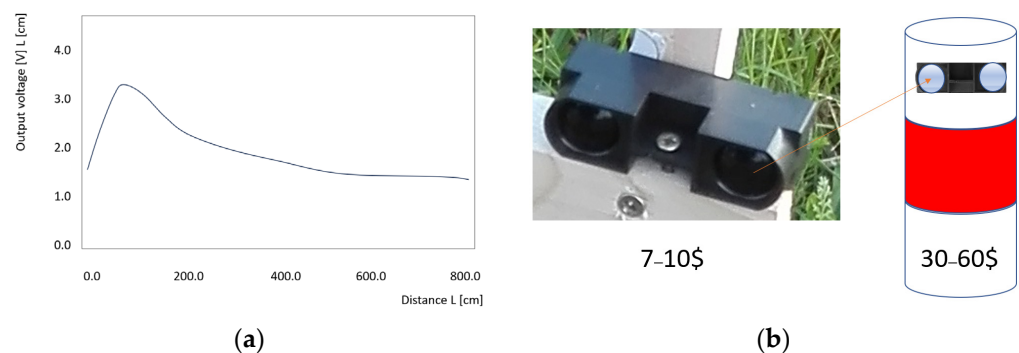


Figure 4. Characteristics of the Sharp GP2Y0A710K0F optical distance sensor, showing (a) the voltage response and (b) a comparison of the sensor price versus the price of a road bollard. Source: [22].

During the in situ testing, the optical sensor was oriented perpendicular to the road axis, as indicated with a dashed red line in Figure 3. During the testing, the sensor was pointing away from the sun, the air temperature was approximately 10 °C, the road was dry, there was no precipitation, and the wind strength was somewhat high. The decision to select the Sharp GP2Y0A710K0F sensor was influenced not only by its relatively high accuracy at a competitive price point but also by its minimal power consumption. This could facilitate the integration of future systems with photovoltaic sources. In July 2022, the cost of the sensor ranged from \$7 to \$10 for bulk orders. As illustrated in Figure 4b, the sensor was approximately four to six times less expensive than a bollard on which it could be mounted. For any kind of traffic sensors, system equipment must be protected from the environment. These types of devices are designed to operate continuously, 24 h a day, 7 days a week. In high latitudes, high humidity, significant rainfall, and severe frosts must be taken into account, as well as the possibility of direct sunlight. In some areas, strong daily temperature fluctuations and poor sunlight will make it difficult to power devices. Furthermore, this problem is much broader and encompasses the fields of rugged packaging, chip upgrading, and weatherproofing, mounting configuration, edge, and central applications. These factors, in all likelihood, significantly increase the cost of introducing an experimental sensor prototype into production-ready devices and solutions. Therefore, the authors' intention is to reduce the complexity of the device structure and its size. This will enable them to be built even in cat ponds (eyes). The next stage of implementation is TRL8, demonstration of the final form of technology. It is planned to expand the scope of product work, prepared to work on the construction of low-cost housings made of light and durable materials. Chip upgrading is an important problem, particularly in the context of cybersecurity of C-ITS systems. This is an area that has not yet been addressed.

Table 1 presents a comparison of mainstream solutions (magnetic sensors, radar, and cameras) and emerging technologies (lidar and distributed acoustic sensors). The table compares the following parameters of individual solutions: the purchase price of the device, range, interference with the road in terms of installation and possible repair, only vehicle counting, the measurement of selected traffic flow characteristics, the measurement of a large number of traffic flow characteristics, and trajectory measurement. Ratings were assigned a value on a scale from 1 (least appropriate) to 5 (most appropriate), with 3 representing an average value. If the solutions have the same functionalities, they are assigned the same rank values. Finally, the ranks for individual solutions are summarized. In order to assess effectiveness with particular emphasis on costs, the ranks given in this way should be weighted, taking into account the high importance of the purchase price of the device. The following acronyms are used in Table 1:

- Magnetic sensors (MS);
- Radar (R);
- Cameras (CV);
- LIDAR 1D (L1D);
- LIDAR 2D (L2D);
- LIDAR 3D (L3D);
- Distributed acoustic sensors (AS);
- Infrared sensor (IR);
- Accelerometers sensor (ACC);
- Optical sensors (OS) as presented in the article SHARP.

Table 1. The device comparison.

	P	D	I	C	QS	QM	T	Overall
MS	3	1	1	5	4	2	1	2.4
R	4	3	5	5	4	3	3	3.9
CV	2	4	5	5	5	5	5	4.4
L1D	5	4	5	5	3	3	1	3.7
L2D	5	3	5	5	4	3	1	3.7
L3D	1	4	5	5	5	5	4	4.1
AS	2	3	5	5	4	3	3	3.6
IR	5	1	5	4	3	2	1	3
ACC	5	1	4	4	2	2	1	2.7
OS	5	1	5	4	3	1	1	2.9

The authors have experience with all of the aforementioned types of devices. They obtained satisfactory results when it came to estimating the number of vehicles using the measurement of the temperature of objects in the road lane and ground vibrations resulting from vehicle movement [33,34].

The following acronyms represent selected analysis sections:

- The purchase price of the device (P);
- Range (D);
- Interference with the road in terms of installation and possible repair (I);
- Only vehicle counting (C);
- The measurement of selected traffic flow characteristics (QS);
- The measurement of a large number of traffic flow characteristics (QM);
- Trajectory measurement (T).

The presented ranking is conventional, but it reflects the characteristics of the individual types of devices. A comprehensive analysis is a task for a separate manuscript. As can be seen from the comparison, the general functionality of the optical sensors of this type places them at the bottom of the pack in third place from the bottom. However, if we assume that the price parameter is given as a weight of 0.7 (as is typically the case in public tenders in Poland), and that the SHARP optical sensors are the most optimal choice, then

these devices are worth considering despite the limitations of their use shown in the paper, as long as price plays a major role in tenders.

During the testing phase, the sensor was found to be capable of detecting reflected signals at distances of up to 14 m, which is significantly greater than the 5.5 m suggested by Sharp. However, due to the voltage response of the sensor at distances greater than 5.5 m, it was not possible to transform the measurements into an accurate distance value. The use of the sensor has been verified in field conditions. The traffic flow measurement experiments were conducted during the morning rush hour on a main road of the Polish road network. The Sharp GP2Y0A710K0F sensor was employed to ascertain the distance to vehicles passing by the measured cross-section (Figure 3). The sensor was situated outside the road gauge, approximately 2.5 m from the central axis of the road. A researcher was situated at an analogous distance and employed a tablet computer to manually document the vehicles. The manual measurements encompassed both the type of each vehicle and its direction of movement. Consequently, both the relative and generic structure of traffic flow were quantified. The traffic flow in the far lane was gauged to ascertain whether both lanes could be tracked simultaneously with a single sensor. The traffic was measured over three periods of 15 min each. In other experiments, a manual vehicle traffic recorder was employed, equipped with an infrared remote control, which allowed the operator to position themselves appropriately and avoid interference, as described in [34].

3. Results

The road on which the measurements were conducted was divided into two traffic directions, relative to the orientation of the sensor and the researcher performing the manual recording. The vehicles in the near side lane were defined as moving to the right; the vehicles in the far side lane were defined as moving to the left. Table 2 illustrates the generic traffic structure recorded by the manual measurements.

Table 2. The generic traffic structure, recorded manually.

	Direction of Movement		
	Both Direction Together	Left	Right
Personal car	216	132	84
Delivery truck	46	24	22
Truck	0	0	0
Truck with a trailer	0	0	0
Bus	4	2	2
Articulated bus	4	2	2
Motorcycles and bicycles	2	0	2
Tractor	0	0	0
Other vehicles	0	0	0
Overall	272	160	112

The data show that the traffic in the analyzed cross-section is asymmetric, with the majority of vehicles traveling to the right during the analyzed period. The study of traffic asymmetry is important from the perspective of the research objective, as it relates to the simultaneous measurement of both traffic directions.

Figures 5–7 illustrate the vehicle detection events for the vehicles moving to the right, the vehicles to the left, and all the vehicles, respectively. Despite the high intensity of reports observed in Figure 7, in the absence of congestion, the reports for each direction do not coincide in time. This suggests that both directions can be measured by the same sensor simultaneously. A crucial aspect of this study is the uniformity of the time distribution of vehicle detections. The objective of this study is to assess the viability of measuring traffic flows with high dynamics, which necessitates a continuous distribution of vehicle detections. A highly variable distribution is also a viable option. Figure 8 compares the dynamics and homogeneity for the two traffic directions.

