Agent-based modelling of car platooning for traffic optimization

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***Abstract*—Transport is a fundamental aspect of the economy and society. In the area of mobility, there is always environmental safety involved. This case is no different. In fact, with greenhouse gas emissions still increasing [1], it is a major issue in Europe right now. Therefore, it is crucial to explore ideas that can minimise the existing air pollution. Alongside smog, road safety also needs to be considered. For instance, in 2015, over 26,000 people died and nearly 1.5 million people were injured on the roads [1] across the European Union. Therefore, it should be noted that human error has been identified as a contributing factor in over 90% of all road accidents. Hence, ideas that can jointly reduce human errors and air pollution are worth exploration. Autonomous vehicle technology is becoming more advanced every day. However, even without it, it is possible to "improve" car travel. In this context, we consider how an agent system that brings together multiple vehicles to form a "platoon" can effectively address problems in both areas.**

***Index Terms*—vehicle platoons, autonomous vehicles, agent system, pollution reduction, road safety**

I. Introduction

Even though autonomous vehicles (AVs) are among us for a couple of years already, their long-term impact on mobility is still uncertain. Due to the complexity of transport systems, only results from preliminary experiments exist ([2]–[4]), which suggest that "free" vehicles may become the future of transportation. However, there are always two sides to the same coin. On the one hand, giving a car, so to speak, "independence" of action eliminates the main source of errors, the human factor. On the other hand, it might result in the need to deal with very peculiar cases, e.g similar situations where AI is a part of the (in)famous Trolley Problem [5].

Similarly, while autonomous electric vehicles (EVs) are likely to increase the general safety of their drivers and other traffic participants (e.g cyclists, pedestrians, etc.), they may not reduce pollution but only change its main cause. The long-term environmental impact of EVs remains unclear. Specifically, at the time of writing this text (June 2021), there remains strong (though often ignored) evidence that currently available methods of producing and disposing of key elements of EVs and EV-related infrastructure are not eco-friendly [6], [7].

Nevertheless, the advanced capabilities of modern AVs would allow the development of an advanced system — vehicle platooning – where we could minimise the negative factors of traffic. It has been established that vehicle platooning has positive environmental effects due to reduced fuel consumption and use of "road space". One has to notice that fully autonomous vehicles may face obstacles to become a reality. However, during transition state, it is still possible to set up a platoon in which the first vehicle is not fully autonomous and the remaining ones are. Hence, "followers" can drive autonomously by "following the leader". Even if we consider only long-distance roads like motorways, this idea is worth pursuing.

This example is the foundation of the proposal explored below. Assume that each participating vehicle has an onboard software agent which is capable of "taking over" the driving function. In that case, vehicles can be electric but it is not a must. Cars are assumed to be autonomous to the level that will allow them to lead or be a part of a platoon on a multi-lane main road. They can connect using communication mechanisms available today. Hence, they can exchange messages in a way that is proposed for multi-agent systems [8]. Cars within platoons can change the gap between them, increase/decrease the number of cars in the platoon, slow down, speed up, change the order of vehicles in the platoon, etc. These operations involve communication between pertinent vehicles within the platoon.

In the proposed agent-based system, a single car will dynamically form platoons (join and leave them) while travelling towards its destination. Forming a platoon is a "voluntary activity" and if it is not possible to be part of a platoon, vehicles will continue their travel alone.

In what follows, we describe the proposed system in detail and use simulation to validate that this approach can reduce "fuel consumption". Specifically, we present a simulator [9] where the emulated agent-vehicle system visualizes the benefits of car-platooning.

II. Vehicle platooning

Let us continue with a detailed description of what platooning is and how it works. A vehicle platoon can be defined as a group of vehicles (trucks and/or cars) that travel together in a coordinated formation. Vehicles form a "road train" where they follow the leader in very short distances between each other. The specific distance between vehicles varies depending on the reported experiment, usually, it ranges between 5 and 15 meters [10].

