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Cellular Automata-based Anthropogenic Heat Simulation *

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Abstract

Cellular automata (CA) models have been for several years, employed to describe urban phenomena like growth of human settlements, changes in land use and, more recently, dispersion of air pollutants. We propose to adapt CA to study the dispersion of anthropogenic heat emissions on the micro scale. Three dimensional cubic CA with a constant cell size of 0.15 m have been implemented. Simulations suggest an improvement in processing speed compared to conventional computational fluid dynamics (CFD) models, which are limited in scale and yet incapable of solving simulations on local or larger scale. Instead of solving the Navier-Stokes equations, as in CFD, only temperature and heat differences for the CA are modeled. Radiation, convection and turbulence have been parameterized according to scale. This CA-based approach can be combined with an agent-based traffic simulation to analyse the effect of driving behavior and other microscopic factors on urban heat.

Keywords: CA, Traffic Simulation, Heat Simulation, Urban Heat

1 Introduction

A significant amount of energy consumed in large cities can be attributed to traffic. For example, more than one fifth of the total energy consumption in Singapore can be attributed to transportation [1]. Despite the advent of electric vehicles in recent years, the majority of vehicles in use today are still conventional Internal Combustion Engine Vehicles (ICEV) which are known for their low energy efficiency. Approximately only 17-21% of energy [2] stored in gasoline is converted into power at the wheels. Heat emitted by traffic is thus a contributor to the Urban Heat Island (UHI) effect [3].

Although there are studies that investigate the impact of traffic on CO2 emissions [4], there is relatively little work on heat emission by traffic and the contribution to the UHI effect. Heat emissions have been studied in the context of underground car parks [5] as well as on a city-scale using relatively crude macroscopic models [6]. However, microscopic models that

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describe the underlying processes of heat emissions do not exist yet. Existing methods, based on Computational Fluid Dynamic (CFD) models [7], while detailed, are computationally expensive and cannot be used on a large scale at the required resolution (centimeter range) and thus are not suitable for large-scale microscopic analysis. Current efforts to gain a better understanding of the complex process of traffic heat emissions are hampered by the limitations of existing methods in analysing the larger scale effects of local changes. For example, it is impossible to study the effect on urban heat of a large-scale (or even a small-scale) conversion of ICEVs to electric or autonomous vehicles.

In order to study traffic heat emissions, a suitable model is needed. Cellular Automata (CA) may offer a solution to this problem. CAs are space and time discrete finite state machines (FSM) that operate on a set of cells. Some kind of spatial relationship is introduced to define a *neighborhood* between the cells. Every time a cell is updated, its new state is determined by the neighborhood state of all cells. Such a decentralized mechanic allows to model even non-linear systems.

Stephen Wolfram famously argued that many complex phenomena such as fluid dynamics are beyond the description of traditional mathematics and should be simulated by simple computer programs like one-dimensional CA [8]. Due to their ability to produce a fair amount of complexity, CAs are also used to describe a variety of physical processes which cannot be easily described with traditional models. CA-based solutions have been applied to a broad range of topics, including, but not limited to, simulation of fire spreading in buildings [9, 10], flooding in cities [11], dispersion of pollutants [12] and traffic [13].

In this paper, we introduce a novel computational approach to microscopically model the heat effect of traffic using a CA-based approach, coupled with an agent-based simulation of the traffic. The agent-based model is used to simulate how individual agents (vehicles) accelerate and decelerate. In addition to classical agent-based traffic simulations, we not only simulate the driving behaviour (acceleration, deceleration) but also all vehicle components (such as the drivetrain and engine) that are relevant for heat emissions. Dispersion of heat emitted by a vehicle is simulated by the CA model which distinguishes between different kinds of heat transfer. We also demonstrate the unique advantages that the proposed model offers by analysing the impact of driving style on traffic heat emmissions.

