

Article

Is the Green Wave Really Green? The Risks of Rebound Effects When Implementing “Green” Policies

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Abstract: Traffic and transportation are main contributors to the global CO₂ emissions and resulting climate change. Especially in urban areas, traffic flow is not optimal and thus offers possibilities to reduce emissions. The concept of a Green Wave, i.e., the coordinated switching of traffic lights in order to favor a single direction and reduce congestion, is often discussed as a simple mechanism to avoid breaking and accelerating, thereby reducing fuel consumption. On the other hand, making car use more attractive might also increase emissions. In this study, we use an agent-based model to investigate the benefit of a Green Wave in order to find out whether it can outweigh the effects of increased car use. We find that although the Green Wave has the potential to reduce emissions, there is also a high risk of heaving a net increase in emissions, depending on the specifics of the traffic system.

Keywords: traffic modelling; traffic flow optimisation; urban CO₂ emissions; green wave; agent-based modelling



Citation: Bloder, E.; Jäger, G. Is the Green Wave Really Green? The Risks of Rebound Effects When Implementing “Green” Policies. *Sustainability* **2021**, *13*, 5411. <https://doi.org/10.3390/su13105411>

Academic Editor: Armando Carteni

Received: 14 April 2021

Accepted: 10 May 2021

Published: 12 May 2021

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1. Introduction

Climate change is one of the biggest challenges society currently faces [1,2]. In particular, human-induced CO₂ emissions, of which 88% come from the consumption of fossil fuels, are a decisive factor in this context [2]. Although GHG emissions indicate a decreasing trend in some sectors, this is not the case for the transport sector [3]. In the European Union, for example, road transport causes around a quarter of GHG emissions and a fifth of CO₂ emissions [3]. Consequently, CO₂ emissions from the transport sector accounted for 21% of total CO₂ emissions in the EU in 2017 [4], and the total emissions from the transportation sector rose by 36% compared to 1990 [3]. Globally, there is a transition towards a low-carbon, circular economy, which means that the European Union must also take action to remain competitive and meet people’s needs for enhanced mobility [5]. As part of this, the Commission’s low-emission mobility strategy was launched in July 2016 [4]. The aim of this strategy is to reduce GHG emissions from the mobility sector by at least 60% by 2050 compared to 1990 levels [4].

Cities and urban areas play a significant role in this context. Between 71% and 76% of the world’s energy-related CO₂ emissions, and 67–76% of the world’s energy consumption are associated with cities and will be further increased due to the rising number of people residing in urban areas [1,6–8]. Forecasts predict that 6.7 billion people, equivalent to 68% of the world’s population, will settle in cities by 2050 [6]. In addition, the IPCC report (2014) states that in several urban areas, there are barriers to advancing sustainable development and minimising energy and carbon use. These include a lack of political will, as well as institutional and financial capacity constraints [1]. Nevertheless, studies indicate that government-imposed regulations can have an effect on the climate impacts of urban areas [1]. As a result, cities have the potential to counteract climate change [9].

Due to the continuing increase in the number of private vehicles worldwide, with the US having the highest number of passenger cars per 1000 inhabitants, followed by the

EU and Japan, which indicates a trend in the undesirable direction, attention is focused on PMT [10]. Since it is difficult for people to change their behaviour—for example, an annual visit to the dentist is an effort, or they lack the persistence to lose weight through diets and regular activity—humanity cannot be required to withdraw their own needs in order to help the common welfare or mitigate climate change in the future [11]. For instance, restricting mobility in the sense that people should refrain from using their own cars would lead to reluctance. Therefore, the core literature on climate change deals with the search for technological solutions [12]. Among others, there is a portfolio of actions by Pacala and Socolow [13] that would contribute to mitigating emissions. The majority of these measures are based on technological solutions, but eliminating car use by half represents a behavioural approach. According to Pacala and Socolow, however, achieving this solution involves additional behavioural changes, which in turn makes technological instruments preferable.