For instance, the Safe Road Trains for the Environment (SARTRE, [10], [11]), is a European Commission-funded project to investigate technologies and strategies, then test them for safe platooning of road vehicles. It aims at examining the operation of platoons on real-world main roads with full interaction with other vehicles. The SARTRE definition of platooning assumes that the platoon is led by a vehicle that is driven by a qualified driver. This driver is required to undergo special training for leading such a platoon. For the rest of the group, the vehicles are under automated control. However, it is assumed that each of these vehicles has a driver on board. Note that the platoon can consist of heavy vehicles (trucks or buses) and small vehicles (cars). Either type of automobile can be a leader of the platoon as long as the driver is qualified. For safety reasons, it is assumed that a small vehicle cannot travel between trucks and/or buses. Here, it can be presumed that soon the leader will be able to be autonomously driven. However, it will still require a human driver on board and platooning would be initially limited to motorways (long-distance roads). Nevertheless, a realization of these assumptions is not required for the presentation that follows.

Vehicle platooning has been widely recognized as a mean to provide environmental and safety benefits. Some of them are: (1) greater fuel economy due to reduced air resistance; (2) reducing abrupt acceleration, deceleration, and stopping of traffic flow; (3) increased road capacity as platooning vehicles operate much closer to each other (since it is the human reaction combined with tiredness that introduce a significant delay between "signal" and action) [12]; and (4) fewer traffic collisions due to use of (semi)autonomous vehicle control systems. Therefore, it is not a surprise that this topic was explored already at the end of the 20$^{\text{th}}$ century, in San Diego, where an eight-vehicle platoon demonstration was conducted [12].

It successfully depicted the technical feasibility of vehicles traveling under automatic control at close distances at main road's speeds. The experiment involved real travel of automated cars and showed that high capacity, automated travel is technically possible. However, this platoon scenario did not integrate all functions that would be essential for a complete automated main road system. Despite its technical success, further investment was moved towards autonomous intelligent vehicles rather than the development of a specialized infrastructure that would support vehicle platooning.

Currently, platooning is systematically explored and tested. However, the attention is directed towards heavy vehicle platooning which has been proven to be a clean, safe and efficient alternative to standard transport system [13]. In this context, it is interesting to notice that in 2016 Netherlands organized a European Truck Platooning Challenge [14], which aimed at bringing truck convoys to public roads. Here, six brands of automated trucks – DAF Trucks, Daimler Trucks, Iveco, MAN Truck & Bus, Scania AB and Volvo Trucks were involved. This challenge was the first cross-border initiative that exploited smart trucks. Its main focus was to test platooning in practice, i.e. to investigate its impact in a real environment, traffic and infrastructure, and consequently to implement a safe platooning system by creating safe interaction between all roads users through secure wireless communication. This successful demonstration has also pointed to the importance of establishing a regulatory framework for digital mobility and supply chain management in digitized road transport. However, some issues are to be addressed in the update of the European traffic regulations. For instance, the 1968 Vienna Convention on Road Traffic defines a minimum inter-truck driving distance as 164, while 72 feet (or less) is needed for truck platooning.

Separately, note that nowadays, "talking" or "gossiping" cars are not a "futuristic concept" but almost a reality. The main limitation stems from the fact that so far, only limited in scope real-world trials have been conducted. Nevertheless, Volvo has made SIM card installation a standard in all new cars [15]. Please note, that creation of a 5G network should enable higher speeds in data transmission, lower latency, and higher bandwidth. Therefore, connecting a larger number of vehicles and establishing complex ecosystems of connected cars will become possible. Furthermore, the continuous development of autonomous vehicles with a vast range of sensors and high computational power should facilitate scenarios where cars could communicate and organize themselves without the intervention of drivers.

In summary, platooning is a realistic approach to road traffic management that has potential and is worth further investigation. Hence, our interest and experiments that came out of it that are presented in what follows.

III. Related work

The idea to create an organized, autonomous transport system was documented in 2017 in a paper entitled "Coordinated Automated Road Transport System" (C-ART; [1]). C-ART is to be an extension of the automated driving concept. This is to be done by adding communication capabilities that connect vehicles with the infrastructure managed by a central coordination unit that steers traffic based on a set of criteria, e.g. fuel consumption, gas emissions, safety, and travel time. Hence, C-ART is founded on connected vehicles classified as level

5 autonomous according to the SAE [16] taxonomy (i.e. Full Automation). This automated road transport management system is presented as an ideal (if not idealistic) solution. Moreover, it defines and provides ground rules for the central coordination unit and defines the scope of its' abilities. Those are not only the capacity to regulate transport network but also the ability to manage its' accessibility and usage. However, the proposed implementation would require a shift from the conventional vehicles where human is responsible for driving while the computer is only a "helping hand" to fully automated cars. Since it will take time before all (at least the majority of) vehicles will be level 5 autonomous, this work remains a very interesting exploration of the future of transport.

