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# Methodology for Estimating the Effect of Traffic Flow Management on Fuel Consumption and $CO_2$ Production: A Case Study of Celje, Slovenia

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**Abstract:** The manuscript discusses the investigation of vehicle flow in a predesignated junction by an appropriate traffic flow management with an effort to minimize fuel consumption, the production of $CO_2$, an essential greenhouse gas (hereinafter referred to as GHG), and related transport costs. The particular research study was undertaken in a frequented junction in the city of Celje, located in the eastern part of Slovenia. The results obtained summarize data on consumed fuel and produced $CO_2$ amounts depending on the type of vehicle, traffic flow mixture, traffic light signal plan, and actual vehicle velocity. These values were calculated separately for three different conditions of traffic flow management. Amounts of fuel consumed were experimentally investigated in real traffic situations, whereas $CO_2$ production was calculated by applying the actual European standard entitled EN 16258:2012 associated with a guideline for measuring emission values, as well as by examining specific traffic flow parameters. The key objective of the manuscript is to present multiple scenarios towards striving to minimize environmental impacts and improve transport operation's economic consequences when implementing proper traffic flow management. As for crucial findings, we quantified fuel consumption and $CO_2$ emissions based on real data on the number and type of vehicles crossing the examined intersection and traffic light switching intervals. The results show that most of the $CO_2$ was produced while waiting and in the accelerating phase in front of traffic lights, whereby in the running phase through the intersection, significantly less fuel was used. This study represents a mosaic fragment of research addressing endeavors to reduce $CO_2$ production in urban transport. Following the experiments conducted, we can see a notable contribution towards reducing $CO_2$ production with known and tested interventions in the existing transport infrastructure. A procedure embracing individual research steps may be deemed as an approach methodology dealing with traffic flow management with an aim to decrease the environmental and economic impacts of traffic and transport operation; this is where the novelty of the research lies.

**Keywords:** urban transport; crossroads; fuel consumption; $CO_2$ production; greenhouse gas



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## 1. Introduction

The average temperature of the Earth is rising at nearly twice the rate it was 50 years ago. This rapid warming trend cannot be explained by natural cycles alone, scientists have concluded. The only way to explain the pattern is to take into consideration the effect of greenhouse gases (GHGs) emitted by humans [1]. Warming more significant than the global average has already been experienced in many regions and seasons, with higher average warming over land than over the ocean [2].

Currently, GHG levels of carbon dioxide, methane, and nitrous oxide in the atmosphere are higher than at any time period over the past 800,000 years, and their capability

to capture heat has changed our climate in a variety of ways. Most of them arise from fossil fuel combustion in vehicles, factories, industrial buildings, and power plants. Carbon dioxide, referred to as $CO_2$, is the gas that causes the highest increase in warming [3]. Other contributors involve natural gas, methane released from landfills and waste dumps, petroleum industries, and agriculture; i.e., nitrous oxide from fertilizers, gases utilized for refrigeration and industrial processes, and the loss of forests [4]. Greenhouse gases have different heat-capturing potentials [5]. Some of them can trap more heat than an equivalent amount of $CO_2$. Molecules of methane do not persist in the atmosphere as long as molecules of carbon dioxide; nevertheless, they are at least 84 times more effective over two decades. Nitrous oxide molecules are 264 times more powerful than $CO_2$ [6]. However, none of these gases capture as much heat in the atmosphere as $CO_2$ does. The more greenhouse gases in the atmosphere, the more dramatic the effect and the more warming that occurs [7].

The production of greenhouse gas emissions in the European Union (EU) over the years 1990–2018 for various sectors is illustrated in Figure 1.

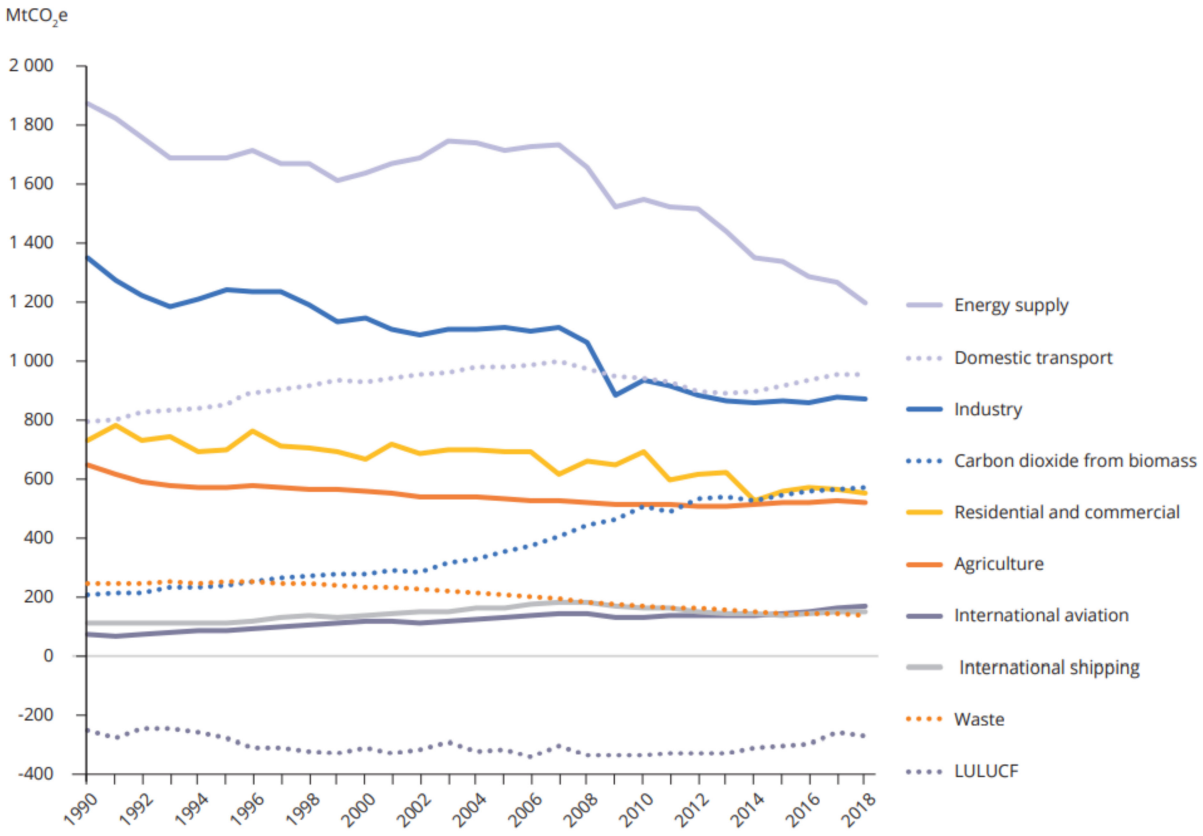



**Figure 1.** GHG emissions by aggregated sector in the EU [8]. (Creative Commons—Attribution 2.5 Denmark—CC BY 2.5 DK).

Over time, numerous activities and initiatives to reduce the negative impact of transport operation on the environment have been developed at regional and national, as well as international levels. Experts and researchers have begun to tackle this problem and have elaborated a series of research studies focusing on an extensive scale of negative environmental consequences. Those studies comprise many designs and suggestions to discuss such a state, tips being considered more or less acceptable in relation to a sustainable increase in regional and national economies, and living standards of their residents. This refers to a fundamental issue; i.e., How can we minimize the negative environmental impact of transport operation as well as all other human activities while maintaining the current economic growth level and living standards [9,10]?