The introduction of a Green Wave offers a rare occasion to both enhance personal comfort and reduce emissions. This technological solution can avoid a social dilemma that describes a conflict of short-term personal interest with long-term societal goals [14]. Traffic light strategies subsumed under the term Green Wave can be rather complex [15,16], and their implementation depends on many factors of the existing traffic system and of the users of that system. However, the main idea of such strategies is the same: the green phase of each traffic light starts with a time delay that is equal to the travel time between the traffic lights in a certain direction. In a simplified way, vehicles that drive in this direction with the recommended speed will only encounter one red light, while all other lights will then switch to green shortly before the cars arrive at the intersection. This has the aim of reducing the mean stopping times of vehicles and consequently optimising the traffic flow [17,18]. Improving the flow efficiency of the street system reduces stop-and-go traffic [18], which saves emissions [19]. Especially when accelerating, the vehicle needs more fuel and causes increased CO₂ emission levels, which is decreased when driving at constant speeds [19]. A reduction in stopping times also cuts overall travel time, but it potentially raises the attractiveness of driving. Thus, optimising traffic flow may lead to an undesirable feedback or even a negative overall effect.

Therefore, this study deals with the estimation and comparison of CO₂ emissions from passenger cars in an urban area considering two different traffic light strategies, the Green Wave with 50 km/h and a usual interval switch. The study does not aim to provide a complete overview of the influence of the transport sector on greenhouse gases, but analyses one transport policy, namely the Green Wave traffic light strategy, in order to provide possible recommendations for policy makers regarding more sustainable urban transport. There is a particular focus on the attractiveness of driving, as the study investigates how much more attractive driving can become before the break-even point is reached. The solution to this research question is not trivial, as the opposite direction to the route with a Green Wave is also affected. The oncoming traffic can have an influence on the emission levels and thus on the benefits of the Green Wave compared to the interval switch case. This system can be ideally analysed using an agent-based model. Since the benefit of a Green Wave is highly dependent on the specifics of the traffic system, we do not use an abstract system, but rather model an existing real-world traffic system as a case study. We have chosen a specific road section in the City of Graz, Austria, that is described in more detail in Section 2.2. This section was chosen because it is a popular route for commuters and as such features highly asymmetric traffic density: high density into the city in the morning and high density exiting the city in the evening. Additionally, the road sections includes segments, where the allowed speed limit is beyond 50 km/h. This offers the possibility of introducing a Green Wave at 50 km/h without drastically decreasing travel time, which would increase attractiveness and might lead to increased car use and emissions. The selected road section is modelled in NetLogo [20], an agent-based modelling platform.

2. Materials and Methods

2.1. The Model

The specially developed traffic model was created using NetLogo 6.1.1 [20]. This agent-based modelling environment was used because it is especially suited for simulating highly complex natural and social phenomena that evolve over time [21]. In addition to pre-defined models, NetLogo allows for quick and easy extensions and/or modifications to existing models [22,23]. It is also possible to create own models in NetLogo with basic programming skills, as NetLogo has its unique programming language [22,23]. The comprehensive documentation and tutorials available online encourage the use of NetLogo for simulations [22]. Like other agent-based modelling environments, NetLogo has the ability to model traffic dynamics and create visualisations of individual traffic units, such as cars or pedestrians [23]. NetLogo was chosen as a modelling platform because it offers ample opportunities to expand the model in various directions. With more specialised micro-simulation software [24], the implementation of this model might be easier, but one will always be limited to a traffic flow model or a car-following model. In this implementation, all other aspects of mobility (and beyond) can be easily implemented. For example, a realistic decision-making process regarding the choice of travel mode or the destination can be done straightforwardly within NetLogo, while traditional traffic models offer no such opportunity.

The aim of the developed car-following model is to estimate the CO₂ emissions of passenger cars with various vehicle-specific data for a street in the city of Graz based on selected traffic light strategies. A prototype of this model was developed in [25]. The CO₂ emissions of cars depend on specifics of the car (age, fuel, size) as well as driving speed. Subsequently, we compare the determined CO₂ emissions of the considered traffic light strategies and investigate the potential benefits of a Green Wave.