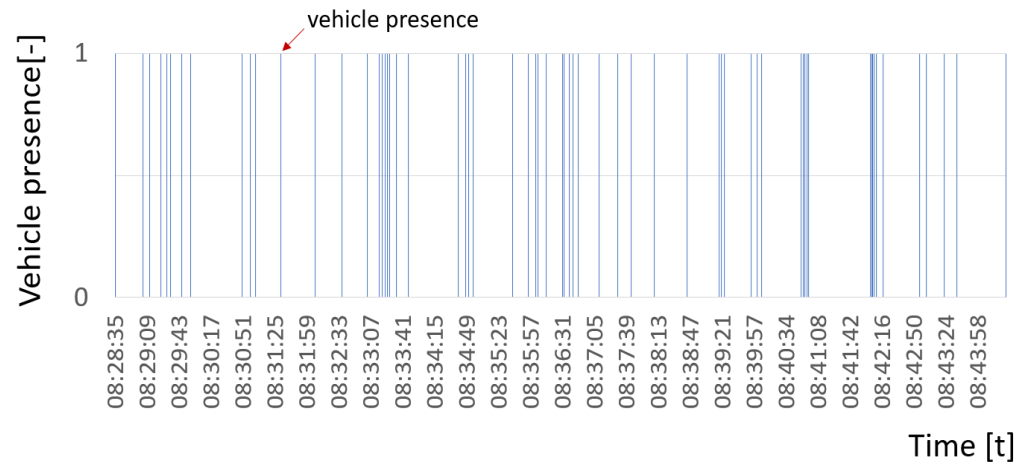


Figure 5. An excerpt of the recorded vehicle detections for traffic moving to the right.

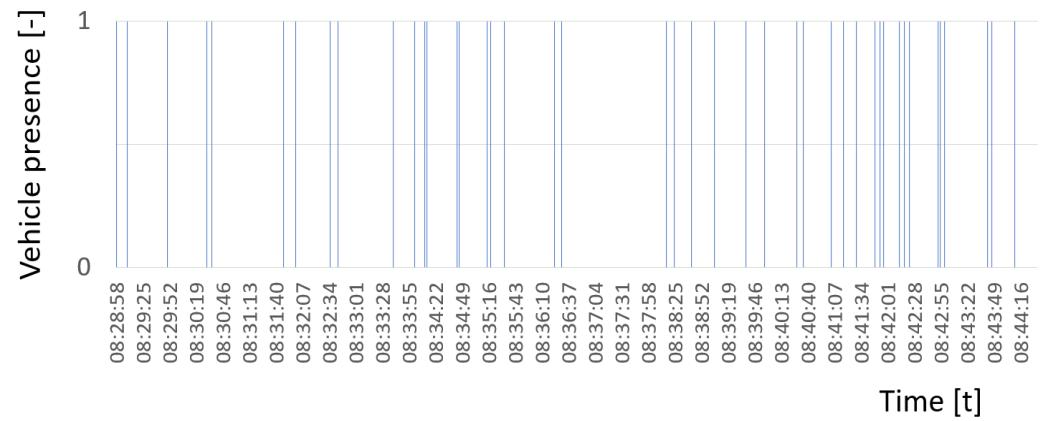


Figure 6. An excerpt of the recorded vehicle detections for traffic moving to the left.

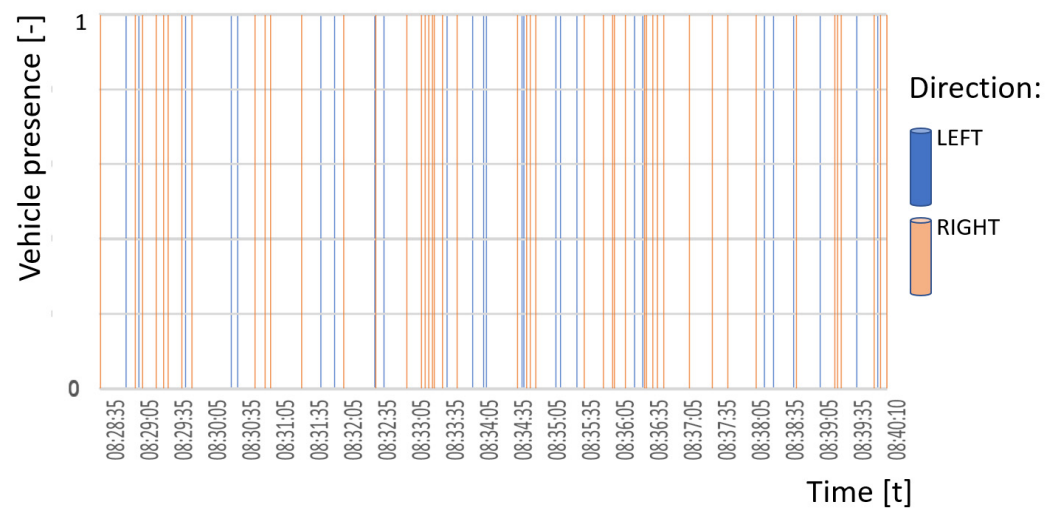


Figure 7. An excerpt of the recorded vehicle detections, showing both traffic moving to the left (blue) and traffic moving to the right (orange).

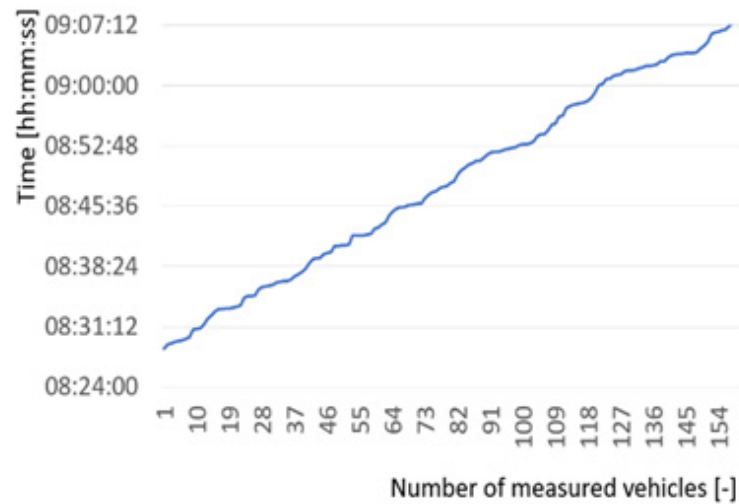


Figure 8. Dynamics versus homogeneity of the recorded vehicle detections.

Figure 8 illustrates the movement of traffic in a rightward direction. For both directions, the traffic flow is continuous and displays changes over time. The following plots on the abscissa axis, described by the sample number, also include a time variable. Two additional sample lines of the measurement file are shown below (the data format in the output file to which the measurement time and distance are saved is shown below).

- 00:00:01 → 1376;
- 00:00:02 → 951;
- etc.

The sensor operated at a frequency of 20 Hz. Figure 9 shows 40 min of the operation of the measuring device.

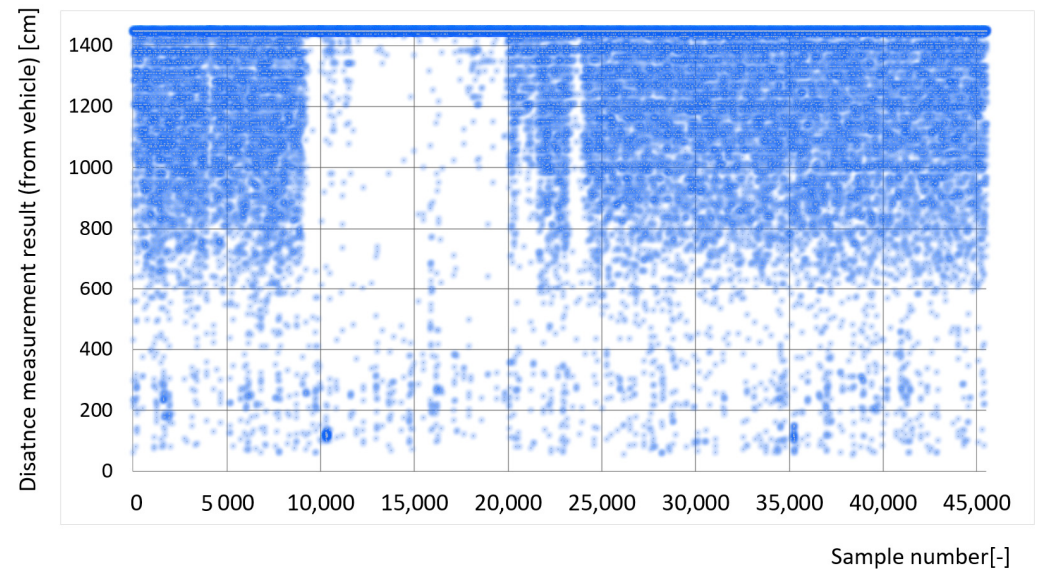


Figure 9. The distance measurement results (more than 45,000 samples).