The common idea, that is investigated in multiple contributions, is the existence of fast, reliable means of communication between cars with the presence of "central unit". Of course, one can achieve the desired effect by using multiple technologies, such as 5G or Bluetooth. Here, some form of a *CommunicationAgent* represents software that utilizes one of them and is present in each vehicle. It is one of the simplest ways of realizing the needed communication without involving the actual driver.

A research paper from 2016 ([17]) brings an interesting topic of need for formal verification in vehicle platooning. Authors claim that an appropriate representation for columns of vehicles is a multi-agent system where each agent is responsible for the autonomous decisions of each vehicle. Here, the formal verification for vehicle platooning establishes measures which ensure that platoons never violate safety requirements. However, while we decided to follow a multi-agent system representation for vehicle platooning we decided to not bring up the formal issues of this approach. Instead, we focused on developing a simulator that properly utilizes the idea of an agent system in vehicle platooning and investigates its benefits – in our case, the decrease of fuel consumption.

It is crucial to mention that to the best of our knowledge, the majority of academic and industrial work in the field of vehicle platooning is directed towards truck platooning [18]–[20]. In SARTRE Project [10] fuel consumption was measured individually for each test vehicle to compare it with the fuel consumption while in the platoon. The distances between vehicles were: 5, 6, 7, 8, 9, 10, 12, and 15 meters. However, actual fuel consumption measurements are not available for cars in the full platoon system at gap sizes of 7 meters and below – distances which theoretically gave the best results (biggest fuel saving in %) for trucks. An analysis of results showed that the internal safety function in cars triggered a pre-charging of the brakes while driving at very close proximity. This precharging affected the measurements, therefore they could not be included in the final analysis. In our simulations, we have excluded brakes pre-charging and included scenarios where distances between platooning cars start at 5 meters.

Finally, researchers stress the legal aspects of platooning like the need to provide proper certification for drivers or autonomous vehicles [21]. They also emphasize the importance of the formal verification of autonomous decision-making agents that are used within the system. Moreover, they notice that every new feature added to the autonomous platooning should be formally verified and certified.

IV. Tools available for traffic simulations

In our work, we consider vehicles travelling to various destination cities. Therefore, as already established, a multi-agent system is a well-suited approach to handle both common, conflicting interests and resulting interactions. In this context, several agent frameworks may be capable of providing necessary tools to create proposed simulator. However, upon further evaluation, we have realized that all of them are not suitable for our conditions regarding the solution we want to create.

(1) Eclipse Simulation of Urban Mobility (SUMO [22]) is open-source software that is easy to use for the development of urban traffic simulations which can be placed within actual geographical locations. However, what makes it unsuitable for our work is the difficulty to model the behavior, functionality, and logic of individual (independent) vehicles. We want to focus on main roads while SUMO does not offer the "right granularity of modelling tools". Specifically, it is oriented toward the simulation of the city center traffic comprising many types of road users, starting from pedestrians and finishing on trains, which adapt to the behavior of traffic lights.

(2) Cityflow [23] is an open-source traffic simulator. It is claimed to be twenty times faster than SUMO, while supporting large-scale traffic simulations of complex road networks. Cityflow is characterized by a simple interface that provides resources for the creation of Intelligent Transport Systems, without the necessity of paying extra attention to details, such as with SUMO. Like SUMO, Cityflow does not support access to vehicle logic. It allows simulation of the vehicle movement, but interactions between simulated agent-cars are not considered. Hence, it is not possible to "naturally" code a scenario where the cars communicate with each other.