The cars and traffic lights are the key agents in our traffic model. We have assigned vehicle-specific characteristics to the cars, such as size, engine type, and year of construction, and with a defined chance a car is generated in the model. The distribution of these properties is based on a different traffic model [26]. The vehicles move at a certain speed and interact with each other as well as with the traffic lights. Section 2.3 offers a detailed explanation about the creation and the interaction of the vehicles, the traffic lights, and the environment, as well as a more detailed explanation of the model.

2.2. Data Sources

The relevant data were collected from statistical data, scientific studies, results from other models, such as [27,28], and online mapping service (Google Maps, Open Street Maps) as follows: The values of the number and composition of passenger cars were extracted from [26], which is based on a survey [29]. The survey data include details about the used cars: Vehicles are differentiated on the basis of three main factors: the size, the engine type, and the age of the vehicle. The cars weighing up to 1150 kilograms (kg) denote the group of compact cars, in our case named small cars. The mid-range cars consist of vehicles with a weight between 1150 kg and 1550 kg, and the large cars have a weight above 1550 kg. In classifying the engine type, there is a distinction between diesel- and petrol-powered vehicles and cars with electric engines. The classification by age was based on the data from [26], and we distinguish between a total of seven age groups. Based on these survey data, the model used in [26] produces realistic routes for all vehicles, which can then be used as an input for our model. This has the advantage of having access to vehicle information that cannot be obtained by usual measurements, e.g., the age of a car.

The necessary material for the map comes from Google Maps (2021). In total, the analysed street stretches over a length of 7.3 km and is shown in Figure 1.

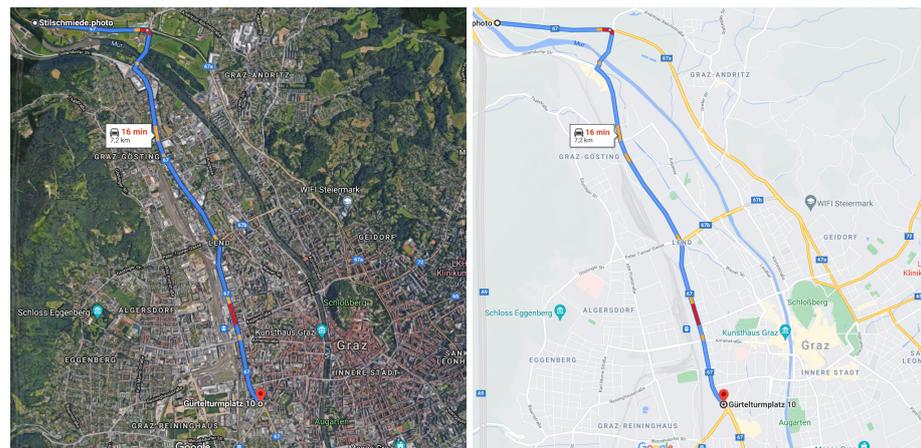


Figure 1. The investigated section of road as seen in Google Maps (2021). **Left:** Satellite View. **Right:** Map.

The positions of the traffic lights were also defined using Google Maps (2021). On this road section, there are 19 intersections, which we subdivided into 11 small and 8 large traffic lights. With regard to the calculation of emissions, secondary data from scientific studies [19,30,31] were used. We took the fuel consumption data of the automobiles as a function of the mean speed, the engine type, and the size of the vehicles from these studies and prepared them in Table 1. Lacking fuel consumption data were supplemented with the help of available data from the literature. For idle cars, we assume a fuel consumption of 1 litre per hour.

Table 1. Speed-dependent fuel consumption (l/100 km) for different car types.