2 Related Work

The Urban Heat Island effect [3] describes how heavy urbanization of cities can significantly influence local temperature levels. Asphalted streets and concrete buildings store large amounts of heat by absorbing solar radiation. At night time stored energy is released into the environment, keeping the temperature at a higher level than in more rural areas. For example, in the case of Singapore, temperature differences between urban and rural areas can amount up to 7°C [1]. While the built environment is generally the most prominent contributor to the UHI, streets and road going traffic have a measurable impact as well.

There have been numerous studies on energy balance models to provide a way of modeling energy fluxes in urban places [14]. These models vary in the scale of the area covered. Oke [15] for instance modeled thermal emissions at a macroscopic level to compare man-made and natural energy flow on a city scale. This work is based on the fundamental law of conservation of energy, which states that energy cannot be lost or gained.

Ksaibati et al. [16] consider the spatial distribution of heat in the pavement as a result of meteorological factors like solar radiation. A network-based model of heat dissipation inside pavement layers using a finite difference mesh is proposed. Similar to a CA, the pavement layer is modeled in the form of a grid where the thermal energy is propagated between neighboring nodes.

The work done by Prusa et al. [17] makes an attempt to model the effect vehicles have on the environment in a comprehensive way. It features the most important energy flows between a vehicle and the environment, which consists of an asphalt layer and a dissipative air mass above it. They propose a numerical model, which is used to gather information about the quantity of energy fluxes between vehicle and environment, rather than about the spatial or temporal distribution of energy. Likewise, work done by Fujimoto [18] has a similar premise, but chooses to focus entirely on the road surface heating and does not regard the air layer. Both models are intended to examine the influence of vehicles on road conditions in a winter climate.

3 Computational Model

We are interested in modeling the heat emissions generated by vehicles. Furthermore, we are interested in modeling how the heat emissions affect the environment, i.e., how heat emitted by a vehicle is dispersed in the environment. For this purpose, we need two kinds of models: (1) a traffic model that includes all relevant vehicle components (i.e., those components that generate heat) as well as driving behaviour components that describes the acceleration and deceleration behaviour as this will influence the energy consumption and thus the heat emissions of individual vehicles; (2) a model of the environment that includes the various physical processes relevant for describing heat dispersion. In this paper, we focus on the computational modeling part. A detailed discussion on the physics behind it is not within the scope of this paper and will appear elsewhere.

3.1 Vehicle Model

Acceleration and deceleration behaviour is very important in the context of simulating how much heat is generated by a moving vehicle. There are a number of standard driving behaviour models (referred to as car-following models) described in the literature that are typically used to simulate acceleration and braking of individual vehicles. These models ensure that realistic patterns of acceleration and braking are captured by the simulation. They typically directly or indirectly calculate the acceleration that needs to be applied by a vehicle for moving at the driver's preferred speed while considering other vehicles in the proximity; in particular, the vehicle directly ahead. Examples of such models are the intelligent driver model [19] and the Gipps' driver model [20].

For the work presented in this paper, we use the Gipps' driver model. The Gipps' model works on the idea that a vehicle accelerates towards its preferred speed at a rate not exceeding its maximum acceleration. In a normal scenario (free flow) it approaches this velocity asymptotically. As the distance to the vehicle in front decreases (congested scenario), it decelerates to ensure that a minimum safety distance is maintained. The reaction time of the driver is also a parameter of the model and is assumed to be a constant for all vehicles.