Each lane of the road had a width of 8 m. Consequently, the sensor face was 2.5 m from the central axis of the near side lane and 6.5 m from the central axis of the far side lane. Figure 9 illustrates the results of the distance measurements. The sensor range is specified by the manufacturer as 5.5 m. Further investigation is necessary to ascertain the circumstances of the large sparse region between 9000 and 24,000 samples, and the smaller sparse region at approximately 24,000 samples.

Figure 10 illustrates the relevant distances between traffic streams and the distance sensor in the experimental area. Based on the distribution of distance measurement results, it was determined that further experiments should consider only measurements up to a distance of 6.5 m from the sensor, which is the distance between the sensor and the central axis of the far side lane. Consequently, the Sharp GP2Y0A710K0F sensor is sufficient to measure up to two lanes on a straight road section, with a maximum width of 4 m each, or up to three lanes with a maximum width of 2.5 m—the legal minimum for lane widths in Poland. This is a promising result for the application of a small number of sensors to a large number of lanes in an urban setting such as a smart city.

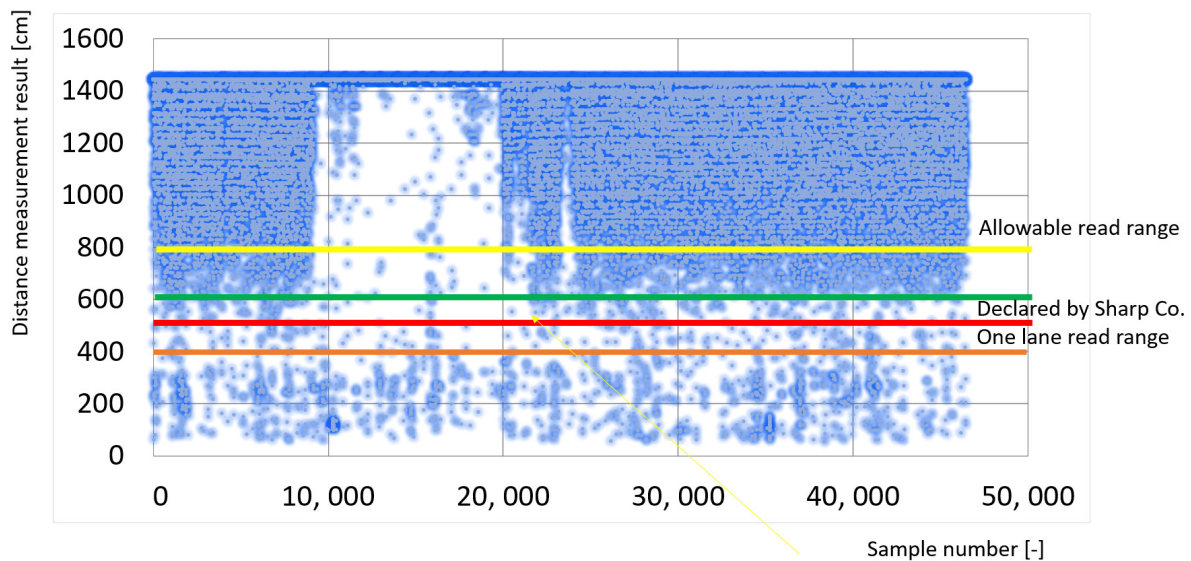


Figure 10. Analysis of the spatial relationships in the distance measurement data.

The sampling frequency during the test was 20 Hz. This equates to approximately 48,000 samples obtained during an experiment of greater than 40 min in duration. It is possible to increase this number by approximately 10–20% by utilizing the results acquired during the configuration of the modules used during the experiment for centralized time synchronization external to the measuring system. The measurement system can be synchronized with one of three approaches:

- Using the DCF77 clock circuit mounted within the measurement system;
- Using the connected PC;
- From connected networks with the communication module installed.

Figure 11 illustrates the results of the distance measurement process, which have been filtered to remove measurements exceeding 6.5 m. The spatial distribution of measurement points for a given vehicle detection is influenced by a number of factors, as illustrated in Figure 12.

- The location of the vehicle axis in relation to the lane axis;
- The reflection of the control beam from the side of the vehicle, which further depends on the profile of the vehicle, with some measurements not appearing in the distribution (as shown in Figure 10);
- The improper reflection of the beam due to the type, paint scheme, or lighting of the vehicle, among other factors;
- The vehicle speed;
- The presence of overlapping simultaneous movement in both directions;
- Thermal currents in the air;
- The weather conditions, particularly heavy rainfall.

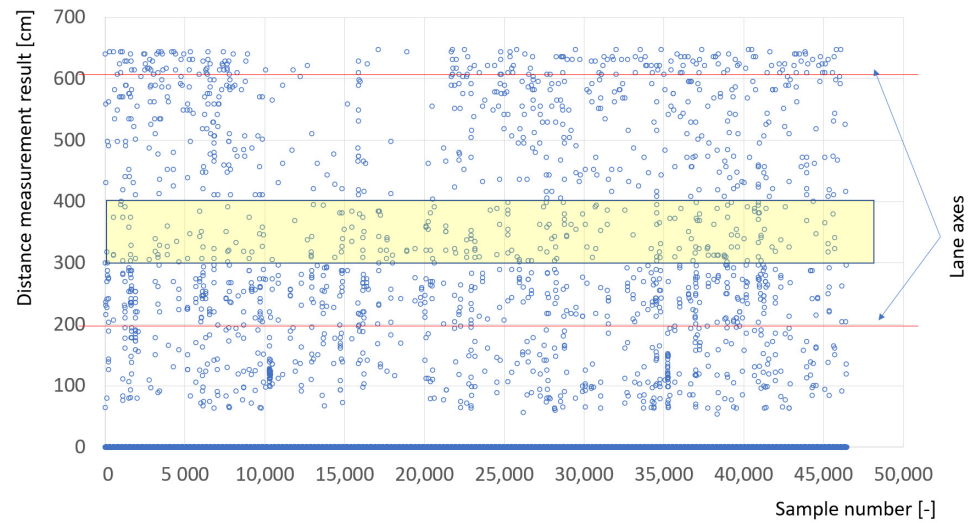


Figure 11. The distance measurement results filtered to show measurements below 6.5 m.

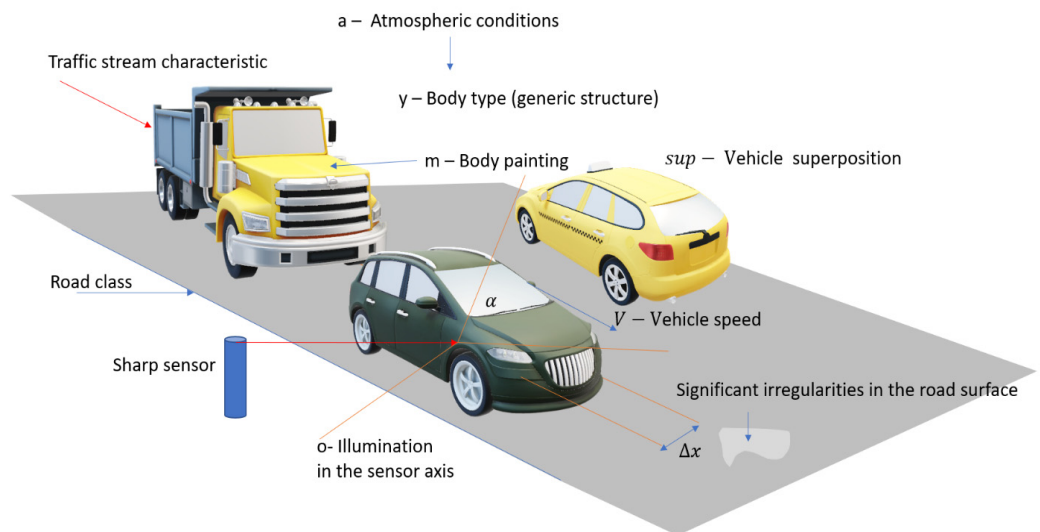


Figure 12. The factors that affect distance measured by the distance sensor.