Car Type	20 km/h	30 km/h	40 km/h	50 km/h	60 km/h	70 km/h	80 km/h	90 km/h	100 km/h
petrol-big	12.8	10.1	9.0	8.3	7.4	7.0	6.5	7.2	7.4
diesel-big	8.2	6.7	6.2	6.1	6.2	6.3	6.5	6.6	6.7
petrol-medium	10.0	8.2	7.5	5.4	5.8	5.6	6.7	7.9	8.7
diesel-medium	6.1	5.0	4.6	4.5	4.6	4.7	4.8	4.9	5.0
petrol-small	8.2	6.5	5.8	5.4	5.2	5.3	5.4	5.5	5.8
diesel-small	5.3	4.3	4.0	3.9	4.0	4.1	4.2	4.2	4.3

In the next step, these fuel consumption data in litres per 100 kilometres (l/100 km) were transformed into emission values using emission factors from [32]. An emission factor of 2.64 kg CO₂/l was chosen for diesel and 2.33 kg CO₂/l for petrol. For cars that operate on electric power, we assume an emission value of zero due to the assumption that these cars do not cause any emissions during their use [33,34].

2.3. Model Details

In the following section, we provide a detailed insight into the generation of the cars, the different interactions between the stationary and mobile agents, and the time evolution of the simulation.

Basically, the cars consist of mobile agents that can move across the road system and have different properties and behaviours. With a defined chance, a car emerges in the model, and through its interactions with other cars and with its environment, emergent phenomena occur. Driving into the city, a new car enters the model with a realistic probability of the traffic system between 7 and 8 a.m., taken from the model results in [26].

Since the density of the opposite direction is paramount for the success of the Green Wave, we investigate three different scenarios, where the vehicle density in the direction out of town is 10%, 25%, and 50% of the traffic going into the city, respectively.

Cars are equipped with the properties discussed in Section 2.2. In addition to the vehicle-specific data, the different year of construction of the vehicles is also decisive for the determination of emissions. The effect of age is taken from [26]. The emissions of a car rise by 2.5% each year relative to those of a new car. Since we consider seven age groups in the model, the mean values for the emission percentages per age group are taken into account. For the age groups, we used the following classification based on [26]:

- 0–2 years
- 3–5 years
- 6–8 years
- 9–11 years
- 12–14 years
- 15–17 years
- 18 years and more

A significant part of the simulation is the calculation of the resulting CO₂ emissions, which is done for every car in every time step. CO₂ emissions (EM) are calculated from Equation (1):

$$EM = base_{s,f} * em(f) * d * a, \quad (1)$$

with the base fuel consumption value $base_{s,f}$ for a car with size s and engine type f given in Table 1, the fuel dependent conversion factor from fuel consumption to CO₂ emissions $em(f)$, the age factor a and d , and the distance traveled within one time step, which is calculated from the speed of the car and the length of one time step.

In addition to the cars, traffic lights are the second group of agents in the model. Traffic lights can change colour between red—cars must stop in front of a traffic light—and green—cars are allowed to pass the traffic light. Depending on which traffic light switching strategy is examined, the traffic lights switch based on interval switching or with a time delay. For the Green Wave, the behaviour of the traffic lights is simplified: The time delay between two neighboring traffic lights is the estimated travel time between those points, given the relevant traffic conditions.

Crucial for understanding the model is which movement patterns and behaviours the cars possess and which interactions they generate among themselves and with their environment.

The cars try to accelerate to the maximally allowed speed and slow down if necessary to keep their distance to other cars or stop at red lights. Cars can also leave the system via intersections, while new cars can enter the system at these points. Probabilities for this choice of direction are based on the data from [26].

The time development of one simulation run is then as follows. Since there are no vehicles on the track after the initialisation of the model, we have taken into account a certain time period in which the model can adjust to the number and composition of vehicles on the road in real conditions. This time period is half an hour. Due to the ability of agent-based models to represent real time in a much shorter time, the model only needs a few minutes of simulation time. After this initialisation phase, we consider a period of one hour for each simulation run so that we can compare the results obtained. For each scenario, we consider 10 simulation runs to minimise the statistical error. From each of these 10 runs, we calculate mean values and standard deviation of the CO₂ emissions per distance, which provide the basis for our findings and interpretations.