This paper analyzes the results acquired during an investigation of the impact of traffic management on fuel consumption and, subsequently, $CO_2$ emissions by examining one of Celje's road intersections, namely, Kidričeva and Mariborska roads, in twelve traffic directions. The intersection under investigation is described in the ensuing manuscript sections. The territory under examination is specified by extensive and frequent stop-and-go traffic lying on the main corridors through the city center and a connection to the highway up North. Individual outcomes summarize amounts of fuel consumed and $CO_2$ emissions depending on multiple factors, specifically, type of vehicle, traffic flow composition, traffic light signal time-period, and vehicle velocity. The values were investigated separately for several traffic flow conditions, wherein the fuel consumption amount was measured in real traffic situations, and the production of $CO_2$ and other GHG emissions were measured according to the specific standard entitled BS EN 16258:2012 [11] relating to a guideline for measurement of emissions.

The subsequent parts of the paper are focused on as follows: (a) compiling a literature review section presenting a number of topic-related literature sources dealing with the subject of greenhouse gas emissions under traffic (transport) operation at a macroscopic as well as microscopic scale; (b) defining the input data sets and describing the methods relevant to conduct all the research steps; (c) elaborating the research study consisting of an overview of the results obtained and a proper discussion of these findings; and last but not least, (d) composing the final part of the manuscript justifying individual conclusions from the performed study as well as suggesting potential research activities that may be tackled in this area of focus in the future. The whole quantification procedure may be regarded as an approach methodology or guiding principle to minimize the environmental and economic impacts of transport operations when implementing proper traffic flow management; this is where the novelty of our research lies.

## 2. Literature Review

The topic of greenhouse gas emissions in terms of transport operation has been addressed in a whole series of published literature sources in terms of macroscopic as well as microscopic research standpoints. For instance, the authors [12–15] state that transport operation sustainability encompasses more efficient and environmentally friendly coordination and collaboration of various transport modes. As discussed in the publications [12,13], such a coordinated and optimized modality can enhance the qualitative level of providing transport activities. The research study [14] written by Santos et al. analyzes several policy instruments and measures for sustainable road transport while maintaining an effective modal split, whereby [15] presents key issues and challenges towards developing integrated multimodal environmentally friendly national transportation networks with a special emphasis on regional modal interconnectivity.

In the literature [16–19], the authors describe multiple scenarios to utilize alternative types of fuel in road transport as a potential method for minimizing fuel and energy consumption and reducing the production of greenhouse gas emissions. For example, Held and Bos outline aspects of integration of land use into a life cycle assessment with an example of biofuels in road transport [16], whilst according to Ullah et al., availability of gaseous alternatives enhances the diversification of fuel choices for the road transport sector in various countries [17]. In their study, the authors suggest the multi-criteria decision analysis approach based on the AHP method to evaluate three gaseous alternatives, namely, compressed natural gas, liquefied petroleum gas, and liquefied natural gas. On the contrary, Hagos and Ahlgren select and evaluate the potential of natural gas, renewable natural gas supply pathways, and natural gas vehicles regarding well-to-wheel energy expended, greenhouse gas emissions, and regulated (air pollutant) emissions [18]. The publication [19] compiled by Gis et al. discusses individual possibilities of using biomethane and hydrogen cars in Poland by showing some interesting and significant research results in that area of focus.

In line with the very concept of reducing the negative environmental impact of sustainable transport operations involving a specific traffic management, numerous works have been published as well, e.g., [20–24].

Specifically, the research study [20] conducted by Burchart-Korol and Folęga analyzes different greenhouse gas emissions. It assesses the impact of an operation of means of road transport in Poland on human health using the life cycle assessment technique based on an analysis of emission of dust and gas pollutants. The manuscript [21] discusses using an internal catalyst in a car, which allows for reducing the emission of harmful compounds from an internal combustion engine and thereby vehicle operation. According to the authors Cuthill et al., to reduce the harmful effects of austerity, public money could be spent more effectively if diverted to areas most in need, which can be highlighted through localized investigations [22]. They also demonstrate that the pursuit of sustainability has been at the forefront of recent planning initiatives so far; however, most recent research has dealt with the environmental and economic aspects of developing a sustainable urban environment while largely neglecting the social aspects. Remarkably, their study aimed to analyze the impact of transport infrastructure on a variety of social measures in an empirical and ideologically unbiased fashion when using both quantitative and qualitative specific methods.

On the other hand, Anisimov et al. point to various opportunities of the "negative technologies" applied in the field of climate change mitigation and the formulation of the hypothesis of mobility modification using fuel consumption reduction methods [23]. Those technologies are studied from a technological point of view, analyzing the potential advantages and disadvantages, and stressing the technical challenge. A new approach to reduce the negative impacts of vehicle operation on the environment by changes in vehicle parameters is suggested. Furthermore, the study [24] conducted by Guzman et al. compares the potential of four transportation policies designed to reduce greenhouse gases and pollutant emissions in urban areas. The systems being analyzed comprise both pricing policies aimed to increase car costs and fleet renovation. The study applies a land-use and transportation interaction model combined with an optimization algorithm that provides each policy's optimal design.

Even methodologies for estimating the effects of traffic flow management for microscopic objects such as road segments or intersections proposed in a wide array of research studies have been written [25–28]. In our manuscript, this subject entails an area of research.

For example, Bento et al. report the design of innovative intersection traffic management systems for road vehicles and analyze their impact on fuel consumption as well as GHG emissions when considering conventional traffic signal and crossroad control systems. The proposed traffic flow management approach states that a vehicle passes through a crossroad section without colliding with other vehicles and, simultaneously, reducing the crossroad hold-up time and negative environmental impacts [25]. Similarly, in the literature [26], the authors suggest a novel traffic flow management system through a crowdsourcing-based traffic recording scheme allowing a transportation management center to retrieve various data relating to traffic flow at junctions in a versatile, effective, as well as privacy-preserving way.

On the other hand, in the publication [27], a new traffic flow management methodology involving an innovative data-driven framework to quantify and classify critical road network node importance through data mining from comprehensive vehicle trajectory data is reported. In this approach, the authors implement a trip road network modeled by a tripartite graph to specify the road network dynamics. To this end, they apply two different algorithms in order to more suitably utilize the road traffic data in the tripartite graph and to appropriately evaluate the critical node importance. Naturally, this dimension covers the environmental impact during the occurrence of critical and collision traffic flow situations. Likewise, Alfeo et al. focused on a novel traffic flow management draft methodological guideline encompassing an adaptive biologically inspired approach for swarm aggregation

of on-vehicle GPS device positions enabling the detection of traffic congestion and other critical traffic flow nodes based on efficient relevant data acquisition [28].