Using these conditions, a detection at time t can be written as follows:

$$L_p(t) = f(\Delta x, \alpha, y, m, o, v, sup, a, RTF, TFF) \quad (1)$$

$L_p(t)$ —measurement distance [cm],

Δx —displacement of the vehicle axis in relation to the lane axis at time t [cm],

α —the angle of the side of the vehicle from which the control beam is reflected at time t [deg.],

y —vehicle body type [motorcycles, passenger cars, SUVs, buses, or trucks]

m —the vehicle paint type at the point of impact of the sensor beam at time t ,

o —the illumination of the vehicle along the sensor axis at time t ,

v —vehicle speed at time t ,

sup —the superimposition of vehicles traveling in both directions, and

a —the weather conditions at time t .

RTF —road type factor, taking into account the type of road [-].

TFF —Traffic flow volume, taking into account the dynamics of the traffic stream [-].

The road type factor is a variable that takes into account the type of road. In Poland, the following types of roads are distinguished (public road class): highways, expressways, main roads of accelerated traffic, trunk roads, collector roads, local roads, and access roads.

The type of road often translates into an achievable measurement distance. The roads of higher classes require an increase in the distance of the sensor from the axis of the lane of motion, which results in a less accurate measurement. The volume of traffic flow is also a factor to be considered, as it affects the dynamics of the traffic stream. This is reflected in the mean, which takes into account the effect of density and movement dynamics on the measurement result. Some calculations in this regard are presented in the summary section.

The yellow section in Figure 11 indicates the measured values between 3 m and 4 m. This distance corresponds to the collision zone between the two lanes, within which vehicles should not be detected due to the presence of double solid lines between the two lanes. Such measurements were assumed to arise due to inaccurate measurements, and hence these measurements were disregarded. Removing these points also provides a clear separation of the measured points for the two lanes. The fifth section provides further detail on the problem of accurately positioning the distance sensor.

Figure 13 illustrates the filtered distance measurements for the vehicles moving to the right during the initial seven minutes. Table 3 provides a comprehensive analysis of the set of reflected signals that correspond with the single vehicle detection indicated by the second clearly visible peak in Figure 13.

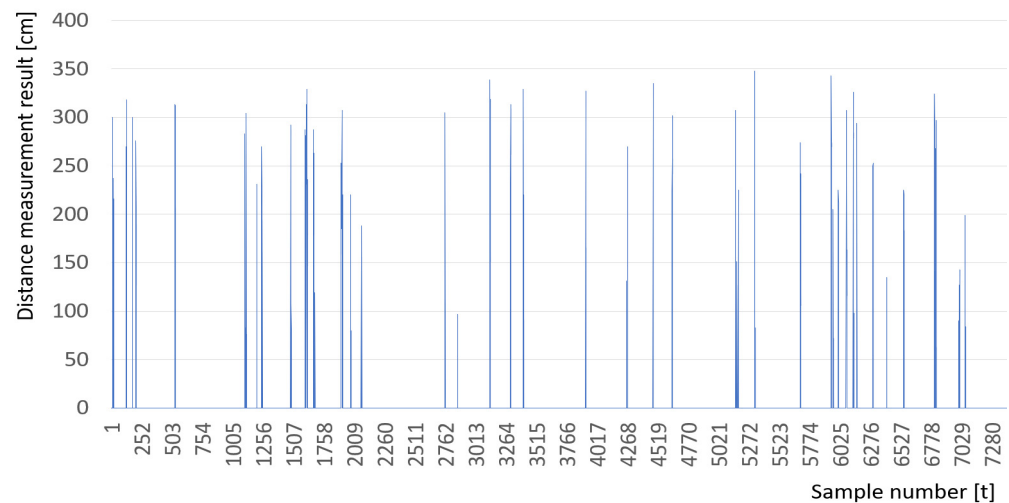


Figure 13. Results from the first 7 min of distance measurements for the vehicles moving to the right, with results filtered between 0.9 and 3 m.

Table 3. Analysis of signals corresponding to a single vehicle detection—case 1.

Input Data [cm]	Filtered Data *	Row Data Comments	General Remarks
1199	0	-	-
1446	0	-	-
973	0	-	-
270	270	Reflection from the car	Two proper measurements were taken before and two after.
241	241	Reflection from the car	
227	227	Reflection from the car	
318	318	Reflection from the car	
80	80 **	-	-
1446	0	-	-
1289	0	-	-

*—unreliable data was removed (measured value assigned as zero distance); **—measurements in the range of 50–80 cm are assumed to be reliable.

Table 4 presents another case study. The highlighted lines in both Tables 3 and 4 indicate distances of more than 3 m or less than 1 m. These measurements provide insight into the dimensions of the vehicles and, consequently, their types (the generic structure). The

data include various values that, while accurate, differ from the adopted range depending on the observed type of vehicle. This issue requires further in-depth research, as detailed in the Discussion Section.

Table 4. Analysis of signals corresponding to a single vehicle detection—case 2.

Input data	Filtered Data *	Row Data Comments	General Remarks
1446	0	-	
1384	0	-	
498	0	-	Reflection from a short bus moving to the right
279	279	Reflection from the car	-
300	300	Reflection from the car	Correct measurement in the right lane
287	287	Reflection from the car	Correct measurement in the right lane
139	139	Reflection from the car	-
491	0	?	-
562	0	-	
156	156	Passenger car	
1446	0	-	

*—unreliable data was removed (measured value assigned as zero distance).

Table 5 presents a third individual case. The values in Tables 3–5 indicate that the proposed measurement technique can also be used to categorize vehicle speeds. During measurement, vehicles typically generate between one and ten samples, with an average of approximately three to four samples. The number of samples allows the vehicle speed or length to be categorized. Such categorization can be determined by the following relationship:

$$V_i(t) = \alpha (n \text{ dl cal, } RTF_v, TFF_v), \tag{2}$$

$V_i(t)$ —the speed category of the i -th vehicle,

n —the number of samples of the determined vehicle distances according to tests 1–10,

dl —the distance from the sensor, and

cal —the calibration factor (skew, interleaving, etc.).

RTF_v —vehicle speed according to road type factor, taking into account the type of road [-].

TFF_v —vehicle speed related to traffic flow volume, taking into account the dynamics of the traffic stream [-].

Table 5. Analysis of signals corresponding to a single vehicle detection—case 3.

Input Data	Filtered Data *	Row Data Comments	General Remarks
1446	0	-	Reflection from a fast-moving passenger car

*—unreliable data was removed (measured value assigned as zero distance).

The number of speed categories that can be measured is directly proportional to the number of measurement points for a specific vehicle. This number of speed categories is achieved using a sampling rate of approximately 20 Hz. Theoretically, the measurement system is capable of sampling at a rate of up to 70 Hz. Testing indicated that a sampling rate of 50 Hz could be sustained without a significant degradation of data quality. This allows the legal speed range of 0–130 km/h to be discretized into possible speeds each of range 2.6 km/h. However, further research is required due to the nonlinear nature of Equation (2) with increasing speed. Moreover, the number of samples detected per vehicle is also a function of the vehicle type and length, with longer vehicles generating more samples.

In addition to the speed category, the distance measurements also provide information on vehicle dynamics. Figure 14 shows an analysis of selected distance measurements. The measurements contain a surprisingly large quantity of information. The speed category can be estimated from the total non-zero width of each measurement (indicated with a thick red line). The interval between successive vehicles can be estimated from the number

of zero samples between the non-zero samples of each detection. The standard deviation of the distance values for a single vehicle can be used to determine the driving style of the driver, in addition to any steering maneuvers that may have been performed. After sensor error has been accounted for, the standard deviation can also be used to estimate the vehicle type. In addition to the speed category, the number of measurement points per vehicle can be used to estimate the vehicle type. The generic structure of the traffic can be estimated by analyzing the data points above 3 m. The dynamics data can be calculated directly from the number of samples for which the correct measurement of the distance was obtained in the range from 0.9 to 3 m. During this phase of the research, 0.9 m was adopted as the lower limit of accurate measurements due to the statistically significant percentage of measurements within this range. This differs from the lower limit recommended by the manufacturer, which is 1 m [35].