3. Results

Figure 2 shows the resulting emissions in g/km for different amounts of oncoming traffic for both interval switch and Green Wave. It is clearly visible that the Green Wave leads to lower emissions than the interval switch. The trend regarding oncoming traffic is reversed: while the Green Wave leads to more emissions when oncoming traffic increases, emissions are reduced for the interval switch in that case. The main reason for this behavior

is that oncoming cars drive rather efficiently in the interval switch case because of the low traffic density, while they have to drive against the direction favored by the traffic lights in the Green Wave case. Still, up to an oncoming traffic density of 50%, the Green Wave produces significantly less emissions.

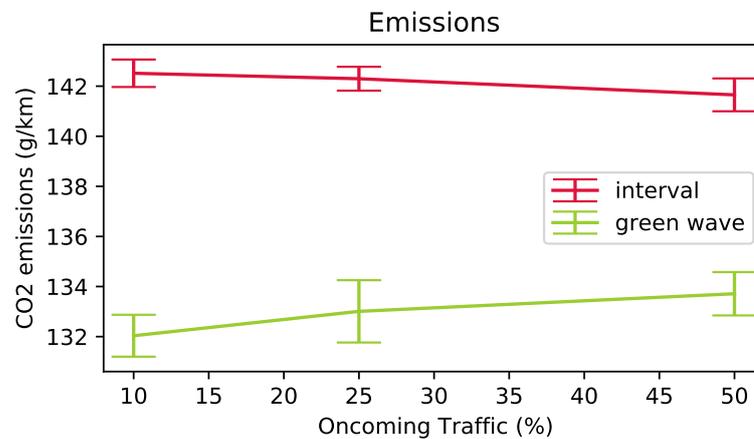


Figure 2. Resulting emissions in g/km for different amounts of oncoming traffic.

In Figure 3, we compare the travel time of both traffic light strategies. The travel time serves as a main indicator of the attractiveness of the use of personal cars. We see that the travel times are nearly identical for both strategies at all investigated percentages of oncoming traffic. The advantage of the Green Wave in terms of traffic flow is exactly compensated by the lower speed limit.

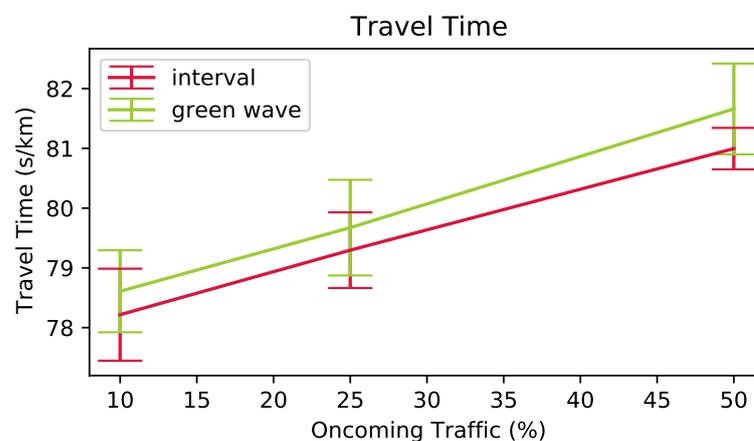


Figure 3. Resulting travel time in s/km for different amounts of oncoming traffic.

Figure 4 shows the relative advantage of CO₂ emissions of the Green Wave for different amounts of oncoming traffic. As expected, the benefit decreases, but it is still above 5% for 50% oncoming traffic. This relative decrease in emissions can give a first estimate of how much more attractive car use can become when using a Green Wave, while still reducing overall emissions.

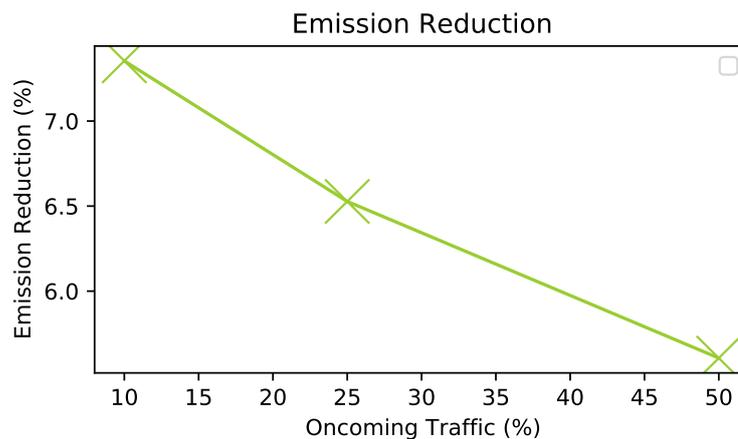


Figure 4. Emission reduction in percentage for different amounts of oncoming traffic.