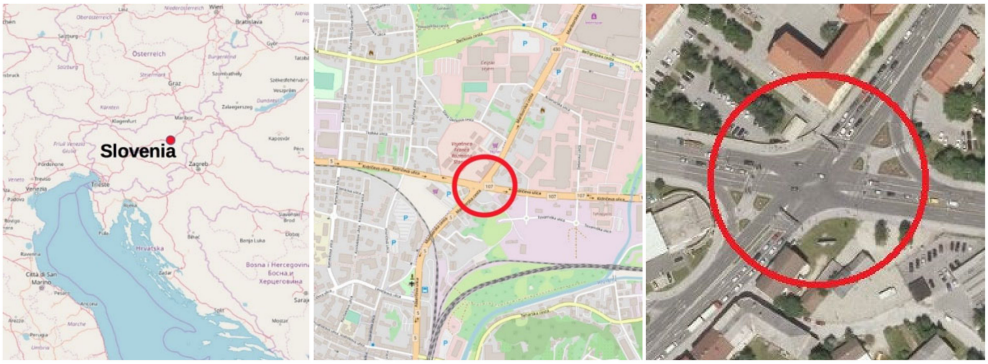
In addition, some authors and related literature sources discuss a variety of application options of advanced information systems and technologies for traffic flow management systems at a microscopic scope [29,30]. For instance, Yusupbekov et al. apply soft-computing technology to the fuzzy modeling and synthesis of traffic management systems under conditions of uncertainty and insufficient initial data on traffic flows at multiple intersections of a road network in the city of Tashkent, Uzbekistan. The authors develop several techniques for a formal description of traffic processes in controlled intersections on the basis of innovative mathematical methods of fuzzy sets and logic. The research publication [30] presents a novel two-order information-technology-based (namely, Synchro 7 simulation SW) traffic flow management optimization model of a breakdown of time-of-day control segmented points of intersections located in Yuecheng District, Shaoxing, China, to cope with limitations of artificial experience randomness, avoid complex multi-factor division calculation, and optimize the conventional existing models regarding traffic safety attributes and traffic flow data-driven methods.

Based on the literature review, it can be stated that the subject of investigating greenhouse gas emissions in terms of transport operation has been addressed in a variety of literature considering macroscopic as well as microscopic scales. In addition, even the topics of using alternative types of fuel in road transport as a potential method for minimizing fuel and energy consumption and reducing the production of greenhouse gas emissions, as well as the very concept of reducing the negative environmental impact of sustainable transport operations when involving specific traffic flow management, have been discussed. Furthermore, the field of introducing various advanced and smart information systems and technologies to traffic flow management systems at different traffic levels has also been analyzed.

Unlike the previous findings published in the literature sources overviewed above, the present manuscript is aimed at distinct approaches dealing with fuel consumption as well as the abatement of $CO_2$ production, particularly at an urban transport microscopic scale. It strives primarily to detect existing research gaps in regards to reducing the environmental and economic impacts of traffic (transport) operations when using proper traffic flow management. In the paper, this is achieved by investigating several appropriate traffic flow management operations with the aim to introduce the proper one in a given territory (the city of Celje) in order to reduce the negative environmental impact and improve the positive economic effect of the transport operation. This is the innovative approach of our research. The proposed methodology itself is designed and profoundly explained throughout in Sections 3 and 4. While having compiled this guiding principle, the authors tried to point to values calculated separately for three different conditions of the traffic flow management. Fuel consumption values were measured in real situations, whilst $CO_2$ production values were calculated by applying the specific standard related to the guideline for measuring emissions [11] and according to an examination of the defined traffic flow parameters. Hence, it can be concluded that no similar methodology aiming at an analogous field of research has yet been published.

## 3. Case Study

The research study was carried out in Celje, the 3rd largest city in Slovenia, with about 40,000 residents (Figure 2). Celje was chosen since it has the highest number of days with daily PM exceedance among Slovenian cities [31]. This is a consequence of its geographic location, being at the lowest point of the basin surrounded by hills, causing frequent occurrences of temperature inversion and windless conditions and impacts of regional traffic through the city [32]. The city lies next to a motorway and railway junction of two vital European traffic corridors. Therefore, the local government is implementing action plans [33] to reduce air pollution and, thus, exposure of the local population to PM air pollution [34].




(**a**) (**b**) (**c**)

**Figure 2.** Detailed location and situation of investigated intersection: (**a**) location of Slovenia and Celje (marked with a red dot); (**b**) map of Celje with the main roads and observed intersection; (**c**) photo of the intersection of the study where the city traffic management and vehicle density were investigated. (based on map source: © OpenStreetMap (**a**,**b**) and Municipality of Celje (**c**)).

The study was focused on the effect of the traffic management on fuel consumption (and consequently $CO_2$ emissions), observing the road intersection crossing Kidričeva and Mariborska roads in Celje, with twelve traffic directions in total (Figure 2). The area being examined is characterized by heavy and frequent stop-and-go traffic lying on the main corridors through the town and the connection to the highway up North.

## 4. Methodology

The research methods are based on real-world data related to the fuel consumption and distance traveled during acceleration, obtained with empirical in-situ measurements and analyses in previous research studies, e.g., in [35,36]. Celje's municipality has statistical data on traffic light intervals and measured traffic density on an average day [37]. The number of vehicles, according to their types, was acquired from the state statistical data [38]. Figure 3 illustrates the methodology and methods used. All the sources are described in the following subsections.

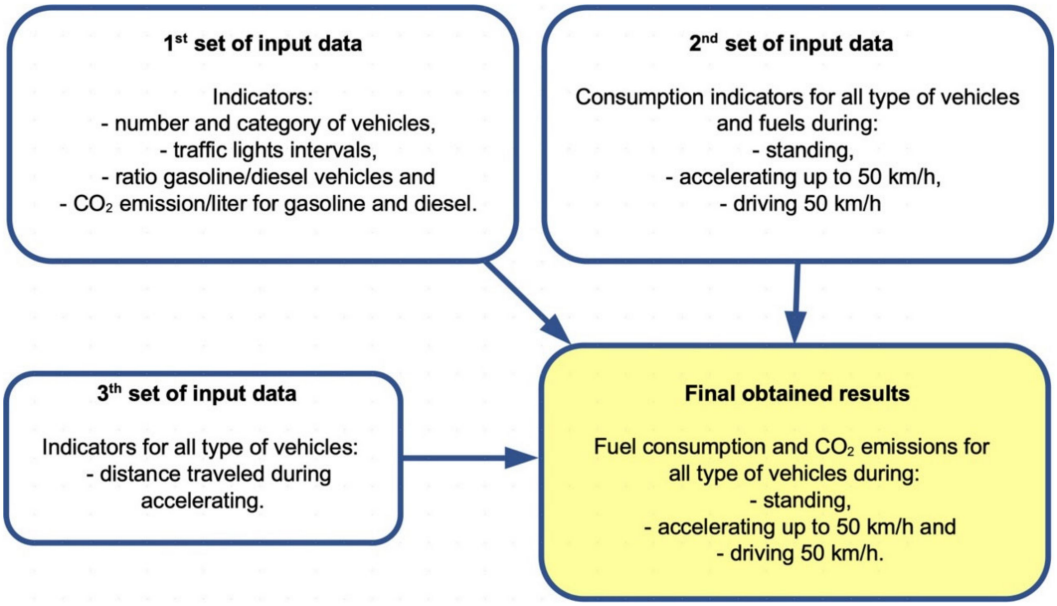



**Figure 3.** Methodology for evaluating fuel consumption and $CO_2$ emissions produced by traffic at the location under investigation.