Given the acceleration/deceleration behaviour generated by the Gipps' model, the energy generated by the vehicle and dissipated to the environment can be calculated. Ideally, the total energy generated by a vehicle in one time-step of the simulation would be the sum of the change in kinetic energy of the vehicle during this time-step and the energy lost due to friction and air resistance. However, due to the inefficiency of ICEV engines that are the subject of this study, a significant portion of this energy is lost through radiation and convection from the engine, exhaust and cooling system. The engine is generally maintained at a constant temperature by

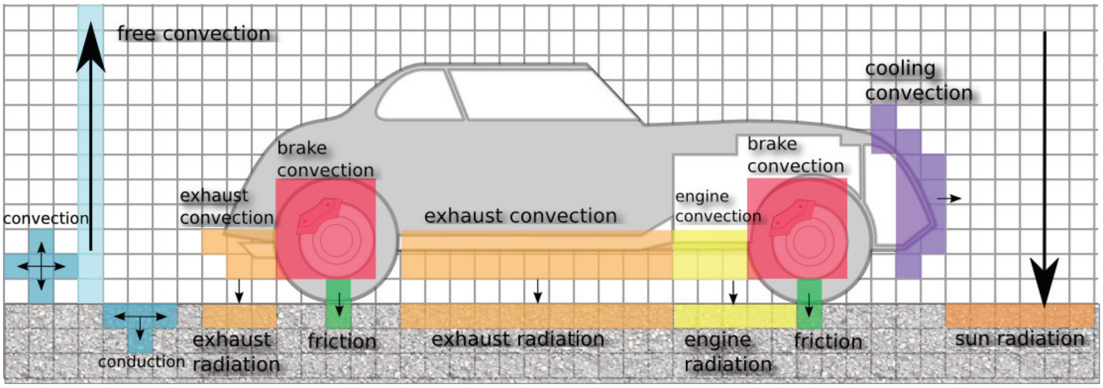


Figure 1: Physical processes in the cellular automata, viewed from the side. Cell and car overlays demonstrate origin and direction of energy input into the system. Additionally examples are given for direction of environmental energy propagation: convection, conduction, free convection and sun radiation

the cooling and exhaust system that redirects this extra heat to the environment in the form of radiation and convection. In cases where the vehicle is decelerating, the kinetic energy lost by heating vehicle's brake disc and is dissipated to the environment in the form of brake radiation and convection. We assume that the heating effect of brake radiation [1], and cooling system radiation on the environment is negligible. This is because they are distributed over too many cells to have a significant effect on cell temperatures compared to the other components. The relatively low average temperatures of the cooling system and brake discs leads to potentially very low radiation energy. It can be computed, but is physically irrelevant as it usually amounts to changes of not more than a fraction of a degree per cell. Additionally, radiation of these components is not, or only to a small part, directed onto the pavement, where it is measurable in our simulation. The remaining part leaves the boundaries of the simulated space through the air, which again only takes up a minor part of radiation heat. In summary, there are six ways in which the vehicle contributes to urban heating: air drag, rolling friction, braking, engine heat, exhaust heat and convective cooling. These are shown figuratively in Figure 1.

3.2 Environment Model

Besides the vehicle based components there are also certain environment based factors that affect urban heat (as are also shown in Figure 1). Energy is constantly added to the system even in the absence of vehicles, in the form of solar radiation which causes the heating up of asphalt cells. Conduction causes heated asphalt cells to dissipate energy to their cooler neighbours. Air cells are affected by three processes: diffusion, free convection and turbulent mixing. Diffusion is modeled using a Finite Difference Model [21]. Free convection is the process by which hotter, less dense air rises up and cooler, denser air moves downwards. This process is modeled in the simulation by considering each vertical column of air separately. The average temperature of this column is used to determine the rate at which it rises based on the temperature difference with the boundary cells. Thus, hotter columns of air may move up by several cells in a single step while less hot columns may take several seconds to rise by a few cells. The final process,

[1]Brake radiation, however, does result in the lowering of brake disc temperature and is thus modeled.