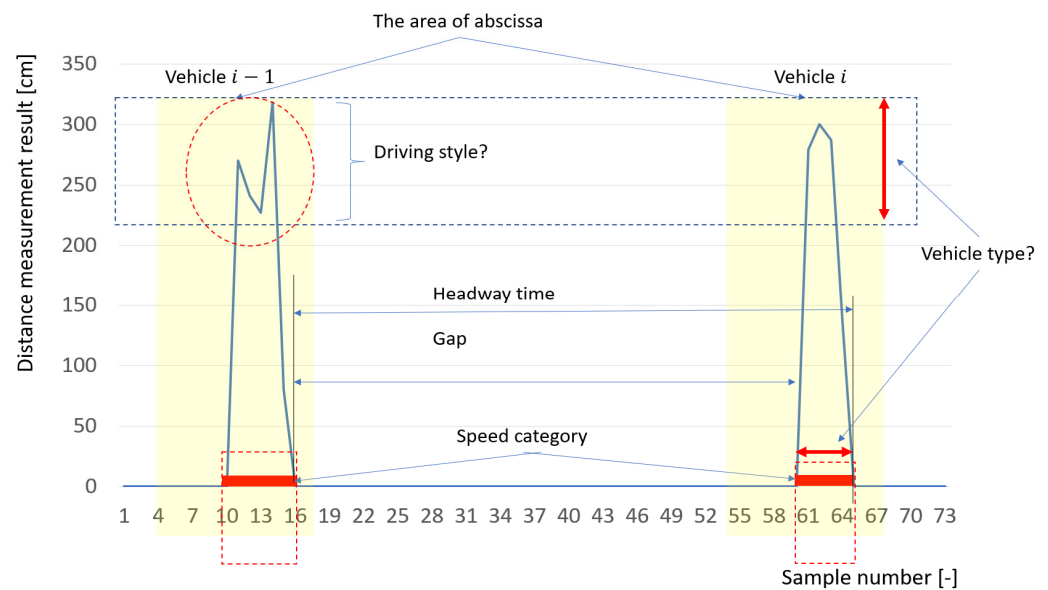


Figure 14. Dynamics analysis of selected distance measurements, with key elements highlighted.

It is evident that data such as those presented in Figure 14 permit the determination of various parameters, including the distance of the vehicles in the traffic stream (both the headway time and the buffer). This approach enables the measurement of both the quantity and quality of traffic. The specific distance in question can be compared in sections based on the readings of subsequent sensors along the road. This approach allows for a scientific approach to the examination of impacts (interactions between vehicles and streams) in the road network. In order to achieve this, various methods may be employed, including [36]:

- LISA, local spatial correlation (Figure 15a);
- Gravitational potential model;
- Traffic unions;
- Vehicle interactions in spatial regimes;
- Stream and flow impact measures;
- The tides of traffic flow by spatial regimes (Figure 15b);
- Machine learning.

The results of the analyses conducted on the basis of the aforementioned data are presented in Figure 15a,b.

Figure 15a,b illustrate the potential for the insightful analysis of road traffic characteristics based on two key measures: buffer and distance between the vehicles (headway). These measurements are made possible by the sensors presented in [36]. Figure 15a depicts the interactions between the spatial regions of the city's 300,000 population road network, computed using the LISA procedure. Figure 15b illustrates the vehicle interactions in

spatial regimes in transport network. All the characteristics are described based on simple distances between the vehicles, which can be read using the aforementioned sensor. Complex scientific analyses can be performed from simple numerical values read from the traffic sensors using a variety of methods, including statistical methods, computational procedures such as the potential (gravity) method, and various machine learning methods. These methods are widely recognized in the field of traffic engineering and transport systems.

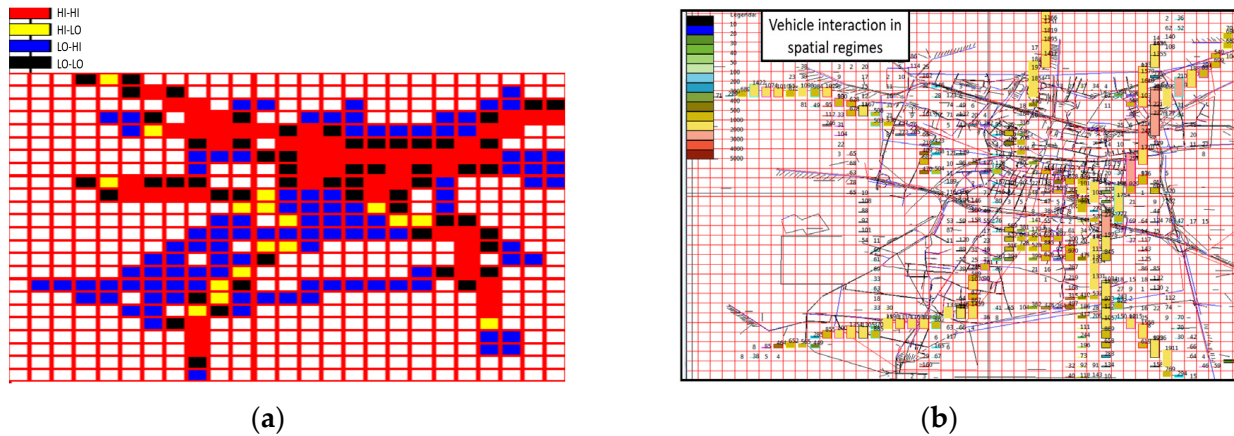


Figure 15. Analysis of traffic based on gap and headway between vehicles, (a) LISA procedure and (b) vehicle interaction in spatial regimes [36].

Table 6 presents the statistical characteristics of the full set of distance measurement data. The results indicate the usefulness of categorizing the measuring ranges. Only a small percentage of the results lie within the range declared by the manufacturer. This is important when using these types of sensors in intelligent networks that operate in parallel. In future work, the authors of this study intend to eliminate redundant data at an earlier stage, during the programming of the sensor’s microcontroller.

Table 7 presents the numerical characteristics of the complete set of distance measurement data. The majority of the measured values within the shortest range are close to the shortest distance that can be reliably determined by the sensor manufacturer. This range of measurements also displays the smallest standard deviation, which is approximately 15% of the average. Further research is required to explain the low value of the dominant. Due to the observed asymmetry of the traffic, the majority of measurements within the range of 1–5.5 m correspond with the vehicles moving to the right. The low value of the dominant is also relevant in this context. A statistical analysis of the measurements exceeding 5.5 m indicates that distance readings at this range are likely to be influenced by the reflection of sensor signals from obstacles situated outside the road lane, with an average distance of 13 m. This hypothesis is corroborated by the relatively low standard deviation of measurements in this range, which is approximately 16% of the average. However, a definitive conclusion regarding this issue necessitates further research, including experiments with a fixed obstacle located beyond the road.

Table 6. Statistical characteristics of the total set of obtained distance measurement results.

Statistic	Value	[%]
number of measurements	46,454	100
≤100 cm	139	0.29
≤550 cm	1287	2.77
>550 cm	45028	96.93
300–400 cm	240	0.51

Table 7. Numerical statistics of the total set of the obtained distance measurement results.

Statistic	100–550	0–100	550–∞
AVG	281.97	80	1310.46
STD	122.21	12.52	212.03
Mode	119	63	1446
Median	266	80	1446

4. Discussion

A variety of distance sensors are employed to collect data on traffic patterns, including road traffic. Ultrasound sensors are a particularly prevalent topic in the literature, with numerous references available, for example, see [37–39]. Additionally, light detection and ranging (LIDAR) sensors are gaining traction as a means of collecting traffic data [40–42]. Ultrasonic sensors are inexpensive and widely available, but their reliability is limited by the diverse shapes and color schemes of vehicles, which can cause significant interference [42,43]. While less susceptible to interference, LIDAR sensors remain expensive. The least expensive short-range, linear LIDAR sensors cost more than EUR 100 [44].