The input data related to the quantification itself are divided into several sets as follows: (a) general, (b) fuel consumption, and (c) vehicle acceleration-specified indicators.

Such a breakdown of the data sets did not have an effect on the calculation and was executed in order to facilitate the research organization. To obtain a holistic and comprehensive evaluation of fuel consumption and $CO_2$ emissions, the following set of data was elaborated; see Sections 4.1–4.3.

### *4.1. The First Set of Input Data*

The first set of input data consists of the following indicators:

- **Number and category of vehicles:** vehicles were divided into four categories: car, bus, truck, and motorcycles. The car category was further diversified by fuel type, diesel, and gasoline according to the statistical data [37]. An assumption was made that all buses and trucks use diesel, and motorcycles, gasoline, not taking into account LPG (liquefied petroleum gas), CNG (compressed natural gas) electro-, and hybrid-driven vehicles. As for the "truck category", trucks, trailers, and tractors were merged. The number and categories of the vehicles in 15-min intervals were obtained by the real-time measurement of traffic flow on Mariborska road, based on the official road traffic counting data provided by the Slovenian Infrastructure Agency [38].
- **Traffic light interval:** the traffic flow regulated by traffic lights was obtained from a local company Elektrosignal that manages city fixed and portable control systems for traffic control and management. The frequency and intervals of traffic lights remained constant during the observed period. It is crucial to notice that in the intersection, vehicles that turn right in the West–East direction and vice versa do not need to pass a traffic light but use a bypass (see Figure 2c). However, they need to be included in the traffic flow as long as they reach the bypass. Based on additional in-situ measurement and analysis of the traffic flow, it was indicated that vehicles turning right spend 10 s on average to reach the bypass due to the queue in front of the traffic light and traffic flow from the sideway.
- **Fraction (in %) of gasoline and diesel vehicles:** as mentioned under the indicator "number and category of vehicles", only gasoline- and diesel-driven vehicles were considered. According to the Statistical Office of the Republic of Slovenia (SORS) [37], almost all LPG & CNG driven buses in Slovenia are city buses. In Celje, no LPG & CNG driven city bus is registered. Based on this, it was assumed that all buses and trucks were diesel in the observed intersection. However, there was a small difference between the $CO_2$ emissions according to the fuel type in the case of buses and trucks in the overall $CO_2$ production, which was neglected. Another assumption made was that all motorcycles were petrol driven.
- **$CO_2$ production is the most crucial GHG produced by gasoline and diesel-burning:** the quantity of $CO_2$ emissions per 1 L of burning fuel varies in terms of gasoline and diesel vehicles [39].
- About 2.3 kg of $CO_2$ emissions are produced from burning one liter of gasoline, and 2.6 kg of $CO_2$ emissions are produced from burning one liter of diesel fuel [11,40,41].

### *4.2. Second Set of Input Data*

The second set of input data consists of indicators focusing on:

- **Fuel consumption while standing at traffic lights:** this consumption and the next two from the same group of input data were measured in previous research works. The results of these experimental investigations were published in [42,43].
- **Fuel consumption while accelerating up to 50 km/h to drive through a traffic light**;
- **Fuel consumption while driving through a traffic light at 50 km/h**.

It has to be noticed that 50 km/h is a statutory speed in Slovenia's urban settlements. For each type of vehicle, average consumption data and values of distance traveled during acceleration up to 50 km/h were measured; for details, see the previous studies [42,43]. In these manuscripts, it was perceived that the acceleration time and consumption of trucks vary greatly depending on cargo weight. Hence, the average values for trucks that fluctuated around the mean value was used.

### *4.3. Third Set of Data*

**Distance traveled during the acceleration** represents the third set of data. These data also come from previous studies [42,43]. The data are vital in this study since, during a vehicle accelerating period, fuel consumption is much higher compared to a period while evenly driving a vehicle. A longer acceleration time (longer distance) results in a further fuel consumption increase and thus contributes to higher $CO_2$ emissions.

### *4.4. Final Results Obtained*

The data were based (calculated) on the above specified three sets of data: number and type of vehicles, the distance traveled during acceleration and traffic light intervals with data on vehicles and crossroads; consumption during standing, accelerating, and evenly driven vehicles refer to data on fuel consumption. The data on $CO_2$ emissions per liter of fuel consumed allow for easy conversion of fuel consumption to $CO_2$. As far as this article goes, $CO_2$ emission entails the criterion for fuel consumption. Other pollutants such as PM particles, black carbon, $NO_x$, and others are skipped in this scenario. Figure 2, as a central point for achieving the desired findings, is described in more detail with the semi-code calculating vehicle consumption and $CO_2$ emissions, as shown in Table 1. As apparent, the semi-code includes all the equations relevant to calculations and assumptions, which are explained in the following Section 4.5.

**Table 1.** Semi-code quantifying the vehicle consumption and $CO_2$ emissions.

```
for all observed hours (6:00 to 18:00; i.e., 12 h)
begin
    for all types of vehicles (car, bus, truck, motorcycles)
    begin
       for vehicle fuel type (diesel or gasoline)
       begin
          for all traffic lines with traffic lights (10 directions)
          begin
             NoStandingVehicles = NoAllVehicles * RedLightPeriod/WholeLightPeriod;
             NoGoThroughVehicles = NoAllVehicles—NoStandingVehicles;
             WaitingTime = RedLightPeriod/2;
             Consumption1 = (NoStandingVehicles * WaitingTime * ConsumptionStanding) +
                            (NoStandingVehicles * ConsumtionAccelerating * PathLenght) +
                            (NoGoThroughtVehicles * ConsumtionGoThrough * PathLenght);
        end;
        for all traffic lines without traffic lights (2 directions)
          NoStandingVehicles = NoAllVehicles;
          WaitingTime = 10;
          Consumption2 = (NoStandingVehicles * WaitingTime * ConsumptionStanding) +
                         (NoStandingVehicles * ConsumtionAccelerating * PathLenght);
      end;
      VehicleCO2Emission = (Consumtion1 + Consumtion2) * FactorCO2(FuelType);
   end;
  end;
end.
```

The sign * represents multiplication.