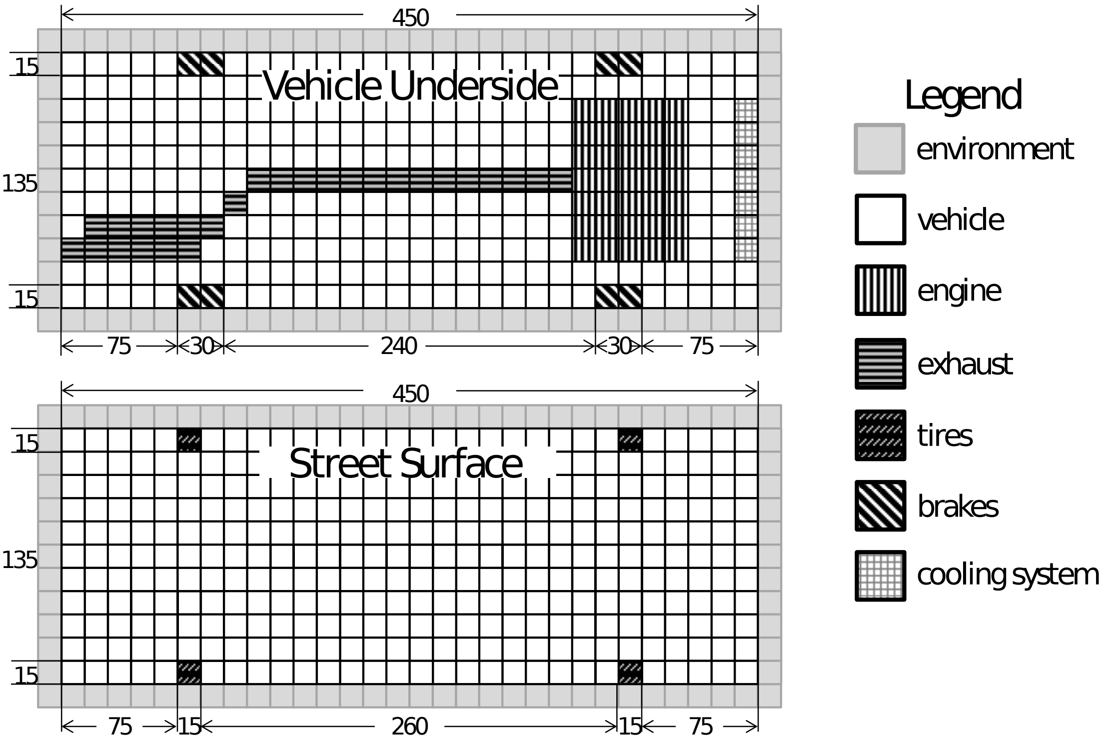


Figure 2: Raster representation of a vehicle: surface under the vehicle with parts of varying temperatures (top) and raster of a vehicle at surface level where only the tires have direct contact to the asphalt (bottom). Distances shown are in centimeters.

turbulent mixing, takes place due to air being pushed by vehicles moving in the environment. This process causes a homogenous mixing of air at a rate much faster than natural diffusion and is modeled by increasing the diffusion constant of the affected cells in proportion to the amount of turbulence. Figure 1 summarizes all the vehicle and environment based factors that are considered in the proposed model.

3.3 Cellular Automata Implementation

A CA model is one in which space and time are discrete. In each time step, the values of all cells are updated synchronously based on a set of rules and the values of cells in their neighborhood.

In order to project the energy released by a vehicle into the environment, we use a rasterized representation of the vehicle. All components necessary for the heat simulation are represented in form of CA cells and are used as an overlay for the CA model (see Figure 2). At any point in the simulation, the cells of the CA which are occupied by the vehicle can be determined by combining the vehicle raster model with the vehicle location obtained from the agent-based traffic model. The vehicle-related rules are used to determine the power transferred by the vehicle to the different cells of the vehicle raster model at a time step of the simulation using the current velocity and acceleration of the vehicle. Cooling and exhaust convection are different from the other rules in that they also affect cells outside the immediate area occupied by the vehicle itself. Cooling convection is simulated to affect one layer of cells in front of the vehicle. Exhaust convection affects a region in proportion with the speed of the vehicle.

Table 1: Implemented Rules of the CA Model.