Low-cost sensors are well suited for deployment in urban smart city infrastructure, where they can facilitate the smooth functioning of such cities. Smart cities are designed to embody flexibility, innovation, and creativity. In this context, flexibility is a particularly pertinent concept, as it refers to the city’s capacity to adapt swiftly to changes in internal and external conditions. This encompasses the rapid adaptation of city road infrastructure and the associated organization to observable shifts in traffic dynamics. The concept of a smart city is inextricably linked to the use of information and communication technologies [45–52]. Consequently, the deployment of a network of low-cost distance sensors to measure traffic parameters is an appropriate strategy. The objective of this system is to enhance the mobility of city inhabitants by improving road travel. This study, therefore, proposes to equip the road network with the low-cost sensors described above. It is recommended that these sensors be distributed throughout the entire network, rather than being located in discrete sections, in order to enable the continuous monitoring of road traffic processes.

This approach necessitates the development of two techniques: one to discriminate between the captured data and one to transmit the data. It is essential that the measured data be limited in size and structure in order to ensure that only key information is transmitted, including vehicle detection, the time of detection, vehicle speed, and vehicle type. Such limitations would enable the efficient transmission of information without overwhelming the network capacity. The aforementioned data could be transmitted in the following manner: time in hours, minutes, and seconds (integer data type), vehicle number (integer), vehicle length (integer), vehicle speed (integer), and vehicle type (integer). In practice, this means that a single detection event measured by a single sensor requires 20 bytes of information to be transmitted via the urban network. Similarly, the networks of this type can be structured using marriage and divorce logic, as described in [53,54].

Figure 16 presents a series of anomalous measurements obtained during the experimentation. The regions of interest within each subfigure are indicated by red outlines. Figure 16a illustrates a transient increase in detection distance, within the range of 10,000–20,000 samples. Such artifacts reoccur many times to a lesser degree within the measurement data, such as at approximately 21,000 samples and 24,000 samples in the same figure (around 21,000, 24,000 samples). The distance measurements returned at this distance were caused by solid objects on the far side of the road. Several possible hypotheses offer explanations for the existence of the anomalies:

- Strong gusts of wind caused movement in the trees located on the far side of the road;

- Substantial changes in the light levels detected by the sensor were caused by sunlight briefly appearing through gaps between clouds, lighting towards the sensor’s detection field (sunny weather with a cloudy sky);
- Voltage instability of the measuring system caused by a lack of an independent micro-controller stabilizer.

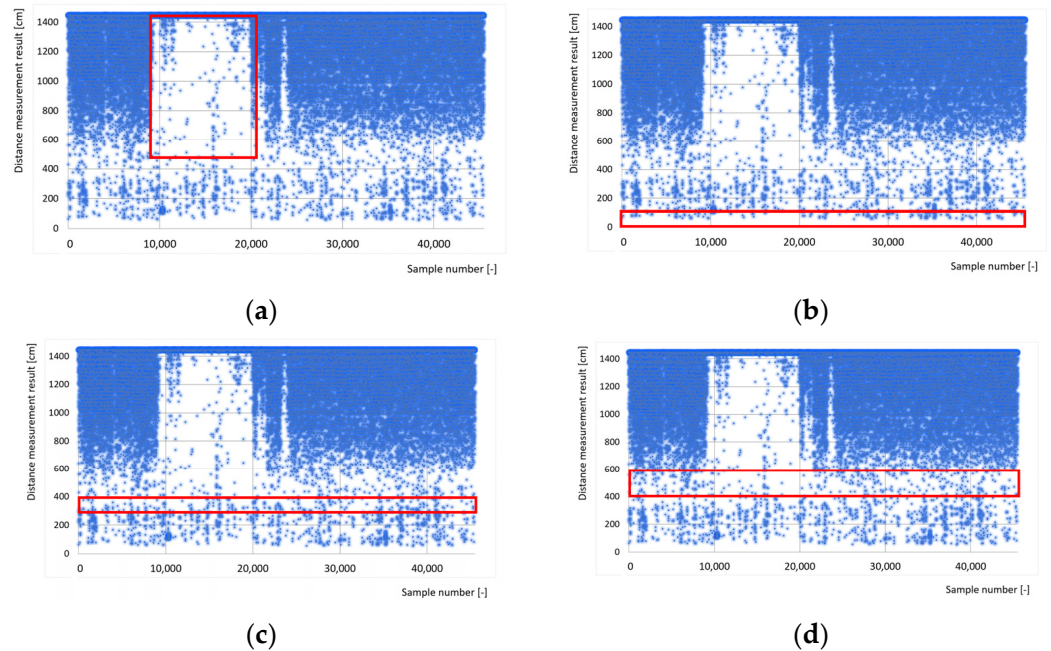


Figure 16. Anomalous data obtained during the experimentation. The regions of interest are indicated by red outlines (a) measurements beyond the distance declared by the manufacturer, (b) dead zone, (c) measurement at section of the near side lane (d) measurement at section of the far side lane.

These hypotheses should be tested by further field experimentation. Figure 16b illustrates the collection of some measurements within the nonlinear range of the distance sensor, beyond approximately 50 cm. Two-wheeled vehicles, including two that were detected during experimentation, could pass the sensor at this distance. Further research should be conducted to determine if detection at such a range is acceptable, or if the sensor should be positioned further from the road. However, the latter case may restrict the sensor’s ability to detect vehicles on the opposite lane. As previously discussed, data discrimination to prioritize the specific ranges of measurement distance is beneficial for introducing such solutions to smart city networks.

Figure 16c,d illustrate the varying spatial distribution of the measurement points in the individual fields of interest. The region highlighted in Figure 16c corresponds with the furthest 1 m section of the near side lane. The region highlighted in Figure 16d corresponds with the nearest 2 m section of the far side lane. Data from these regions are critical to determine the accuracy of measuring both lanes simultaneously using a single sensor. The 4 m lanes used during the experiments in this study are of greater than average width (3–3.5 m). Unfortunately, this results in drivers choosing different trajectories within the wider lanes. Additional experiments should be performed using the lanes of width 2.5–2.75 m. Such narrow lanes should cause drivers to maintain similar trajectories.

Figure 17 illustrates both the manual measurements and the distance sensor measurements for both directions. As previously described, the manual recording requires that the user clicks at least once to indicate a vehicle, and may also require an additional click to indicate a change in the direction of movement. The results demonstrate a discrepancy between the results gathered by the distance sensors and the manual recordings. This discrepancy may be attributed to a number of factors:

- The number of recorded values is different for each method, with the manual recording producing just a single event per vehicle, while the sensor produces up to 12 measurements per vehicle;
- The reaction time of the user performing the manual measurements may range from 0.3 to 2 s.

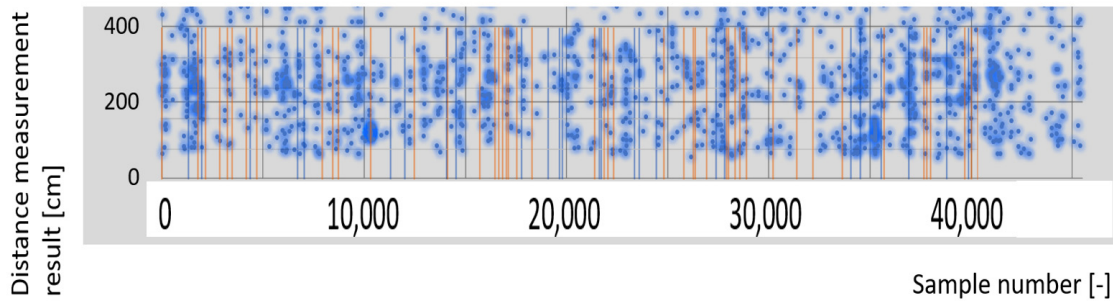


Figure 17. Superimposition of the manual measurements with the distance sensor measurements. The blue lines indicate the vehicles moving to the left, and the orange lines indicate the vehicles moving to the right.

A direct comparison of the two sets of measurements would necessitate the development of a novel measuring system that employs a distinct manual device. The distribution of the measured points can also yield intriguing data, such as vehicle profiles.