### *4.5. Main Assumptions and Approximations during the Calculation*

Main assumptions and approximations are as follows [44–46]:

- Each vehicle accelerates once in front of the intersection with a turned-on green light without interruption. This is an optimistic approach; usually, a vehicle stops more than once in front of the red light. Furthermore, it often happens that, at the same green traffic light, people repeatedly accelerate and brake. Vehicles should usually stop turning to the right where pedestrians and cyclists have a priority.

- The ratio (percentage) of vehicles stopped in front of the red light is as high as the ratio between the red light duration compared to the duration of the whole traffic light interval. This percentage of stopped vehicles represents the lowest possible percentage, and in reality, it is higher because of the reason mentioned in the previous item.
- The time of waiting at the red light is the same as half of the time of the red traffic light duration in an interval. This assumption represents the best possible time, and in reality, vehicles wait longer.
- During the green light, all vehicles go through the intersection with even speed, and they do not need to slow down or even stop the vehicle due to a queue in front of the intersection. Such events, in reality, rarely happen. Consequently, vehicles typically accelerate up to 50 km/h and brake many times during the green period.
- The path of vehicles that went through the intersection was as long as the distance for the acceleration of these vehicles from 0 to 50 km/h. This means that different types of vehicles have different lengths of the route regardless of the geometry of the intersection.

## 5. Results

### *5.1. Input Data*

#### 5.1.1. Number of Vehicles

The data on road traffic flow along the Mariborska road were obtained on the basis of the official road traffic counting data from the Directorate of R.S. for Infrastructure. The very counting was performed in June 2018 from 5:30 until 21:30 at 15-min interval at a time when no precipitation occurred. Furthermore, they distinguished between four types of vehicles as follows: personal vehicles as cars (Car); buses (Bus); light, medium, and heavy trucks, tractors, and trucks with trailers as trucks (Truck); and motorcycles (MC). In the subsequent calculation, it turned out that there was no significant difference between the different kinds of trucks, trailers, and tractors at starting and, consequently, consumption, so we merged them into the group Truck. In this particular group, a significant impact on consumption was the vehicle load and not the truck type.

Statistics on counted vehicles according to their type in one day are summarized in Table 2.

**Table 2.** Number of counted vehicles according to the type in one day.

| Cars | Buses | Trucks | Motorcycles | Total |
|---|---|---|---|---|
| 36,475 | 327 | 3458 | 638 | 40,898 |

Thus, Table 2 represents the sum of vehicles crossing our observed intersection according to the vehicle type in one counting day. However, in wintertime (opposite to June when counting was performed), a higher number of cars is expected due to a lower number of bicycles and motorcycles which are rarely seen during cold, rainy or snowy days. This means that the observed period characteristics encompass a low number of cars for a working day. In subsequent parts of the article, calculations will be focused on an hourly time interval between 6:00 and 18:00. This interval is associated with the most intensive traffic density in one day; Figure 4 illustrates the traffic density in an observed working day.

#### 5.1.2. Ratio between Gasoline (GAS) and Diesel

In the subsequent analysis, a distinction was made between petrol-and diesel-driven cars. Other fuels were neglected given that only small numbers of them occur in Slovenia. Table 3 lists the number of cars, buses, and trucks by fuel type in 2019 [37]. In the analysis, only gasoline- and diesel-driven vehicles were taken into account. It was assumed that for the observed intersection, all buses and trucks are diesel driven. However, a small difference between the $CO_2$ production by a fuel type in the case of buses and trucks in

the overall $CO_2$ production was neglected. Another assumption made was that all the motorcycles were petrol driven.

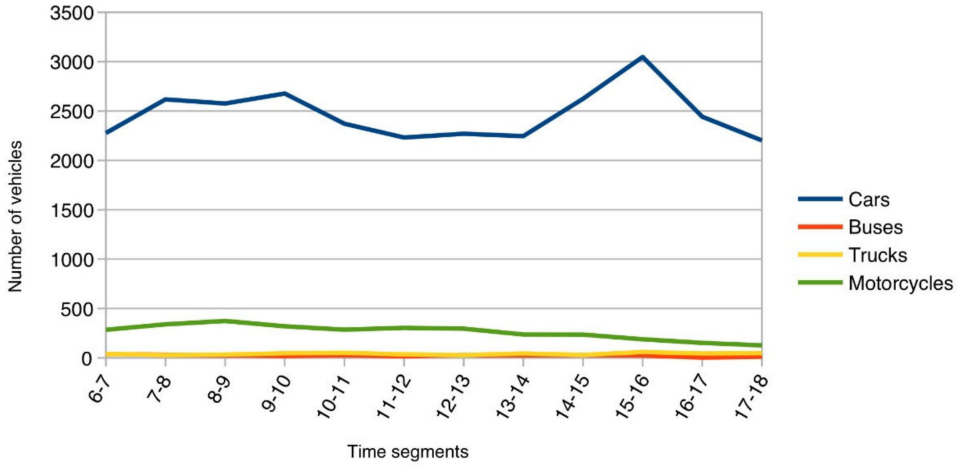



**Figure 4.** Traffic density according to the type of vehicles during a working day.

**Table 3.** Number of vehicles by fuel type in Slovenia on 12 December 2019 [37].

| Fuel Type | Cars | Buses | Trucks |
|---|---|---|---|
| Gasoline | 569,915 (48%) | 2 (<1%) | 3681 (4%) |
| Diesel | 588,134 (50%) | 2760 (96%) | 85,421 (95%) |
| LPG & CNG | 10,176 (1%) | 115 (4%) | 481 (1%) |
| Electric | 2001 (<1%) | 6 (<1%) | 162 (<1%) |
| Hybrid | 6816 (1%) | 1 (<1%) | 5 (<1%) |

#### 5.1.3. Distance Traveled and Fuel Consumed When Accelerating Up to 50 km/h

By analyzing the fuel consumption, it was assumed that vehicles were driven in compliance with the Slovenian regulations; i.e., their speed did not exceed 50 km/h. For each type of a vehicle, average fuel consumption data and the distance traveled during acceleration up to 50 km/h were measured [42,43] and presented in Tables 4 and 5. Concerning trucks, it was perceived that acceleration time varied considerably depending on the load's weight.