In addition to this sensitivity analysis with respect to oncoming traffic amount (Figure 4), we also concluded an analysis with different traffic densities, which determined that the benefit of the Green Wave is mainly determined by oncoming traffic density, while traffic density as a whole plays only a minor role. We also investigated the Green Wave at a different speed of 30 km/h and concluded that such a strategy would even increase CO₂ emissions compared to a regular interval traffic light system.

Implications of these findings are discussed in Section 5.

4. Discussion

We used an agent-based car-following model in order to investigate the influence of traffic light behaviour on the GHG emissions by cars. In a traditional equation-based approach, like that of [35], this would not have been possible, since interactions between cars and traffic lights or other cars are averaged out and implicitly included in average speeds. However, at the core of the investigated phenomenon lies the acceleration and deceleration of cars, so one cannot simply use a mean speed approach.

When compared to similar car-following models like SUMO [36] or VISSIM [37], the presented model has some advantages, because it was specifically designed with this study's research question in mind. Emissions are not calculated afterwards based on the trajectories of the cars, but directly during the simulation. This gives us both temporal and spatial resolution, which would be interesting for non-GHG emissions like particulate matter. Furthermore, we retain the information on which car and which type of car is responsible for which emissions, which is more helpful to policy makers than just overall sums. The cars are generated within the model based on statistical data and a realistic, behaviour-based model [26] that does not rely on input-output matrices, in contrast to traditional car-following models.

The model includes various assumptions and simplifications that should be addressed at this point of the discussion. The roads are simplified, as they do not have information regarding elevation, slope, or curvature. However, since these attributes typically only influence the average speed, they are implicitly included by the speed the agents travel with. Furthermore, the test track is free of any significant slopes, which is a common feature of an urban traffic system. If one wants to use the model on a different system, especially one with significant slopes like ramps, this information should be included, since it influences acceleration, deceleration, and fuel consumption.

A further simplification is the homogeneous acceleration of the cars. In reality, acceleration behaviour is rather complex and influenced by many factors, both of the used car as well as the person driving the car. We assume that those differences in behaviour average out on the macro-scale and that it is valid to use an average value for all cars. Especially in

a congested, urban environment, this approximation is close to reality, since acceleration is mainly influenced by the acceleration of the whole bulk, rather than individual cars.

Furthermore, the study only analyses primary CO₂ emissions. This means that secondary emissions, such as those produced in the extraction process of diesel or petrol [25], are not taken into account. We also did not analyse non-GHG emissions, as the aim of the study is to assess the impact of CO₂ emissions from different traffic light strategies and not the consequences of, for example, particulate matter, which could also be of interest for cities.

Since we only investigate direct emissions, the CO₂ emissions of electric cars are set to 0. However, if one was interested in indirect emissions as well, it would be possible to include energy consumption of electric cars [38] in the model. Since the advantage of a Green Wave mainly comes from traffic flow optimisation, one would expect that energy consumption rates benefit in a similar manner as fuel consumption rates.

The biggest uncertainty of the model arises from the speed-dependent emission rates of individual car types. Since the difference in emissions between the scenario investigating the Green Wave and the business-as-usual scenario is mainly caused by different amounts of accelerating and decelerating, the difference in emission at low speeds is crucial for the findings presented here. For this reason, we took great care in collecting data for the different types of cars and used multiple sources. That way, even if one of the sources overestimates or underestimates the effect of vehicle speed on fuel consumption, those errors would average out and our findings would still be valid. Note that there are many other factors that influence CO₂ emissions, like transmission systems or the vehicle mass function [39,40]. However, none of those parameters change depending on the used traffic light strategy, and some of them are even included in the usual measurements of fuel consumption. For this reason, we chose to estimate CO₂ emissions solely based on fuel consumption.