Another intriguing question that emerged during this study pertains to the optimal height at which to situate the distance sensor. Not only does the precise positioning of a roadside distance sensor present logistical challenges, but the sensor’s height also determines its capacity to accurately detect vehicles, as illustrated in Figure 18. Within the designated height zone A, the vehicle chassis is positioned above the road surface, and only the wheel is discernible. This configuration leads to significant inaccuracy, particularly in the simultaneous detection of traffic on both sides of the road. Zone B presents similar problems for larger vehicles that have a high ground clearance, and will also result in errors. Zone C is more likely to include the curved edges of vehicles in addition to the windows, both of which can cause measurement issues (although this is primarily a problem for ultrasound sensors [30,31]). Zone D is appropriate for detecting larger vehicles, but is too high for the detection of generic passenger cars and two-wheeled vehicles. Furthermore, vehicles are equipped with numerous lights on the boundaries of Zones B and C, which can impede the accuracy of measurements.

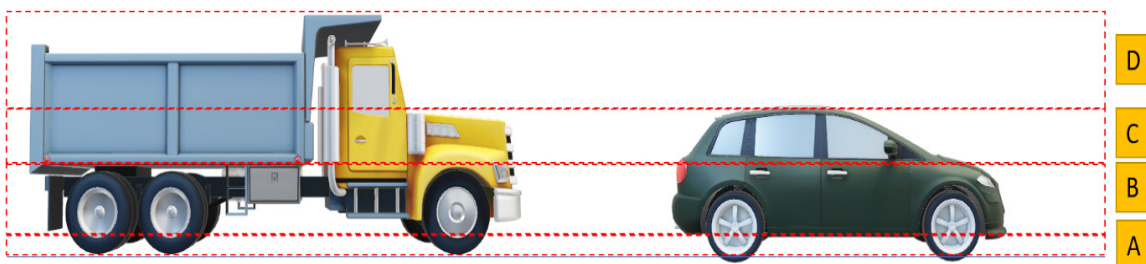


Figure 18. Illustration of several different height zones at which the distance sensor could be located, and the problems that each may entail with regard to vehicle detection.

5. Conclusions

The results of the vehicle detection research at cross-sections indicate a need for further investigation. Future studies should focus on the following:

- The determination of calibration coefficients for the estimation of actual traffic parameters (RTF and TFF coefficients) which requires large-scale research;

- The integration of sensors into smart low-cost area networks;
- Upgrading the measuring devices by integrating with RTC and GPS modules, and wireless network, e.g., mesh based on dedicated wireless modules;
- The miniaturization of the device in order to mount it in small elements accompanying the road infrastructure, e.g., roadside posts, cat's eyes, etc.;
- The calibration and validation of the method depending on the different locations of the device (roadside, on the roadway, above the roadway, etc.);
- Consider a new format for data transfer to the control center/data collection and formats and methods for exchanging data between devices/sensors.

The primary objective of further research is to develop an intelligent network of optical sensors. If operated as a complex network, new possibilities and functionalities can be achieved to control traffic flow parameters and address numerous traffic engineering issues.

This study validated the use of distance sensors for the identification of moving vehicle parameters. Parameters such as speed and type can be measured with high probability using the number of measured data points and their values. A mesh network of sensors would also be capable of determining driving style. Therefore, the method presented in this study can be applied as follows:

- To count the number of vehicles moving in the near side lane, and to partially count the number of vehicles moving in the opposite lane—further experimentation should be undertaken to determine the conditions in which vehicles in both lanes fully overlap, which prevents such measurement;
- Following further data analysis studies, to potentially determine the vehicle type by analyzing data in the range of 3–4 m—initial studies indicated that these data are related to the vehicle type, which might also be determined by the deviation of the vehicle from the lane axis due to its width;
- The categorization of vehicle speeds is a challenging task, particularly given the wide variety of the shapes and colors of vehicles;
- The accuracy of speed detection is also a significant issue, and further research is required to address this;
- To count the number of vehicles of each category, which may be useful for determining the generic structure of the traffic;
- To test the use of the lane depending on its width by determining how much of the lane is used by each vehicle;
- To determine the vehicle dynamics;
- To determine vehicle traffic flow parameters;
- To study the traffic queue generation process; and
- To study interactions between vehicles;
- Vehicle occupancy testing is not possible using this method. However, a sensor placed at the height of the windows could potentially be adapted to work for this purpose;
- Similarly, measuring the axle load or vehicle weight is not possible. Nevertheless, this sensor can be combined with the accelerometers successfully used by the authors to measure vehicle weight [34].

As illustrated by the presented comparison, the sensor in question offers enhanced functionality when integrated with other measuring devices, such as induction loops. It can be reasonably assumed that a network of such integrated sensors would provide additional value to the C-ITS system.

The pilot studies described here have identified numerous problems and ambiguities. However, the substantial benefits of using low-cost distance sensors in urban smart city networks are clear, and these problems should be analyzed in further studies. Subsequent research should also address the complex issue of communication between sensors integrated within various teleinformatic smart city networks and mesh subnetworks.

Another problem that requires further analysis is the impact of traffic dynamics on the recorded characteristics. Subsequent experiments should be conducted using a wide range of variable traffic parameters, with both congested and non-congested conditions analyzed.

Intensive work is currently underway on the development of version two of the measuring system, as shown in Figure 19. The version two system can be connected to intelligent networks for the purposes of deployment within smart cities. The problem of detecting undesirable objects has been partially eliminated for these sensors [30,43,44]. Figure 19a shows an example of three such networked sensors in operation. Figure 19b shows an example set of distance measurement results.

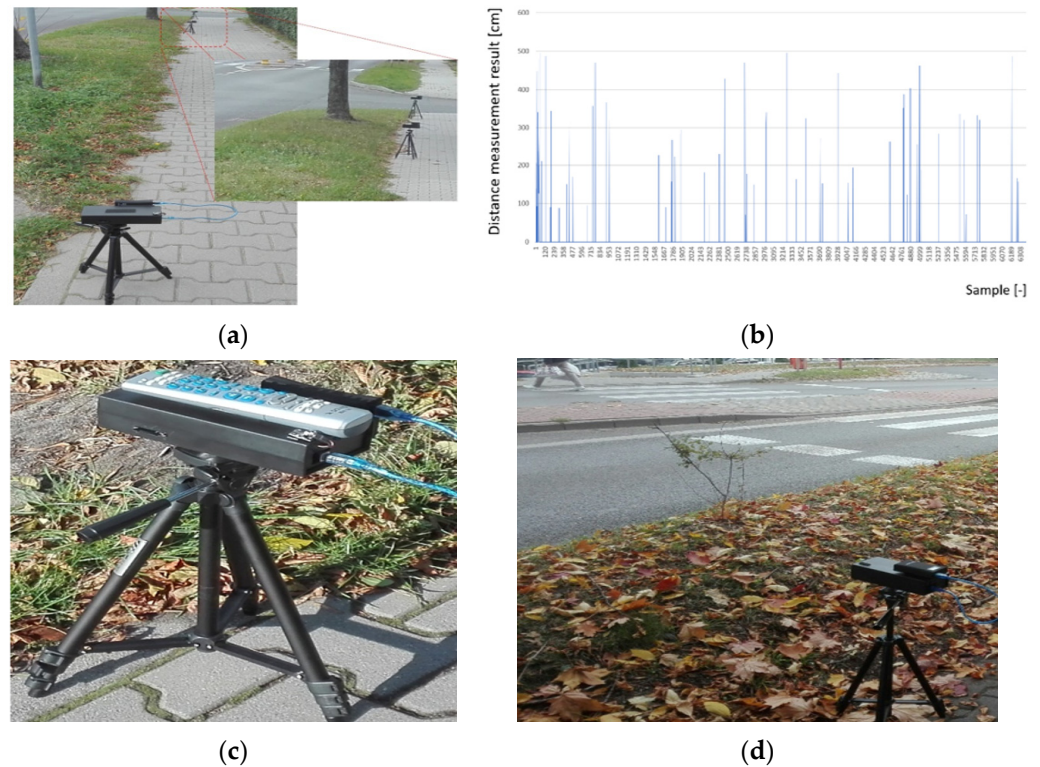


Figure 19. Version two of the measurement system, showing (a) a network of three connected sensors, (b) example data, (c) the new sensor unit with infrared calibration subsystem, and (d) an elevated sensor to account for low field compensation.