(3) GAMA [24] is an environment dedicated to modelling and simulations. It facilitates spatially explicit agent-related simulations. GAMA can be used for any type of application domain. It provides an intuitive advanced agent-oriented language for easy model writing. It allows executing simulations with millions of agents within actual geographical settings. Finally, GAMA provides features such as a declarative user interface that supports inspections of the agents, action panels controlled by users, as well as 2D and 3D multi-layer displays. While GAMA seems like a very useful tool to prepare for our simulation, we decided we do not need to simulate millions of agents, but we have to understand what is happening when the cars interact with each other. Hence, too many cars on the

screen would introduce “unnecessary chaos”. Therefore, it is unnecessary to use visualization features available in GAMA. GAMA simulations require high computational power while our resources are limited. Therefore, we designed smaller, yet meaningful, simulations. This all being the case, going against the grain, we have developed our customized simulation platform.

V. Developing the simulator

Before we begin the discussion of the key concepts of the developed platform, let us first introduce a guiding scenario. A family of 7 people including a single mother, grandparents, and 4 children is going to travel and to achieve higher comfort of travel, is going to use 2 separate cars. They would love to be as near as possible during the trip to take breaks together (here, we assume they are going for a ”long trip”). Therefore, they set up the connection between the vehicles. The first/leader car will go at a ”fixed-speed” and the other will follow it, creating a small (two-car) platoon. While traveling to the destination, other cars which have similar travel plans can join this platoon and share benefits, among others, as reduced fuel consumption.

This use case scenario can be seen as the starting point in the simulator’s development. Therefore, in this section, let us outline its main assumptions. Our approach required programming the driving behavior of vehicles, setting exact driving parts, accessing starting and destination points, speeds, and additional, optional but essential parameters. Overall, we needed to consider each car-agent separately, though similarly. For instance, we did not base our work on modelling a single platoon with (each time) the same starting and ending points. Instead, the starting and destination points can be selected randomly.

A. Requirements and architecture

Therefore, to create a working model of the proposed system, the following assumptions have been made:

- Agent system will use FIPA-based communication [25].
- Only ”main road” platooning is simulated; long, relatively straight roads are considered rather than complex urban junctions.
- Cities and roads are treated as an undirected graph where nodes represent cities, while edges represent roads.

During the development of the simulator, additional assumptions have been planned. The first was related to building the map model. To make the model clearer, to observe, analyse, and understand, only 7 nodes (with 7 different colors) representing 7 cities were used. However, this number can be easily increased (it is a system parameter). Each vehicle “inherits” the color of its destination city. In that way, it is easy to observe its movement, recognize its target, and check for simulation errors, e.g. if a given car ends its journey in the incorrect city. Furthermore, simulation parameters like speed values, the radius of searching for other vehicles, or the maximal number of vehicles in the platoon are system variables (can be easily modified). This facilitates the ease of running multiple scenarios.

To simplify the simulation engine, a single central agent responsible for exchanging messages between other agents in the system was used. Here, it was also assumed that the “central agent” may become a part of a larger system consisting of multiple agents responsible for “different regions”. During the system design, three types of agents have been proposed:

- *VehicleAgent* – is responsible for “driving the vehicle”, by controlling the speed and the direction of movement. Every vehicle in the simulation is represented by one of such agents.
- *CommunicationAgent* – is responsible for communication with the *CentralAgent* and other *CommunicationAgents* in its proximity. It is working in every vehicle that has the platooning mechanism enabled.
- *CentralAgent* – is responsible for storing information (location, destination, route, platoon information) about all vehicles registered in the system.

The simulator realises the following lifecycle for each vehicle. The vehicle is spawned (with *VehicleAgent* and *CommunicationAgent* “on board”) in the specific or randomly selected city (node) and the path (through other cities) to its destination is calculated using the Dijkstra algorithm. The *CommunicationAgent* in each vehicle connects to its *VehicleAgent* and registers with the *CentralAgent*. *CentralAgent* controls a “global registry” of all spawned agents. In the case of multiple *CentralAgents* controlling the regions in the system, additional information would have to be implemented and a distributed registry would have to be realised. However, this potential development is out of the scope of the current contribution.

