Heavy-Duty Vehicle Platooning: Efficiency, Communication, and Simulation Challenges

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CSC 53445 EP - IoT Project & Workshops

March 2025

Contents

1 Introduction

The transportation industry, especially the heavy-duty vehicle portion struggles to keep energy efficiency low and be environment friendly. The companies involved in this business sector need to find ways to reduce CO_2 emissions as new regulations are set in place. These regulations are pushing companies to find innovative solutions to conform to the new by-laws [3]. One of the innovative solutions that reduce emissions without any groundbreaking invasive measures is considered to be truck platooning; by letting the drivers drive close by behind each other like trains to reduce aerodynamic drag coefficients.

1.1 Truck Platooning

When trucks travel in a tight formation, similar to a train, they benefit from aerodynamic performance, and this concept is called platooning. These are the following steps on how platooning takes effect:

1. Airflow is disrupted by the lead truck (1st truck).
2. Following trucks (2nd - nth truck/s) create a train-like formation.
3. When this formation is kept they create a slipstream effect, allowing lead truck and the 2nd - nth truck/s to benefit from reduced air resistance.

In effect, keeping this in practice helped trucks to consume less fuel, due to lower demand of power from the engine. Different research has shown that when the truckers were able to keep this in practice, it resulted in 5% to 10% of fuel-saving measures [4, 12, 22]. Reducing fuel consumption is directly correlated with lower CO_2 emissions, which results in less pollutants released in the air. Moreover, there are a lot of benefits in truck platooning than just fuel savings. They offer indirect benefits to the community with less traffic, due to the trucks taking smaller spaces on the road [5]. There is a potential for automation where the driver may benefit from self-driving features on the highway leading to less stressed drivers and increased safety [8]. It is important to note that, as new regulations are in place. Operators with a fleet of trucks who can reduce greenhouse gas emissions are able to get incentives.

Currently, there are some limitations in the area of truck platooning. There are extensive researches done regarding this topic, but they were all studied under short-term experimentation or in a simulation which were conducted under controlled environments. There are still gaps in this research that need to be followed up.

1.2 Vehicle-to-Everything (V2X)

V2X communication system is crucial for truck platooning to work. It is a reliable truck communication medium with low-latency. There are different technologies that the trucks could use such as: Dedicated Short-Range Communications (DSRC), and Cellular-V2X (including LTE-V2X and 5G NR). This allows the implementation of truck platooning safely, this intervention will help reduce human error and ensure safety on the road [20, 16]. However, this is still a relatively new concept and still needs extensive research.

1.3 Research Objectives

This study aims to:

- Review and synthesize the concepts of heavy-duty vehicle platooning.
- Explore on benefits of aerodynamic drag reduction quantitatively.
- Examine the use of V2X in truck platooning
- Discuss current challenges and gaps on truck platooning implementations.

This research will help evaluate if this concept is feasible with our current technologies and emerging markets.

2 Effectiveness of Platooning

Truck platooning helps reduce fuel consumption, which as a result minimizes emissions and aerodynamic drag. The lead truck will disrupt the airflow, which then creates a slipstream that lowers air resistance for the following trucks. Studies show that even small drag reductions can significantly decrease the engine load, which in result reduces fuel usage and emissions [13].

2.1 Aerodynamic Drag Reduction

Aerodynamic drag is a major reason that affects the fuel efficiency of a vehicle, especially at highways when speeds are high. Close inter-vehicle distances, which is known as a gap, reduce drag for following trucks, which leads to fuel savings of 5%–10% per truck in typical road conditions. With optimal spacing or gap, and if the trucks remain at steady speeds, then fuel savings increase further [13].

2.2 Empirical and Simulation Findings

Controlled experiments has shown that two-truck platoons with 10m gaps were able to achieve approximately 8% fuel savings. Moreover, being able to reduce the spacing to 3–4m has shown an increase in efficiency. Three-truck platoons was able to yield up to approximately 18% on fuel savings for the lead truck, and approximately 23%–24% for the following trucks [11, 22].

Table 1 summarizes fuel savings from key platooning studies, including Bonnet (2000), Browand (2004), Lammert (2014), and Zhang (2020).