In practice, the operation of networks comprising up to six sensors was verified over a distance of approximately 50 m. The deployment of a higher density of sensors necessitates the optimization of the data structure in mesh networks. The use of different networks is possible, but is more costly. Nevertheless, the cost per distance of the quasi-continuous measurement of traffic flow characteristics was determined to be only EUR 300 per 50 m, with a high density of 1 unit per 8 m. Therefore, the authors believe this technology is suitable for use in smart city networks.

Due to the differing geographical and technical characteristics of roads, the proposed method cannot be directly applied to all dense traffic environments and different road classifications. In order to make the method applicable to every environment and road condition, the authors suggest correction factors. These factors are incorporated into the model to expand its applicability in related dense traffic environments. Two correction factors have been proposed. The first is due to the class of the road, RTF (according to the technical classification of the road), and the second is due to the characteristics of the observed traffic flow, TFF (obtained on the basis of other measurements using classic devices for detecting traffic, e.g., vision technique and inductive loop).

The measuring device and the method developed to identify the movement of vehicles were verified in the city streets in Katowice, Poland. A series of tests were conducted on streets with varying technical classes. The investigation encompassed locations with disparate geographical and technical characteristics of the road. In a subsequent study, the

devices (sensors) were placed on streets of varying technical classes, from major arterial roads with high traffic volumes (Polish nomenclature) to local roads. The following Figure (Figure 20) provides an illustrative overview of the characteristics observed.

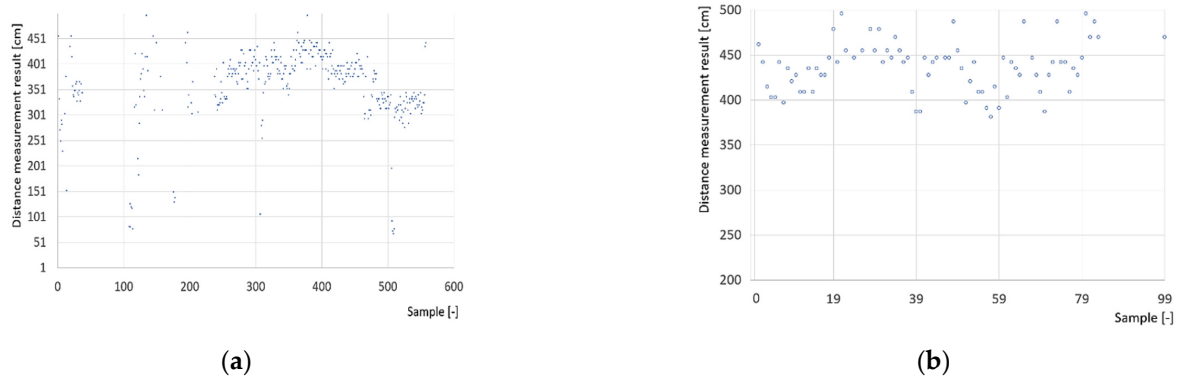


Figure 20. Selected results of an extended study of the Katowice street network, (a) main roads, and (b) local streets.

Based on the results of an extended investigation on the streets with different technical classes and different traffic parameters, we notice that:

- Dense traffic and inhomogeneous traffic especially with inhomogeneous speeds cause data loss;
- In these cases, measuring both directions of motion is unreasonable;
- Due to technical limitations, there are few atypical vehicles on local streets and roads, which increases the reliability of the data;
- There are many single trucks, which is not favorable from the point of view of the measurement technique used; the details of this specific problem will be presented in subsequent publications;
- The parameterization of the RTF and TFF indicators requires large-scale research on the road network in a given country in order to parameterize them in a realistic way;
- The accuracy of the measurement depends mainly on the technical possibilities of locating the sensors in the cross-section of the road; it is related to the adjustment of the dead zone of the sensor and the distance of its face from the axis of the traffic lane;
- The close location of a pedestrian crossing or intersection allows you to increase the accuracy of the measurement.

The recommended applications of the method developed and the measuring device are as follows:

- The analysis of traffic congestion patterns, which is facilitated by the cost of the device and the possibility of using it on a mass scale;
- Alternative to control and analyze road traffic flow instead of monitoring traffic from air (drones);
- The prediction of noise levels in the road network using data on the presence of vehicles at a specific place and time in the road network (known location of the sensor or the use of its GPS version);
- The collection of data from densely distributed sensor networks to calibrate microsimulation models;
- The analysis of the impact of driving parameters on traffic safety by combining cascade sensor data.

In particular, the application of this type of sensor in intelligent networks, in conjunction with the ANPR technique, enables the conduct of a wide range of analyses in the field of road traffic, the results of which will be presented in subsequent articles.

There is a significant discrepancy between the proposed sensor capabilities and smart city solutions due to the limitations of the data outputs. In particular, the inability to provide

reliable readings for the right-most lane volume, lack of speed data, and raw vehicle type classification, as well as no trajectories, are notable shortcomings. The writing should be more concise in related descriptions. According to the authors, however, the sensor network is capable of reading both the trajectory and the type of vehicle. The speed can be calculated from the difference between the readings of neighboring sensors. Furthermore, the trajectory is based on deviations from the road axis of individual vehicles. However, this data require the processing of information from multiple sensors simultaneously. The current authors' works address the problem of configuring the sensor network so that it is more cost-effective than video cameras.

It is important to note that the solution presented in the paper is based on the deployment of a single sensor for experimentation purposes. The optimal solution for this project is a network of multiple sensors across the road. Only a network of sensors can accurately determine the near-full traffic flow characteristics.

The modern road network is a network operating over large areas in conditions of permanent traffic congestion. There is currently a lack of investigation into how the system functions for a long stretch of road and bottleneck traffic on the road ahead.

In this context, it is worth referring to the works of B. Kerner [55–59]. Many observations of moving traffic jams indicate that the spatial context of this phenomenon varies dynamically over a space of sometimes tens of kilometers. Therefore, the entire camera system with implemented algorithms based on vision and image processing techniques should also be used for its research. This includes the use of image fusion techniques and their simultaneous analysis from multiple cameras. This approach is likely to be the most cost-effective method for conducting research in the scope indicated in this article. Alternatively, research can be conducted on the possibility of implementing a sensor network based on the sensor presented in this article. Alternatively, the use of radar or acoustic techniques in the context of investigating moving congestion seems to be problematic. This is due to the acoustic spectrum that accompanies road traffic congestion. In this context, it is not worth mentioning induction loops. From this spatial context, satellite reconnaissance techniques are again the most useful, although it should be noted that they have numerous limitations. Moreover, it is always the infrastructure and traffic context and the physical limitations of individual detectors that should primarily determine the validity of their implementation [60]. Only secondly should economic considerations be decisive. Firstly, we must ensure that our measurements are both reasonable and effective, and that we only proceed at the lowest possible cost, including operating costs over the entire LCA period.

The longest sections examined are 100 m with few simultaneously working devices. The proposed sensor aids in the counting of vehicles and some simple traffic characteristics, but it does not provide a clear image of a long street section. However, it can be said that currently only ANPR camera networks provide such functionalities, and these are still expensive solutions and based on large-sized cameras, often requiring specific installations. Conversely, the advent of the C-ITS systems on a large scale may alter the outlook for the development of traffic-monitoring devices in the road network as outlined in this paper.

It is important to note that the technology market situation is dynamic. Many devices are becoming cheaper, including LIDAR [37,38]. Linear lidars are especially inexpensive, and the range of products offered allows them to be used flexibly in road traffic measurements [61,62]. The same applies to cameras and radars, which become cheaper every year. The effectiveness of a sensor is contingent upon its proper and effective implementation. A key aspect of a smart city is its ability to adapt swiftly to changes in internal and external conditions. It appears that simple sensors, such as the one presented in this article, may be more adept at meeting this criterion than cameras and radars.

6. Patents

In progress. Requires research in the field of cooperation networks.

Author Contributions: Conceptualization, R.B., I.C. and J.M.; methodology, R.B. and I.C.; software, I.C.; validation, R.B., I.C. and V.R.; formal analysis, I.C. and M.R.; investigation, I.C. and R.B.; resources, V.R. and J.M.; data curation, M.R. and J.M.; writing—original draft preparation, I.C. and R.B.; writing—review and editing, R.B., I.C., M.R., V.R. and J.M.; visualization, I.C.; supervision, R.B. and I.C.; project administration, R.B. and I.C.; funding acquisition, R.B. All authors have read and agreed to the published version of the manuscript.

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