To join the platoon, the *CommunicationAgent* (periodically, if needed) asks the *CentralAgent* for columns that are nearby and that travel in the same direction. If there is a free spot in a platoon, a request to join is sent. This request can be rejected or approved by the platoon leader. If eventually, another car joined the platoon earlier and the platoon reached its full capacity, the request is rejected and the car needs to continue its ride alone until another platoon comes into the valid range. Moreover, the acceptance status may depend on the route that the car is going to take. If at least one point of the travelling path is not shared among both the platoon and requesting a car, or if the platoon would have to wait too long for the car to join then there is no sense of approving the request, so it is declined. As our experiments indicate, it is rather rare that a vehicle will not join a platoon during a longer trip since the *CommunicationAgent* repeats continuously the requests to join a platoon. Upon joining the platoon, the *CommunicationAgent* stops searching for one. Upon leaving the platoon (e.g. when only part of the trip has been completed and the platoon moves in a different direction), the *CommunicationAgent* resumes search for a suitable platoon to join. Finally, when two lonely vehicles start communicating with each other, if a platoon is formed, the one that was approached first, becomes the platoon leader.

When moving in a platoon, the *CommunicationAgent* of the leader sends updates about its position to the *CommunicationAgents* of the followers. If a platoon leader is leaving the platoon, e.g. because it goes in a direction that at least the next vehicle is not following or it has reached its destination, it hands over the leadership to the first vehicle behind. Here, platoon rearrangement may happen with multiple platoons moving in different directions forming.

The communication between agents uses asynchronous messaging, except the *CommunicationAgent*–*VehicleAgent* communication which (for simplicity) uses pure functional communication realized via an API within the onboard local computer.

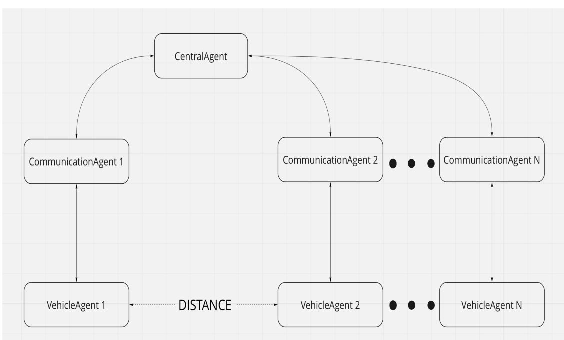

Fig. 1: Basic agent communication schema.

The schema of communications between agents in the system is outlined in Figure 1. For a more complete description one should consult the diagram in GitHub [26].

B. Testing scenarios

Since the existing modelling platforms are not suitable to realize the proposed simulator a minimalist agent-based framework was developed. It was implemented in the C# and combined with Unity engine (for graphics).

To model platooning, recognition of vehicles nearby (e.g. within 10 km range) that drive in the same direction and can create a new platoon had to be implemented. To illustrate vehicle recognition the following "agent story" was created. It starts when a user (driver) of AV_1 (identifying name of the vehicle) wants to drive to Green City. User enters that information, the car system calculates the most suitable route and the *VehicleAgent* starts driving towards the destination. The simulator displays it as a green "dot". Since AV_1 does not belong to a platoon its *CommunicationAgent* asks *CentralAgent* for information about vehicles nearby that are traveling in the same direction. When there are no other *VehicleAgents* in proximity (radius of search in one of the system parameters) the query to the *CentralAgent* will be repeated after some time, e.g 1 min (also a simulator parameter).

Let us now assume that AV_1 passes through a city where AV_2 vehicle starts its voyage. Hence, AV_2 is now in the proximity of AV_1 and also looks for the platoon.AV_2 contacts *CentralAgent* and receives information that AV_1 is a potential "partner". When communication between *CommunicationAgents* is established, vehicles can form a new platoon. Here, the one who sent the proposal becomes a leader. Next, vehicles shorten the distance to each other (one speeds up and another slows down), and complete platoon forming(see, Figure 2).

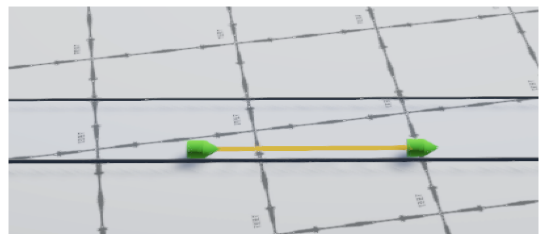
Fig. 2: Two green vehicles form a new platoon.