Vehicle-related Rules	Environment-related Rules
rolling friction	solar radiation
brake convection	heat conduction between asphalt cells
engine radiation	conversion of cell energy into temperature
engine convection	homogenous mixing due to turbulence
exhaust radiation	free convection of hot air
exhaust convection	
cooling convection	

The CA is updated in each step of the simulation by the application of the vehicle and environment related rules in the following order: (1) Solar radiation rules that add a certain power to all the asphalt cells based on the temperature and size of the asphalt cells; (2) Vehicle based rules add a certain power to the cells (air and asphalt) occupied by the vehicle based on the rasterization shown in Figure 2; (3) Conductive heat exchange between asphalt cells adds (or subtracts) the heat based on temperature of neighbouring asphalt cells; (4) Diffusive heat exchange between air cells adds (or subtracts) the heat based on temperature of neighbouring air cells; (5) Change temperature of each cell of the CA-based on the total power received (calculated in steps (1) to (4)) over a time step of the simulation and the heat capacity and size of the cell; (6) For the air cells, turbulence due to vehicle movement results in an increase of the diffusion coefficient for all the affected air cells; (7) Free convection which causes hotter vertical columns of air to move up based on their average temperatures.

The accuracy and performance of the model is substantially influenced by two factors: the spatial and temporal resolution. Depending on the focus of the experiments, the CA has to have cell sizes between 0.1 m and 1 m. Cells larger than that lack the accuracy to simulate temperature differences between tire tracks and the rest of the road. If they are too small, then the computational cost increases more rapidly than the quality of the results. In this study, we use a resolution of 15 cm.

Temporal resolution is a more critical factor. Despite the low timestep size of 100 ms, for a CA with 15 cm spatial resolution, vehicles may “jump” between timesteps. For instance, a vehicle moving at 15 m/s would cover 1.5 m or 10 cells in a single time step. In order to ensure that the simulation does not collapse due to this jumping, vehicle position interpolation is done. So, if the vehicle moves from position x_1 to x_2, the energy is divided evenly across all the cells between x_1 and x_2.

4 Experiments

The purpose of the simulation experiments performed in this study is to first validate the proposed CA-based model and, subsequently, demonstrate the unique capabilities of the model in analysing the effect of microscopic factors like driver behavior. For this, we make use of the simple setup shown in Figure 3, modeling traffic on a 100 m segment of road. The first experiment considers only a single vehicle whereas the following experiments examine a number of vehicles moving in sequence. Each simulation configuration is run a single time because we

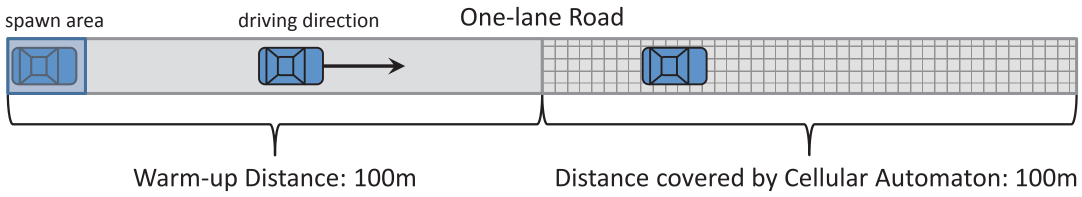
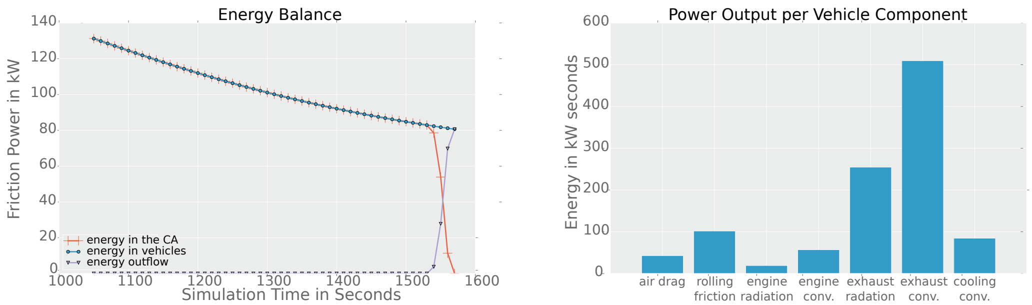