Table 1: Summary of Reported Fuel Savings in Platooning Studies

Study	Configuration	Fuel Savings (%)	Conditions
Bonnet (2000)	Two-Truck	5–10	Controlled track tests
Browand (2004)	Multi-Truck	8–12	Experimental fleet trials
Lammert (2014)	Three-Truck	18 (lead), 23–24 (followers)	Combined simulation and field tests
Zhang (2020)	Review	5–10 (typical)	Synthesis of multiple studies

2.3 Benefits Beyond Fuel Consumption

Platooning was able to reduces CO_2 emissions in direct proportion to fuel savings of the vehicle, and aided compliance with environmental regulations set by the lawmakers. It is to be noted that lower fuel consumption also decreases NO_x and particulate matter, which results in improving air quality along transport routes [4].

Platooning increases road capacity by reducing vehicle gaps, since it does not take up the usual spaces it yields into easement of congestion, and shortened travel times. Automating this process was able to minimize driver fatigue by reducing manual labor, and improving safety and efficiency [19].

2.4 Data Gaps and Future Research

Most studies focused on short-term or predefined conditions (such as simulations) instead of real-world experimentation, and these testing environments overlook real-world variability from terrain, weather, and truck configurations. Long-term field studies are needed to validate its research findings on platooning, which has a lot of different benefits if the long-term study yields similar results to older studies [18, 7].

Although platooning reduces fuel costs, the different complex logistical challenges such as: scheduling, detours, and maintenance may affect the economic viability of its use case. A comprehensive cost-benefit analysis is needed to validate this idea for real-world adoption [22].

Zhang et al. (2020) highlight key research gaps, which include platooning rate optimization and the impact of road grade and curvature on fuel savings. However, further data gathering and analysis is required on tire wear, brake performance, and maintenance costs to assess the long-term feasibility of platooning[22].

3 Communication Technologies for Platooning

For the safe and efficient operation of heavy-duty vehicle platoons, it needs to have reliable and low-latency communication. It is very important for vehicles to exchange information in real-time to coordinate acceleration and braking in a platoon. This section provides an overview of the key communication technologies—DSRC/ITS-G5 and Cellular V2X (LTE-V2X and 5G NR), (1)compares their performance characteristics, (2)discusses the stringent latency and reliability requirements for platooning, (3)outlines the necessary security measures, and (4)identifies current gaps in research.

3.1 Communication Technologies

Dedicated Short-Range Communications (DSRC), and it is known as ITS-G5 in Europe. DSRC is considered to be an established technology for vehicle-to-vehicle (V2V) communication. Vehicles is able to detect and send messages to each other without relying on a central infrastructure in place, and they operate through a 5.9 GHz band by using a decentralized ad hoc network architecture. Therefore, any vehicle can autonomously join or leave the network depending on its use cases, and this happens instantly.

The advantage of using DSRC is its use of very low one-hop latency, which is around in the 2-3 ms range [20]. Moreover, "one-hop" means that it is a direct single-link transmission without intermediate relays between two nodes. For example a communication between one truck to another. Vehicles must exchange information (such as: breaking signals and speed) in real-time with minimal latency, due to its safety concerns.

A promising alternative that uses cellular infrastructure and direct peer-to-peer (P2P) communication is Cellular V2X (C-V2X). LTE-V2X supports direct communication (similar to DSRC's ad hoc transmissions), and assisted modes; where base stations enhance reliability and range. Moreover, the 5G NR V2X enables ultra-reliable, and low-latency communication; achieving 1 ms latency under optimal conditions, whilst supporting vehicle coordination and autonomous driving [20, 16].

Table 2 compares DSRC, LTE-V2X, and 5G NR on frequency, latency, throughput, infrastructure dependency, range, and deployment status.

Table 2: Comparison of Communication Technologies for Platooning

Characteristic	DSRC (ITS-G5)	LTE-V2X	5G NR V2X
Frequency Band	5.9 GHz	5.9 GHz	5.9 GHz
Latency	2–3 ms (one-hop)	down to 1 ms	down to 1 ms
Throughput	Moderate	Moderate	High
Dependency on Infrastructure	No	Yes (for V2N)	Yes (for V2N)
Range	300–1000 m	300–1000 m	300–1000 m
Deployment Status	Mature, field-tested	Commercial trials ongoing	Emerging, pilot projects

Dey (2016) research found out that a hybrid DSRC-LTE network has improved platoon communication in terms of reliability. As of writing this paper, there has been a 5G-AA and 5G-PPP report that explains how 5G NR V2X enables high-speed platooning with ultra-low latency and high throughput, although it is important to note that it is still in pilot testing [1, 2].