**Table 4.** Distance traveled when accelerating up to 50 km/h for all the observed vehicle types [42].

| Cars (m) | Buses (m) | Trucks (m) | Motorcycle (m) |
|---|---|---|---|
| 72 | 104 | 97 | 57 |

**Table 5.** Fuel consumed during different types of vehicle regimes for various types of vehicles [42].

| | Consumption Standing (mL/s) | | Consumption Evenly Driving 50 km/h (mL/m) | | Consumption Accelerating from 0 to 50 km/h (mL/m) | |
|---|---|---|---|---|---|---|
| Vehicle Type | Diesel | Gasoline | Diesel | Gasoline | Diesel | Gasoline |
| Car | 0.190 | 0.310 | 0.038 | 0.040 | 0.203 | 0.233 |
| Bus | 0.560 | 0.000 | 0.280 | 0.000 | 0.742 | 0.000 |
| Truck | 0.330 | 0.000 | 0.300 | 0.000 | 0.456 | 0.000 |
| MC | 0.000 | 0.150 | 0.000 | 0.040 | 0.000 | 0.106 |

#### 5.1.4. Traffic Light Intervals

Traffic flow regulated by traffic lights was based on the official data from the company that manages traffic lights in the municipality of Celje. The data on timing of green, red, and yellow are listed in Table 6. Timing is the same for the whole day. Vehicles that turn right on the east and west sides of the intersection do not have to pass a traffic light (see Figure 2c)—they have a bypass. Nevertheless, in reality, they need to be included in the traffic flow as long as they reach the bypass. Following our analysis in relation to traffic flow, it was ascertained that these vehicles spend 10 s on average to reach the bypass considering a queue in front of a traffic light and traffic flow from the side in which they want to be included [47].

**Table 6.** Time intervals of individual lights at the observed intersection.

| Signal Light | Arrival Direction | Ahead (s) | Right (s) | Left (s) |
|---|---|---|---|---|
| Green | North | 35 | 35 | 20 |
| | South | 24 | 24 | 10 |
| | East | 24 | 10 | 16 |
| | West | 20 | 10 | 14 |
| Red | North | 67 | 67 | 82 |
| | South | 78 | 78 | 92 |
| | East | 78 | 10 | 86 |
| | West | 82 | 10 | 88 |
| Yellow | | 4 | 4 | 4 |

## 6. Discussion

The quantity of $CO_2$ per liter of burning fuel varies with regard to gasoline (with a spark ignition engine) and diesel (with a compression ignition engine) vehicles [39,48]. About 2.3 kg of $CO_2$ are produced from burning one liter of gasoline that does not contain fuel ethanol, and 2.6 kg of $CO_2$ are produced from burning one liter of diesel fuel [11,40,41]. The actual operational conditions of a combustion engine and vehicle do not affect the relative amount of produced $CO_2$ [49–51]. However, as far as fuel consumption and $CO_2$ production are concerned, a simple correlation emerges—by analyzing fuel consumption, $CO_2$ emissions were evaluated. All the findings are presented as $CO_2$ output, which is linearly dependent on fuel consumption calculated for each type of vehicle and according to traffic light intervals.

### *6.1. Findings Obtained for the Specific Intersection*

By using the above-described information characterized in the methodology section and input data (previous subsection), we quantified the fuel consumption represented by an amount of $CO_2$. The very investigation of $CO_2$ emissions produced by traffic was based on the measured data, while on the other hand, we simulated the traffic regime represented by multi-level intersection crossing [52].

#### 6.1.1. Quantity of $CO_2$ Produced According to Traffic Flow

Figure 5 represents the amount of $CO_2$ produced during standing, accelerating, and evenly driving vehicles through the intersection for each hour in the period between 6:00 and 18:00. The figure is composed of three different graphs. These graphs have the same size as the units on the x and y-axes for vivid comparison. Diagrams depicted in Figure 5 involve the following three calculations [53,54]:

- The first calculation (Figure 5a) is based on all counted vehicles of all types in the existing intersection with the current traffic light regime.

- In the second one (referred to as Figure 5b), we have taken into consideration only counted passenger cars. All other vehicles (buses, trucks, and motorcycles) are omitted. The other parameters (intersection geometry, traffic light regime, etc.) of the quantification are the same as for the first calculation with all vehicles. This scenario is implemented to demonstrate car traffic dominance in traffic flow and the resulting impacts on $CO_2$ production in overall traffic.
- The third calculation is based on the assumption that all vehicles in the main traffic directions (vehicles that are not turning left or right) have no reason to stop, as there are no traffic lights (as in multi-level intersections). Vehicles turning left or right should be integrated into the main traffic flow such that 30 to 60% (this varies according to the road traffic counting data) of them should stop and wait 10 s and, thereafter, accelerate to join into the traffic flow. The case of the last calculation is represented in Figure 5c.

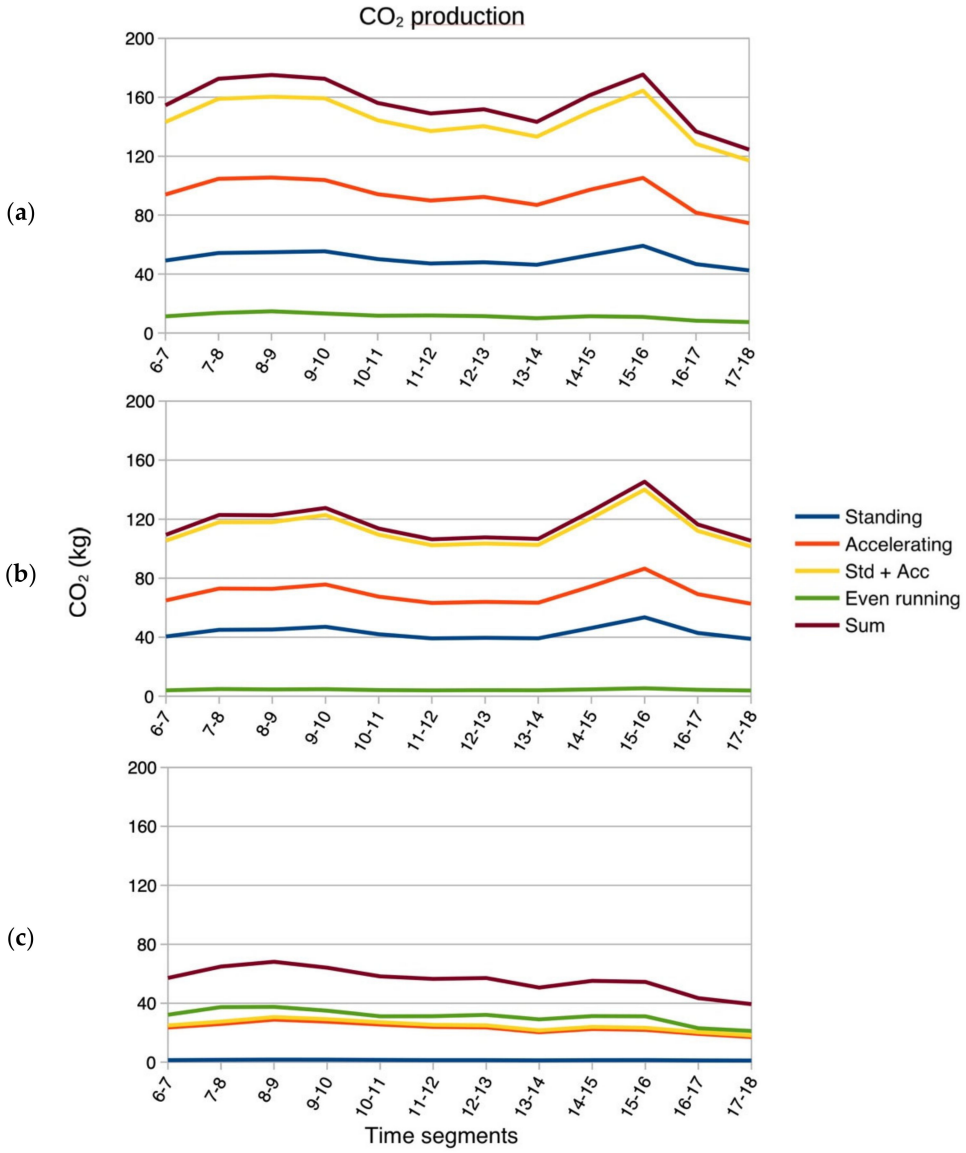



**Figure 5.** $CO_2$ produced according to traffic flow (standing, accelerating, and even running) in the monitored intersection by: (**a**) all vehicles; (**b**) cars only; (**c**) all vehicles without traffic lights in the main traffic directions (scenario of multi-level intersection).