Let us now consider a vehicle joining an existing platoon. Here, the user of AV_4 wants to drive to the Pink City. Thus, *VehicleAgent* calculates the way and starts driving. Since AV_4 does not belong to a platoon it asks *CentralAgent* for information about nearby vehicles moving in the same direction. It can be seen in Figure 3 that there is already a platoon formed by AV_1, AV_2,and AV_3, where AV_1 is a leader.

The communication between AV_4 *VehicleAgent* and *CommunicationAgent* is established. Then, the *CommunicationAgent* sends a request to the *CommunicationAgent* of AV_1 to join the platoon. After getting the positive response (since the vehicle limit in the platoon, 5 in this case, is not exceeded), AV_4 is catching up to the group and becomes the last member of the platoon. Here, we assume that the response is positive. Otherwise, e.g. when there would be no space in the platoon, AV_4 would continue its journey while seeking a different platoon.

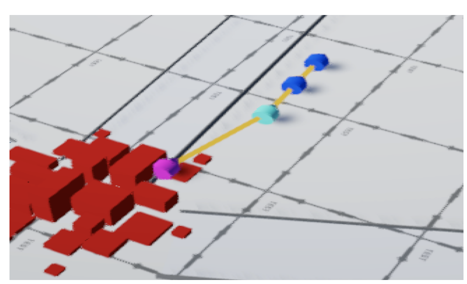
Fig. 3: Last *VehicleAgent* (pink) begin catching up the platoon. At the same time platoon slows down.

In Figure 3 we can observe the moment when AV_4 "attaches itself" to the existing platoon. Here, the platoon leader (the first dark blue vehicle) slows down and as a result all of the members slow down. At the same time AV_4 speeds up to catch up with the platoon. After the joining process is completed all vehicles travel together in a 4 vehicle platoon.

Finally, let us consider the main goal of the simulation, which is fuel consumption measurement. Here, we have found the formula presented in equation 1 that represents relation between speed (x) and fuel consumption ($F_c(x)$).

$$F_c(x) = 0.0019x^2 - 0.2506x + 13.74 \tag{1}$$

This formula was introduced in [27], and is based on empirically collected data. However, in the case of vehicle platooning air drag of each vehicle should also be taken into account. Here, we used the following formula (equation 2) obtained by approximating the results introduced in [28].

$$R_a(d) = 1 - \frac{-\log_{10}(d+1) * 25 + 68}{100} \tag{2}$$

This function "corrects" the fuel consumption model. Note that when the car is not in a platoon then $R_a(d) = 1$.

Together, $F_c(x)$ and $R_a(d)$ are used to model the current fuel consumption. Specifically, for a single vehicle, equation 3 is used. To obtain total fuel consumption results for individual vehicles are added.

$$Consumption(x, d) = F_c(x) * R_a(d) \tag{3}$$

Here, let us note that other function can be used to model fuel consumption. All that is needed is replacing a single module within the simulator while keeping the core logic intact.

VI. Experimental setup

During the development of the platform, we used many scenario variations. Hence, the following naming convention was introduced:

$$ScenarioX.Y$$

where X – denotes version (number), and Y – denotes the simulation type. Hence, "pairs of scenarios" are marked as X.1 and X.2. Specifically, X.1 denotes scenarios where travelling vehicles can form platoons. The X.2 labels those scenarios where vehicles do not create platoons. Since, in the second type of scenario, vehicles drive alone, they do not benefit from decreased aerodynamics drag, which handles decreased fuel consumption. To compare the two scenarios, in X.2 scenario, every car has the same start and the same destination point, as in the X.1 scenario. Therefore, the distance that each vehicle has to travel remains almost the same. The only difference may be related to the maneuvers related to platoon joining. However, effects of this is negligible in relation to the total length of travel. Therefore, we can take a pair of matching scenarios and compare fuel consumption in both cases. In fact, our system allows also to compare influence of additional parameters. Specifically, distance (or gap) between vehicles is denoted as d while the maximum number of vehicles in a platoon is marked as n. Finally, the total number of vehicles in the simulation will also be considered.