Figure 3: The setup of the vehicle experiments. (Illustration not to scale)



(a) Energy Balance (b) Power Output per Vehicle Component

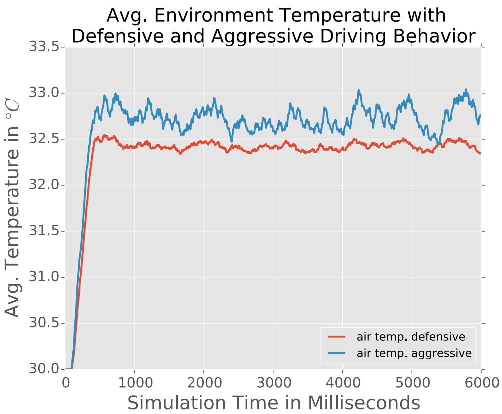
Figure 4: Left: The energy inflow and outflow of a simple single vehicle scenario. All the energy dissipated by the vehicle is accounted for in the CA. Right: The total power output of each component of the vehicle's heat output, accumulated over the experiment run.

aim to demonstrate the model. Experiments to learn about the system itself are out of the scope of this paper and subject to further research.

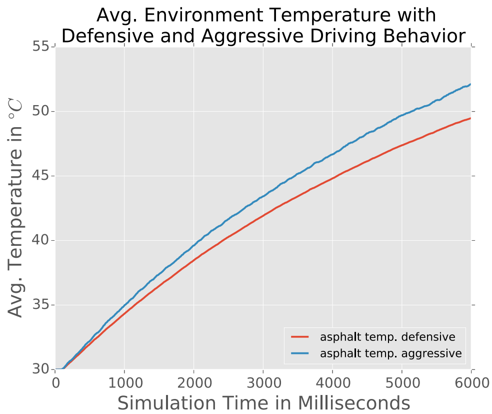
4.1 Validation of the Model

According to the law of conservation of energy, the change in energy in an isolated system should equal the difference between the energy added to the system and the work done by it. In order to quantitatively validate the proposed model, we first consider a scenario where a single vehicle moves across the area of study at 20 m/s. [2]. Figure 4a compares the total energy generated by the vehicle, i.e., sum of kinetic energy, frictional energy, air resistance and engine efficiency losses, with the heat energy added to the environment through radiation, convection and conduction. The overlapping lines indicate that they are equal until the point where the vehicle exits the environment. The mismatch towards the end of the simulation is because the vehicle is only partially in the area of study. In the Gipps Model, a vehicle only asymptotically approaches its preferred acceleration. This is reflected in the slope of the energy curve: as the vehicle reaches its maximum velocity, the acceleration decreases thus gradually lowering power demand. The engine temperature of a normal ICEV is maintained at a constant value by the cooling and exhaust system that prevents engine overheating. Thus it is expected that the exhaust and cooling system have the most significant impact on environment heating. Figure 4b

[2]The results of this scenario can be seen in our video at `http://youtu.be/72frFC5Ozu4`



(a) Effect on air temperature



(b) Effect on ashalt temperature

Figure 5: This graph shows the effect on air and asphalt temperature of aggressive driving behavior. It is observed that there is a greater increase in temperature due to more aggressive driving behavior.

shows that this is indeed the case in the model, where 63% and 8% of the total energy exits the vehicle there, respectively. It is also in compliance with experiment results given in [17]. Thermal energy from the brake discs is negligibly small in this scenario as a solitary vehicle does not need to perform any braking maneuvers. However, we expect that electric vehicles will yield different outcomes, as their construction and energy balances vary greatly from conventional combustion engine cars.