Projects like KONVOI and ENSEMBLE were able to test ITS-G5 systems in different multi-brand platooning scenarios. These projects have demonstrated the importance of standardizing protocols to ensure interoperability between other systems.

Even though there were heightened interests regarding this topic, most studies have occurred mainly in controlled settings, with few large-scale real-world tests [23, 9].

3.2 Latency and Reliability Requirements

It is important to maintain low latency and high reliability as this is a crucial concern for platooning, as different studies have shown that DSRC and Cellular-V2X were able to achieve one-hop latencies in a few milliseconds under ideal conditions [16]. However, it is very crucial for the truck to have an allowable gap of distance, because it imposes strict timing constraints. For instance, a vehicle traveling at the speed of 100 km/h (approximately 27.78 m/s) will be able to cover a 5 m gap in:

$$T = \frac{d}{v} = \frac{5 \text{ m}}{27.78 \text{ m/s}} \approx 0.18 \text{ s} \tag{1}$$

which the calculation shows that 5 m gap results in approximately 180 ms; which explains that delays beyond this time might cause an accident [6].

Furthermore, it is important to note that in-vehicle signal processing and actuation may introduce new delays. Sensor fusion and control logic always precede the action of braking or throttle adjustments. Different studies have reported that onboard computing adds 10–50 ms per side, especially when the user is driving in a complex conditions [22, 21]. As a result, low network latency may not guarantee close-following maneuvers when transmission and processing delays happen parallelly.

While the importance of latency was mentioned above, the packet delivery ratio plays a critical role in latency. In order to maintain platoon coordination, it is crucial for safety-critical messages to require ¿99% reliability. Although when DSRC and Cellular-V2X meet these requirements, that does not guarantee a stable performance as this varies with network load and interference in the environment. In order for this technology to be implemented, there should be an extensive real-world evaluation to ensure its consistent communication even with high traffic and congestion [16].

3.3 Security Considerations

Due to its high risk, it is of utmost importance that platoon communication security is vital for road safety. With the current implementation, V2X security uses Public Key Infrastructure (PKI) with digital signatures and ECC certificates for authentication, which enables them to communicate with each other safely [21]. These mechanisms prevent attackers from doing malicious actions such as: spoofing, replay attacks, and jamming. However, implementing these security measures introduces new problems in processing overhead, which can impact latency in the long run. Currently, balancing security and low latency needs to be explored as it imposes serious implications if it is not done properly, as this requires platoon-specific cybersecurity strategies [21].

3.4 Missing Pieces and Future Research Directions

There were different technologies mentioned in this paper that shows promising results for V2X. However, despite its progress, there are still technological gaps that needs to be filled out in understanding V2X communication performance for platooning. In order for this to be implemented, there has to be real-world studies comparing DSRC and C-V2X in high-speed, and multi-truck platoons scenarios. It is important that these ideas are well tested and experimented to validate its performance under different conditions [20, 16, 6].

Moreover, there are still room for improvements in the cybersecurity aspects of platooning, as this is still an emerging field. There have to be rigorous simulations and testings done in addressing platoon-specific attacks and network resilience against cyber-attacks as it is a crucial point where the technology may be adapted for widespread use or not. Future research should focus on threat modeling and developing countermeasures for coordinated vehicle convoys [21].

4 Regulatory and Safety Aspects

Locally (France) and internationally, truck platooning currently faces significant regulatory challenges. To be specific, France's Highway Code (Code de la Route), which can be observed under Article R412-12. It mandates that a minimum of 50-meter or 2-second gap between heavy vehicles must be observed, which directly conflicts with the platooning idea of needing a short gap between heavy vehicles [17]. However, in recent years there were pilot initiatives, such as France's 2018 autonomous vehicle experimentation law. There are few exceptions that can be made (with proper approval) for testing platooning through controlled testing.

EU regulations reflect similar caution regarding the gap between drivers and autonomous driving. It was specified in the Vienna Convention (1968) that historically required drivers to maintain vehicle control, but a 2016 amendment allowed automated systems to take control of the vehicle. However, it is important to note that there is no comprehensive EU law that explicitly states authorizing platooning commercially. There were some initiatives made by the European Truck Platooning Challenge and ENSEMBLE, which actively seek for harmonized standards and regulatory framework changes across member states.

The reason for this strictness is due to its safety concerns. If platooning systems were to be practiced in the real world, they would be subject to stringent evaluations, including the ISO 26262 functional safety standards. Although platooning builds upon existing technologically advanced systems, it faces several challenges, such as the current driver labor regulations, which mandate regular breaks and prohibit the usage of extended semi-automated driving periods.