For first test, we use two columns of 5 vehicles each that start at the same city and finish their journey at the same destination. This experiment can be seen as a "smoke test" of general parameters' setup and of the simulator. In this test we obtained fuel consumption reduction of 32%.

In the second experiment of both scenarios, i.e. Scenario 2.1 and 2.2, a more complex setup is used. It was designed in a way to further check the fuel consumption change and its dependency on platooning. These scenarios allowed us also to determine the direction of our research. Here, 7 different vehicles were spawned, each controlled by a *VehicleAgent* and having a *CommunicationAgent* responsible for communication between vehicles and with the *CentralAgent*. To effectively simulate the platooning behavior we have intentionally selected starting points such that the vehicles can form a platoon "as fast as possible". Therefore, the first 3 vehicles started at the same city (Node 1) formed a platoon and travelled to the same destination (Node 7). Recall that, during the simulation it was clearly visible to which city an agent travels because of the same color of the car and the destination city. The next 3 agents begin their journey in another location (Node 3). Again, they form a platoon and move to the last "common point" (Node 4). Two of them have their final destination point at Node 5, while the last car of this platoon has to travel to Node 7. Lastly, we have one vehicle starting from Node 2 and moving towards Node 1 where it encounters a platoon it asks to join. Upon joining it, finally, arriving at Node 4. When the specific car reaches its destination it simply leaves the platoon and "disappears". Obviously, one could consider this scenario as a deliberately contrived one. Nevertheless, we can report 22% fuel consumption decrease for the vehicles travelling in platoons.

Being certain that the system works as intended (we have run more tests than the two simple pilots reported above) we start the most important test. Here, starting and finishing cities are chosen at random for every vehicle. This randomization process starts at when the user presses the "Start" button for the Scenario 3.1. Then, start and destination nodes for each vehicle are drawn, stored in a file. They will be read in Scenario 3.2. Therefore, the platooning Scenario 3.1 starts first and the non-platooning Scenario 3.2 starts second.

In order to run various scenarios we created a Control Panel, presented in Figure 4. For first two scenarios it is enough to click *Start* of the desired simulation. After starting the scenario, every button is blocked. Hence, to chose another one one has to click the *Reset* button. For last scenario, it is possible to set custom parameter values by selecting appropriate text-boxes and filling the values.

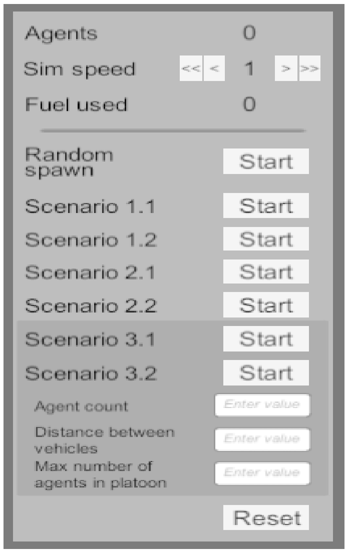

Fig. 4: Control Panel for conducting simulations.

Note that there are three text-boxes with the following labels: *Agent count*, *Distance between vehicles* and *Max. number of agents in platoon*. Their meaning has been explained above. After the values are stated, the scenario is ready to be tested.

VII. Experimental results

Results are calculated from multiple runs of previously described scenarios. As mentioned, initial tests (Scenario 1.Y and Scenario 2.Y) were consistent with our expectation. They illustrate that the decrease of fuel consumption is decreasing for more random environment/system/simulation. Hence, for Scenarios 3.1 and 3.2, we have varied the maximum number of agents in column – using values 3, 6 or 9. For the gap between vehicles we used 5, 10, and 15 (meters). While we have experimented with various total numbers of vehicles, we report results for the two extreme cases. The small simulation with 20 vehicles and the large one with 100 vehicles. Each reported result is an average of at least 5 runs. The results are presented in Figure 5 and in Figure 6, respectively, in the form of 3D plots.

In Figure 5, presenting results of simulation with 20 vehicles we do not see any special patterns for the resulting surface. However, it can be observed that the smallest fuel consumption drop occurs for distance between vehicles equal to 10 and number of vehicles in the platoon equal to 9. The fuel consumption reduction is of order of 8%. Taking into account that there were only 20 vehicles, using maximum platoon length of 9 means that all vehicles that wanted to join the platoon, could do it. This means that, in this case, the number of vehicles in the platoon is not very influential.