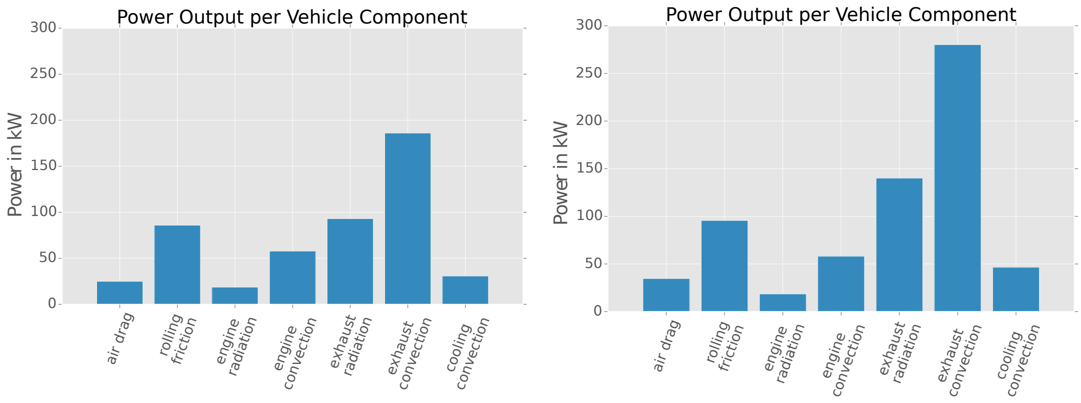
4.2 Analysing the Impact of Driving Behaviors

In this experiment, we use the proposed model to study the impact that aggressive driving can have on the environment. Table 2 shows the different configurations that are used to simulate aggressive and defensive driving behavior. The major difference is that aggressive behavior allows for a larger magnitude in both acceleration and velocity. Additionally, the minimum safety distance between vehicles is lowered in the aggressive scenario. In this experiment, a series of cars is generated randomly at a rate determined by the Poisson Distribution $Pois(\lambda)$ with a mean inter-arrival time of 100 ms. This leads to a steady flow of vehicles passing over the street segment.

Figure 5 shows the temperature of the air and asphalt over time for the defensive and aggressive scenarios. The experiment suggests that there may be an increase of more than $1°C$ in both air and asphalt temperature because of a change in driver aggressiveness. Figure 6, showing the averaged contributions of different components over the duration of each scenario, confirms that the average vehicle in the aggressive scenario contributes more to urban heating.

Table 2: Model parameter values for aggressive and defensive driving behavior

parameter	**defensive scenario**	**aggressive scenario**
min. speed of vehicles (m/s)	16	16
max. speed of vehicles (m/s)	18	22



(a) Defensive Scenario (b) Aggressive Scenario

Figure 6: This graph shows the average power output of each vehicle component, accumulated over the experiment duration.

It also shows that the largest contributor to this difference is the exhaust and cooling convection.

5 Conclusion and Future Work

In this paper we have introduced a CA-based approach to model the effect of traffic on urban heat. The proposed model was shown to produce realistic results. Moreover, the approach has the added benefit that the effect of driver behavior on traffic and urban heat could be observed and analyzed. This raises interesting questions about the environmental impact of driver inefficiency, different engine technologies and the advent of autonomous vehicles. The modeling of individual components of the vehicle like its engine, exhaust, wheel friction and cooling system, enables the investigation of each of their effects in more detail. A more detailed model of the vehicle than the one proposed is currently being developed. This can be used for analysing which parts need to be optimized for creating vehicles that have lesser impact on the environment. Rather more interestingly, the effect of large scale changes in urban mobility like the advent of electro mobility where electric vehicles make up the majority of vehicles on the road, can be investigated using this kind of microscopic model. From an urban development perspective, the proposed model can also be used for simulating the effect of trees and buildings on urban heat by simply adding these components to the environment and adding the related *rules* that need to be applied to the CA.

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