Regulatory differences within the EU countries may complicate cross-border platooning, as different laws are in place for each of the countries. While France remains conservative regarding the idea of autonomous driving and platooning, it is notable that countries like the Netherlands and Germany have proactively conducted successful trials, and highlighted the need for EU-wide implementation for wider use cases [10, 17].

Even with the advancement of technology, if the current laws and regulations will block from the adaption from happening, then the research and investment that went into developing such ideas would be useless. It is important that the policymakers should adapt to these everchanging technological advancements and update the laws and regulations, which will allow for faster adaptations.

5 Simulation

5.1 SUMO for Platooning Scenarios

Traffic simulators allow to evaluate traffic strategies, and one of the leading platforms in this field is SUMO - Simulation of Urban Mobility. This simulator was developed in order to model trajectories of individual vehicle. Configuring the car-follow parameters, engineers can model minimal inter-vehicle gaps required for platooning.

Emission and Fuel Consumption Modeling Fuel consumption simulation is one of the option, which can be added to the core SUMO. There are several models supported for the fuel consumption simulation, and the most advanced over them is HBEFA 4.2, it permits to evaluate emissions based on the physical parameters of the vehicle [15]. Even though the model takes into account air drag, it ignores the the platooning effect, which can cause significant fuel consumption reduction.

Limitations and Adaptations for Platooning One of the research efforts to modify the HBEFA model in order to take into account the platooning fuel reduction effect. Despite the investigations and justifications in the presented work, large-scale tests remain necessary. Therefore, the simulator does not support dynamical adjustment of the ar resistance based on the vehicle ahead.

5.2 Future Directions

Model validation is required to implement the built-in solution to the simulator. Studies show, that it is possible to achieve up to 15% lower CO_2 emission reduction having three trucks platooning. However available test results does not fully correlate with the wind-tunnel experiments.Future researches should focus on the enhancement of the SUMO model followed by comprehensive large-scale tests on the road [15, 7].

5.3 Simulation Configurations

Tight-Platooning Setup I concentrated on promoting the formation of close-following platoons in this first configuration. In particular:

- `minGap`=1 m and `desiredMinGap`=3 m,
- `caccDesiredGap`=3.0 m and `caccHeadwayTime`=0.1 s,
- `speedFactor="normc(0.9,0.1,0.50,1.20)"`,
- `vehsPerHour`=360.

All the vehicles following heavy-duty trailers model (i.e. `vClass="trailer"`) with a maximum speed of 20 m/s, acceleration of 0.7 m/s^2, and deceleration of 1.0 m/s^2. Deliberately enlarged flow rate allows to emerge the stable platoon even on a short simulation track, as tight spacing facilitates joining the previous trailer's air resistance tail.

Realistic Traffic Setup The second configuration represents a heterogeneous flow with extended gap between vehicles. In particular:

- `minGap`=30 m and `desiredMinGap`=50 m,
- `caccDesiredGap`=50.0 m and `caccHeadwayTime`=2 s,
- `speedFactor="normc(0.9,0.1,0.50,1.20)"`,
- `vehsPerHour`=360.

5.4 Simulation

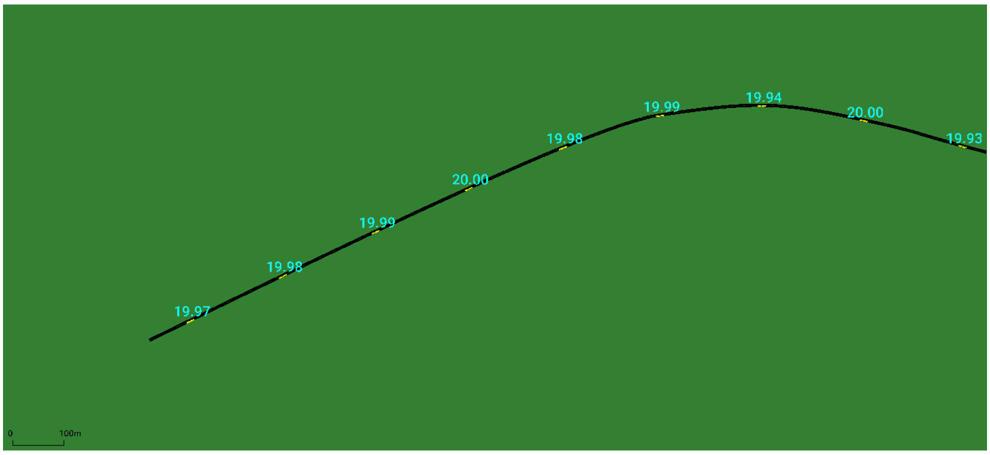

Figure 1: Screenshot from the tight-platooning scenario. Vehicles leaving the start point with `vehsPerHour=360`.