Another parameter that leads to uncertainty in the obtained results is the traffic density, i.e., the number of cars using the road in each direction. We used an average value obtained from [26], but of course this value might change due to demographic change, behavioural change, seasons, or policies. However, the presented sensitivity analysis with respect to this parameter shows that the obtained results are robust in that regard.

Various expansions are possible to increase the scope and accuracy of the model. One could include a more sophisticated traffic light system [41–43] and see if intelligent control outperforms the Green Wave. Especially in combination with partly or completely autonomous, connected cars [44,45], more complex traffic light systems are possible, since these cars can communicate with each other and with the traffic light system. However, such sophisticated systems are out of scope for this investigation, which is limited to the potential of a conventional, non-communicating Green Wave. Nevertheless, even without a change in the traffic light system, autonomous cars have large potential to lead to reduced emissions [46].

Furthermore, an expansion to non-GHG emissions like particulate matter or NO_x [47] might be interesting, especially since we would have local resolution of the emissions. NO_x could still be calculated based on fuel consumption, while emission of particulate matter, especially in an urban environment, requires a more sophisticated approach [48].

5. Conclusions

Using an agent-based model, we studied the effect of a Green Wave in terms of emission reduction and difference in travel time. We found that in the road section we investigated, introducing a Green Wave has the potential to reduce emissions by 5% to 7%, which is a significant yet not a radical improvement.

A major effect we have to keep in mind is that a Green Wave can also increase the attractiveness of car use. Since alternatives to car use are nearly always lower in CO₂ emissions than personal car use [49,50], this could easily compensate the benefit in emissions. Although the most important factor for attractiveness is travel time (and it was

possible to keep travel time constant in this system), other factors are relevant as well. For example, stop-and-go traffic as well as having to stop at red lights decreases attractiveness, even if it would have no effect on the actual travel time. Thus, we cannot conclude that a Green Wave always has an advantage in terms of GHG emissions.

This phenomenon of increased attractiveness becomes even more problematic if we consider the area outside the boundaries of the model. We only model a small section of an urban road. However, since this road is mainly utilized by commuters, effects of increased attractiveness are multiplied here. One per cent more cars on this road increase emissions inside the system by one per cent. However, it also means that more people commute to the city by car. In terms of emissions, the journey to the city is more costly than the journey within the city, and the Green Wave offers no benefit outside the city. Depending on the number of commuters on the road, availability of public transport to the city limits, and the average commuting distance of the city, a minimal increase in attractiveness of just 1% might be enough to effectively increase GHG emissions overall.

To conclude, we find that although introducing a Green Wave has the potential to reduce emissions by optimising traffic flow, this potential is limited. Only if a road

- currently offers a higher speed limit,
- is used highly asymmetrically, and
- is not used by many commuters coming from far away from the city by car

can a Green Wave have a beneficial impact on GHG emissions. If this cannot be guaranteed, investing in alternatives to private car use or making the existing alternatives more attractive will be more effective and more efficient in decreasing CO₂ emissions.

Parts of these findings are not specific to the strategy of a Green Wave. Every measure or policy that reduces emissions inside the city limits by optimising traffic flow has the potential to increase overall GHG emissions due to the increased attractiveness of personal car use. While traffic flow optimisation can still play an important role in the reduction of traffic emissions, it is paramount to include all its effects, even if they appear outside the investigated system. Such a holistic view can minimize the risk of policies that lead to a rebound effect and offers the possibility to find solutions for the challenge of ever rising GHG emissions related to traffic and transportation.

Author Contributions: Conceptualization, E.B. and G.J.; methodology, E.B. and G.J.; software, E.B. and G.J.; validation, E.B. and G.J.; data curation, E.B. and G.J.; writing—original draft preparation, E.B. and G.J.; writing—review and editing, E.B. and G.J.; visualization, E.B. and G.J. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the University of Graz for covering the publication fees. This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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