All three quantification scenarios are based on unique assumptions and are the foundation for the calculations representing the lower limit of the $CO_2$ production. These are not simulations of stochastic events, which in many iterations serve us with results that are

the maxima, minima, means, and other statistical parameters. Such models are also based on achievable or assumed distributions and parameters of the microscopic traffic flow and not on a complete snapshot of the actual situation.

We are also aware that changes in the road network infrastructure do not entail direct involvement in the traffic management but indirectly affect their change.

Following the comparison of graphs (a) and (b) in Figure 5, it can be concluded that personal vehicles (cars) are highlighted as leading fuel consumers, and thereby $CO_2$ producers compared to all vehicles [55,56], which is not in line with the standard assumptions by people who believe that heavy vehicles are the biggest polluters. The number of heavy vehicles is relatively small compared to the number of passenger cars, and in total, they do not represent significant pollution. To reduce pollution, it is primarily necessary to reduce passenger car traffic and find alternative modes of transport; for example, efficient public bus transport or bicycles. This is confirmed by the fact that Celje has poor public transport and people use their own cars for everyday transport to and from the city.

Vehicles with even running speed (at a speed of 50 km/h) produce a relatively small amount of $CO_2$ (and fuel consumption) compared to the stage when vehicles wait in front of the red traffic light and/or accelerate. This apparent difference in $CO_2$ production is caused by the fact that the green traffic light window is relatively small compared to the whole-time cycle of a traffic light (106 s) for any of the observed directions [57].

When looking at all vehicles at the graph (a), even running produces slightly more than 10 kg/h of $CO_2$, compared to about 150 kg/h of $CO_2$ for standing and accelerating traffic. By contrast, cars only (graph (b)) produce an average in even running traffic of less than 5 kg/h of $CO_2$ and approx. 120 kg/h of $CO_2$ for standing and accelerating traffic.

If we ensure that the main directions have no stops (graph (c)), the situation with $CO_2$ production (as well as fuel consumption) will be considerably improved. Even running traffic produces less than 40 kg/h of $CO_2$, whilst standing traffic produces less than 2 kg/h of $CO_2$, and accelerating traffic less than 30 kg/h of $CO_2$ (caused by left and right turns); thus, the very improvement is about 100 kg/h of $CO_2$. As for one day (a whole 24 h), the improvement accounts for more than 1500 kg of $CO_2$ and, in one year (300 days), more than 450 t of $CO_2$. This accounts for more than 180,000 l of fuel, which is more than 230,000 EUR. The overall pollution costs are much higher due to $CO_2$, black carbon, and other PM particles, NOx, health problems, etc. In addition, traffic light maintenance, traffic security, tire wear, and so forth bring costs.

#### 6.1.2. Calculated $CO_2$ Production According to the Traffic Flow

Figure 6 shows the ratio presenting how many times more standing and accelerating traffic costs (considering fuel consumption or $CO_2$ production) compared with even running when driving through the intersection under investigation. The quantification was carried out for all vehicles (see graph (a)), cars only (see graph (b)), and, in the event of no stopping traffic, for vehicles travelling in the main traffic directions (see graph (c)).

In the context of all vehicles, the ratio is on average slightly lower than 15. As far as cars only, this ratio is approx. 25. If vehicles in the main directions have no stops, the ratio is close to 1. These values are directly related to the data from Figure 5. It shows unexpected costs (or $CO_2$ production or fuel consumption) of standing at the green traffic light yet again and, consequently, accelerating after standing. This factor is in particular highlighted in the cars-only scenario. At this point, we should also note that only one acceleration for any vehicle in front of the red traffic light and during turning left or right is assumed [58,59].

Following the charts above, we can see that traffic with personal vehicles (cars only) entails the least cost-effective journey. The municipality authority should circumvent an existing scenario wherein residents mostly use their own passenger cars. On the other hand, multi-level intersections are 25 times more effective than traffic at the examined intersection.

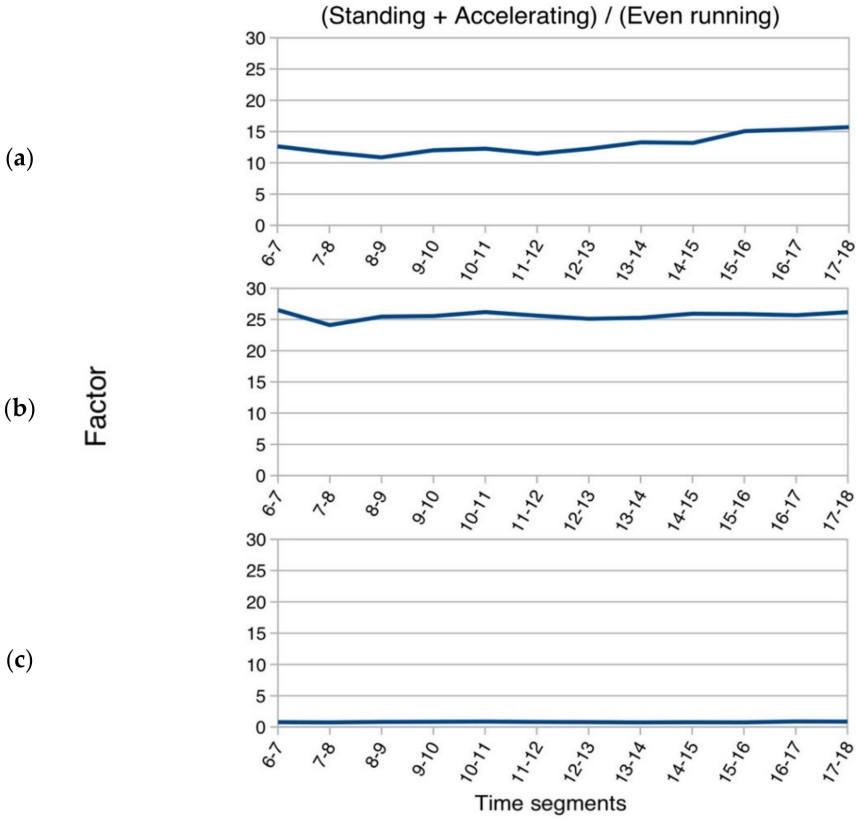



**Figure 6.** The ratio of $CO_2$ production (or fuel consumption) for standing and accelerating, and even running traffic for: (**a**) all vehicles; (**b**) cars only; (**c**) all vehicles without traffic lights in the main traffic directions (scenario of multi-level intersection).