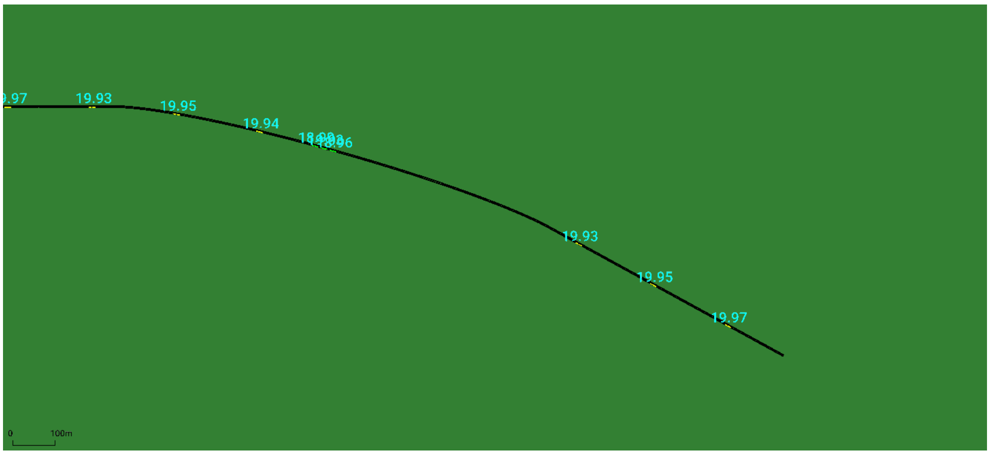

Figure 2: Screenshot from the tight-platooning scenario. Vehicles arriving close to the simulation's exit, The first platoon is created.

Figures 1 and 2 present the way trucks departure and the formation they may establish at the end of the simulation track.

5.5 Gap Distribution Analysis

In order to conduct the analysis, the gap between pairs of two following each other trucks was measured and recorded. Then records were divided in to two groups based on the covered distance. The first half represents all the records, which were measured in the first half of the track, second half refers to the second part of the track respectively.

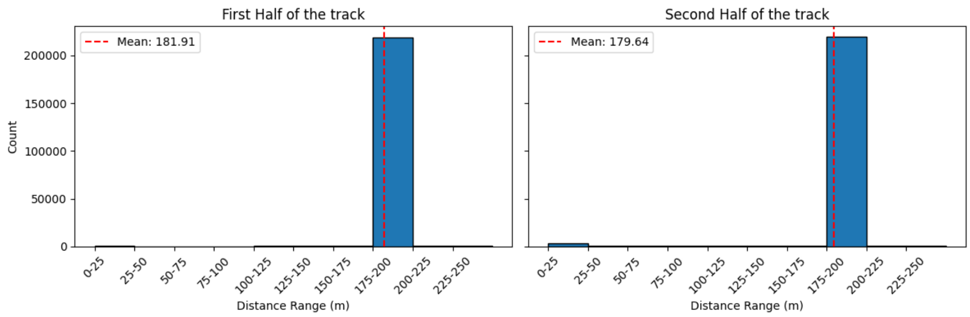

Figure 3: Gap distributions for the platooning scenario. Wide-range view (0-250 m, step 25 m) of the distribution shows a relatively mean of 181.91 m at the departure point and 179.64 m at the arrival point.

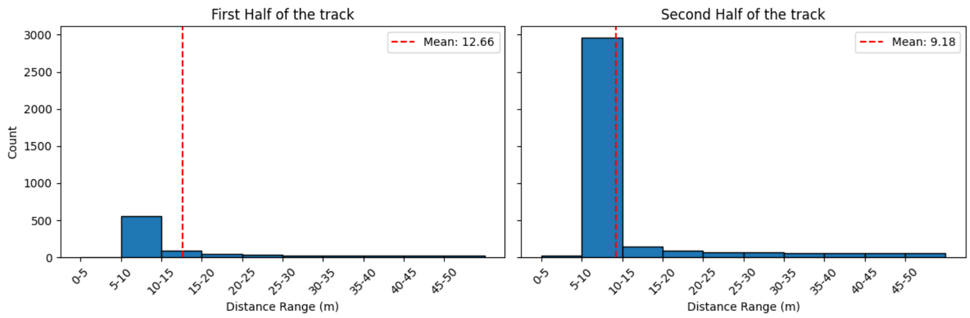

Figure 4: Closer look on the gap distributions for the platooning scenario with a narrow-range view (0-50 m, step 5 m).