However, note that for small gap between vehicles (equal to 5) all numbers of agents in the platoon result in high fuel consumption reduction of approximately 14% to 16.5%. These are the top three best results for 20

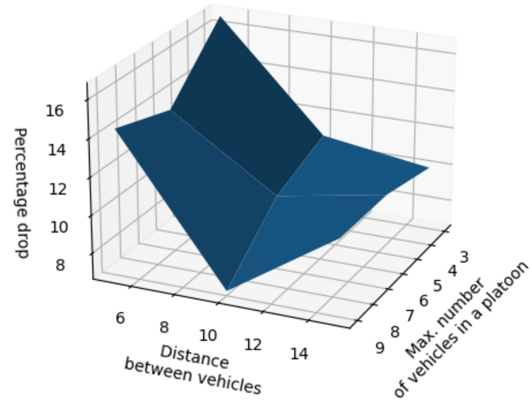

Fig. 5: Results for 20 agents in simulation.

agent simulation. Here one can see that the logarithm part of equation 1, suggests such behaviour for ”gap values”. Obviously, results presented here are based on a specific fuel consumption model. Change of this model could result in different results of the simulation.

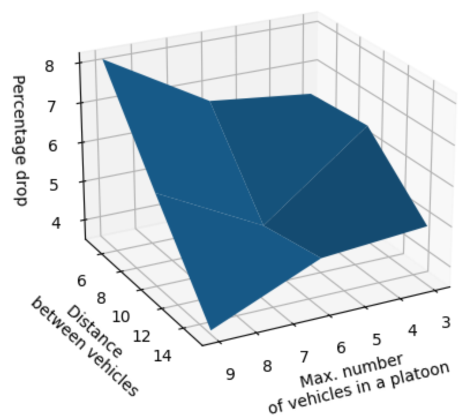

Fig. 6: Results for 100 agents in simulation.

In comparison to Figure 5, we observe a significant change of the fuel consumption reduction for 100 agents. In Figure 6 it can be observed that this parameter varies from 4% to 8%. This is equal to a half of the value range observed for 20 agents.

Similarly to the simulation with 20 vehicles we can observe that percentage drop is the highest for distance equal to 5. Moreover, there exists an interesting pattern that did not present itself in Figure 5. On the one hand, for the gap value equal to 15 we have decrease of efficiency of platooning with increase of the maximum number of vehicles in a platoon. On the other hand, note that a completely opposite correlation occurs for the minimum distance equal to 5. Here increasing the platoon length is beneficial. We observe also a strange transition in the middle part. It can be observed as the “central depression” of the surface.

Obviously, presented results are very preliminary. They are restricted by the number of vehicles, number of cities, and strongly influenced by the fuel consumption function that was used. Nevertheless, they support the initial claim that platooning based on software agent founded interactions is worthy further investigation as a mechanism to reduce fuel consumption in long-distance travel.

VIII. Concluding remarks

Road systems are an international network, with cities recognized as nodes connected by motorways that behave as edges. Hence, recent advances in the automotive industry bring opportunities to refine long-distance transport. Moreover, current progress in vehicle manufacturing gives a chance to introduce car platoons as a mechanism to optimize long-distance travel. One should take note that (1) it can be already today, (2) vehicles can run on petrol or be electric, and (3) level 5 autonomy is unnecessary. In this context, we have applied concepts from the area of agent systems research, to propose an agent-based platooning system.

To establish the potential viability of the proposed approach, we have developed a simulator (available at [9]) and run a preliminary set of experiments. The results we obtained experimentally support our initial assumptions. Depending on the scenario setup, for a large number of vehicles, reduction of fuel consumption of approximately 4-8% was observed.

The developed simulator is limited in scope. However, the results reported above suggest that it may be worthy to either extend its capabilities, or develop a new one. The decision should take into account our analysis of capabilities and limitations of existing agent tools. For instance, since being able to develop logic for each individual vehicle, it may be worthy considering use of generic agent tools. However, this will require combining them with mapping software, which brings ts own set of open issues.

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