### *6.2. Final Evaluation*

The results show that most of the $CO_2$ is produced when waiting and in the accelerating phase in front of traffic lights, while in the running phase through the intersection, significantly less fuel is used. According to the current driving phase through the intersection, the consumption coefficient during the waiting and starting phase is approx. 25 for passenger cars and about 15 for all vehicles (cars, trucks, and buses were taken into consideration). Thus, passenger cars use 25 times more fuel (and production of $CO_2$ and other GHGs) during the waiting period in front of traffic lights and starting than in the scenario of steady driving through the intersection. This ratio is reduced when heavier vehicles with different fuel consumption ratios are incorporated into both related phases.

Although we determined the lower limit of fuel consumption, this still means more than EUR 200,000 in fuel cost per year, which would be saved for citizens by efficient management of transport and investment in transport infrastructure. Indeed, this is only one single intersection; for the observed Mariborska road (the city of Celje, Slovenia), we witnessed; more than ten intersection; hence, the cost would increase to more than 1,000,000 EUR per year, which is spent by citizens when driving on this particular road section.

If the city were aware of the differences between the driving, waiting, and starting phases, it would be easier to decide on possible (even significant) investments in infrastructure, radically reducing the time for traveling, pollution, and fuel costs.

In the following figure (see Figure 7), the simplified scheme of input data relevant to the very quantification of emission production (i.e., emission-based indicators) is depicted.

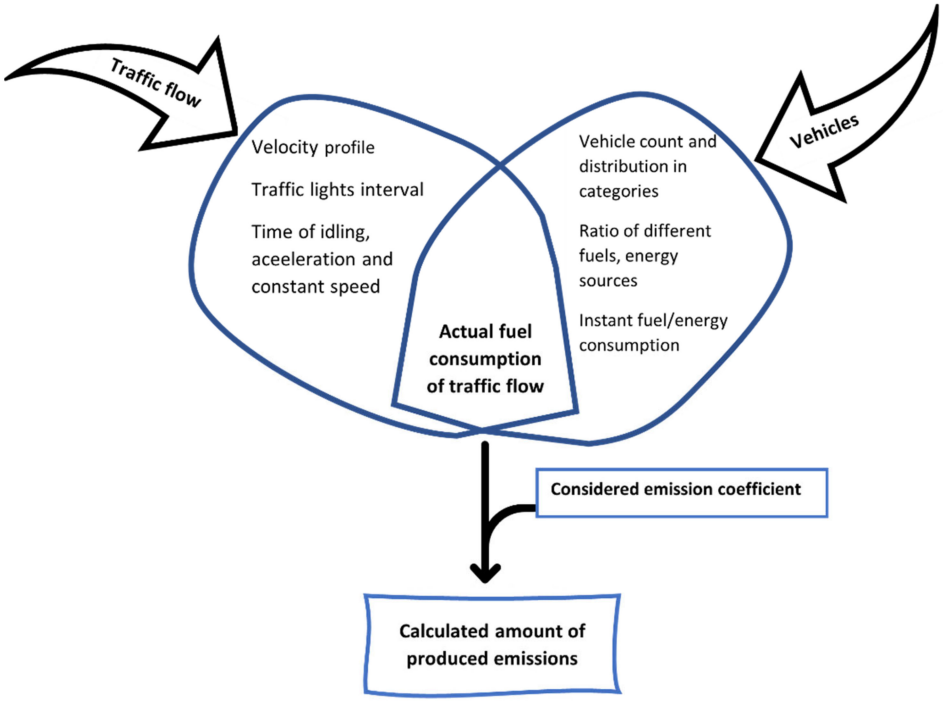



**Figure 7.** Simplified scheme of input data related to the production of emissions.

The structure of vehicles and their technical aspects notably influence the resulting values of emissions produced (this can be seen in Figure 7). One of the weaknesses of this study is the fact that the ever-changing composition of registered and used vehicles also has a significant effect on emissions produced. Given the current trends in automotive technology, people's behavior regarding mobility and technological progress, it can be assumed that the introduction of suggested traffic approaches in this research will become less and less important in terms of emissions, but not from the standpoint of energy consumption. For instance, an ever-increasing number of vehicles with alternative types of propulsion can be seen in Slovenia and overall in Europe, such as battery electric cars (referred to as BEV) or fuel cell electric vehicles (referred to as FCEV), plug-in hybrid electric vehicles (referred to as PHEV) or mild hybrid vehicles that have diverse aspects of operation due to unique operating modes compared to conventional vehicles with internal combustion engines [60]. These do not produce any emissions when standing at an intersection or when decelerating and, while on the road, they do not even produce emissions. Although the number of such vehicles increased by a growth rate of 1.5 from 2017 to 2019, these vehicles still represented less than one percent of all the cars registered in the Republic of Slovenia in 2019 [61].

## 7. Conclusions

Unlike the other publications dealing with this field of research, the presented manuscript is focused on a different approach concerning fuel consumption as well as $CO_2$ production reduction specifically at a microscopic scale of urban transport. It strives primarily to identify existing research gaps in the context of minimization of the environmental and economic impacts of traffic (transport) operation when introducing proper traffic flow management.

The manuscript quantifies the fuel consumption and, thereafter, $CO_2$ emissions based on real-traffic data on the number and type of vehicles crossing an examined intersection and traffic light switching intervals.

In doing so, we calculated the lower consumption limits, as we predicted and simplified some situations that would otherwise occur in practice. Among other things, we assumed that cars at the green light always only accelerate and never brake; we assumed

that during a green interval, in some directions, all cars cross a traffic light and do not have to stop at a possible new red light; we neglected braking in the event of turning right when we gave preference to cyclists and/or pedestrians and so on. Thus, actual fuel consumption and consequent $CO_2$, as well as other GHG pollution indicators were higher than predicted.

Following the literature review and the procedures and examinations executed, it can be stated that no similar study focusing on an analogous area of research has been presented. This research may be regarded as a fragment in a mosaic of experiments posing a challenge to $CO_2$ production by urban transport. Based on the research conducted, it is possible to convince ourselves of the great importance of reducing $CO_2$ production with improvements in transport infrastructure—in practice, there is a wide range of ways to undertake multilevel intersections.

In regard to further potential research activities, additional and more comprehensive knowledge on the behavior of vehicles in front of traffic lights and when driving through intersections could be introduced into the model, which would show even higher $CO_2$ production, and thereby prove the significance of modifications, innovations, and optimizations of traffic management, as well as investment in transport infrastructure in cities.

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