Figures 3 and 4 show distributions for tight platooning on the two half of the track. While the mean gap only reduced on 1.3 %, the dynamic of gap distribution indicate correct simulator operation - especially seen on the Figure 4.

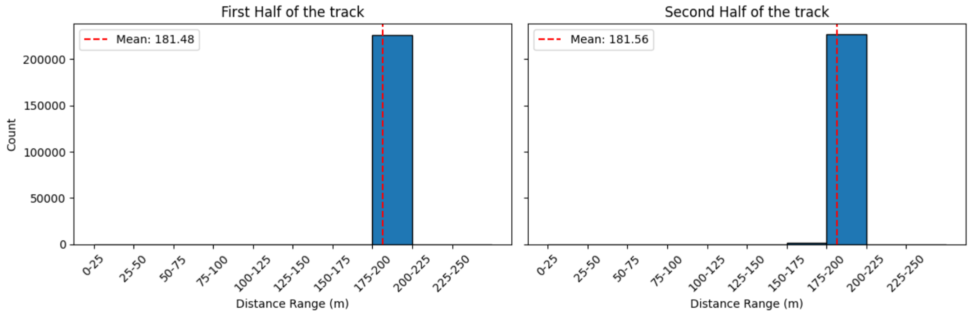

Figure 5: Gap distributions for the Realistic traffic scenario. No significant changes are observed

The realistic scenario's gap distribution results presented on the Figure 5 indicate close to zero mean gap change over the two halfs. Cautious drivers' parameters, which were set up cause the trucks to move steadily.

5.6 Discussion of Findings

Observed difference between Platooning and Realistic Traffic scenarios indicate the impact of the model's parameters (e.g. `caccDesiredGap`, `tau`) on the gap between vehicles. Low values of the minimal gap and reaction speed allow to create truck strings with 5-10 meters gaps.

These simulations demonstrate how small variations of the `speedFactor` can lead to spontaneous creation of the platoons as faster vehicles are catching up the vehicle ahead, but the speed difference between these two vehicles is not high enough for the safe overtake. This results align with the personal observations of the author and the studies on the topic [12, 22].

The limitation of the work, observed during the results revision, is the shortness of the simulation track, what cause limited number of the platoons observed. In real traffic trucks need longer distances in order to catch up with the leading vehicle. Extending the simulation track would increase platoon formation.

5.7 Summary of Simulation Insights

Special requirements and in case of the simulation - tight settings are needed to let the trucks create platoon formation. The flow of 360 vehicles per hour was empirically chosen as a convenient to simulate both - Platooning and Realistic Traffic scenarios.

Under certain conditions the gap between vehicles may fall bellow 10 m, representing the platoon formation. These findings correlate with the previous researches where parameters like speed uniformity, and flow rate were mentioned as crucial for the platoon formation. Realistic traffic, on the other hand, with a variety of vehicle types and driver behaviors, limits the possibility of prolonged close following [12, 22].

In conclusion, SUMO permits to simulate organised traffic with consistent gaps between vehicles, and on the length of the simulation track transform this formation into the traffic with platoons.

6 Conclusion

Air drag reduction caused by the platooning can cause 5–10% fuel consumption and CO_2 emission decrease for the heavy-duty vehicles [3, 4, 12, 22]. This efficiency also correlate with cost savings for the fleet operators.

Nonetheless, there are challenges ahead to solve. Vehicle platooning is impossible without reliable low-latency communication, existing technologies like DSRC and LTE/5G-V2X are promising, but still need more real-world evaluations to validate their performance in road traffic conditions [20, 16]. Conservative regulatory approach as shown in France's "Code of La Route" does not allow platooning idea to be developed as fast as it could be [17].

Simulation using SUMO enables continuous and infinite experiments, yet its fuel consumption model does not take into account the platooning effect's drug reduction [7, 14]. This gap requires improved modelling techniques and long-term field experiments.

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