Merging Truck Platooning on Highways Senario Team-B

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Contents

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Abstract: Truck platooning allows freight vehicles to drive closely together in coordinated groups, improving fuel efficiency and road capacity. One of the most challenging maneuvers is *merging*, especially when a new truck or platoon joins an existing one on a highway. This paper presents the main requirements, communication signals, control strategies, and timing considerations needed for safe and efficient merging. A scenario-based model is proposed, designed for formal verificationwhich we perform using UPPAAL and Timed Automata to model timing behavior and safety constraints.

1 Motivation

Modern transportation is increasingly using cooperative driving technologies to improve fuel efficiency, traffic flow, and safety. One such technology is truck platooning, where trucks travel closely together with coordinated control. While this offers clear benefits, real-world use must handle complex scenarios like merging, splitting, and lane changes. Merging, in particular, is challenging and requires precise coordination between vehicles. Fully automated merging pushes the limits of current algorithms and demands strict safety measures [As23]. This highlights the need for clear merging protocols and system-level models to test and validate merging under different conditions [Zh21]..

2 Scenario Description

In the highway merging context, a truck (or another platoon) approaching via an on-ramp must join an already-formed platoon on the main lane. This operation necessitates the creation of a safe gap within the platoon and the coordination of both lateral and longitudinal dynamics between multiple vehicles [As23].

Maintaining safe and efficient gaps is central to platooning. The inter-vehicular distance should scale with speed and system dynamics. A suggested gap time of 0.8–1.2 seconds allows for aerodynamic benefits while preserving safety [KCS23]. During merging, this gap must be temporarily widened and then re-stabilized post-merge.

A structured protocol is required to manage the interaction. A typical approach involves three stages:

1. **Negotiation Phase** – The merging vehicle requests a slot; the platoon assesses feasibility.
2. **Coordination Phase** – The platoon adjusts to open the gap; merge point and time are agreed.
3. **Execution Phase** – The merging vehicle aligns and enters the gap with coordinated acceleration.

3 Requirements for Merging Platoons

3.1 Communication

Effective merging depends on real-time sharing of key data among all involved vehicles. This includes current speed, acceleration, planned trajectory, and merge intent [As23, Zh21]. The communication system must have low latency and high reliability to prevent collisions due to outdated or lost messages.

3.2 Control Cooperation

Vehicles in the platoon must be capable of decentralized decision-making based on shared data, allowing for dynamic adjustment to support the merging operation [ZZ19]. Specifically, the leading or following truck may need to accelerate or decelerate to open a sufficient gap for the merging vehicle.

3.3 Safety Constraints

Safety is paramount. Inter-vehicular distances must always satisfy predefined constraints to prevent rear-end collisions. Emergency braking and fallback strategies must be in place in the event of communication failures or sensor malfunctions [Zh21].

4 Timing Behavior

The merging maneuver must occur within a tight temporal window to avoid disrupting traffic flow or endangering vehicles. Timing constraints include the window during which the merging vehicle is aligned with the platoon, the delay in data transmission, and the response time of the control system [ERES22]. The entire interaction must be bounded within real-time deadlines to preserve the safety margin of all vehicles.

5 Modeling of Merging Scenarios using SysML/UML

In this scenario, we use SysML and UML diagrams to model a truck platoon merging, focusing on system structure, behavior, and interactions. Key diagrams include the Activity Diagram (merging workflow), Block Definition Diagram (system components), and Requirements Diagram (safety and functional needs). Sequence and State Machine Diagrams model vehicle interactions during the merge. The paper also incorporates Timed Automata and uses UPPAAL for formal verification of safety, timing, and synchronization conditions.

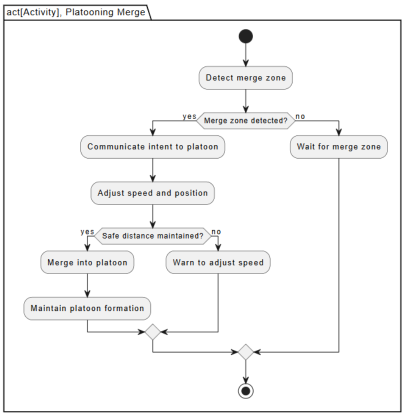

Fig. 1: Activity Diagram

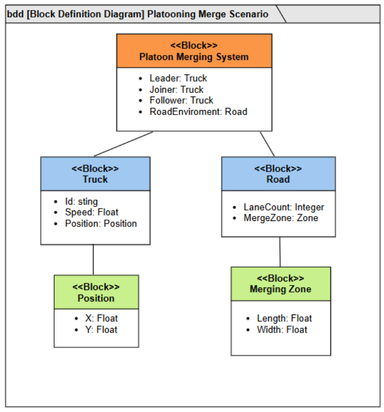

Fig. 2: Block Definition Diagram

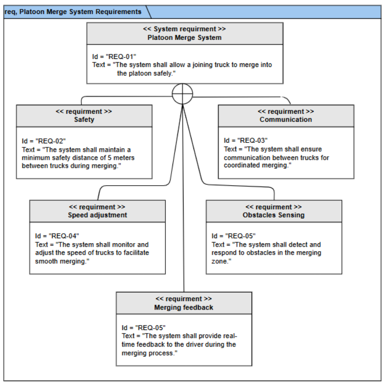

Fig. 3: Requirements Diagram

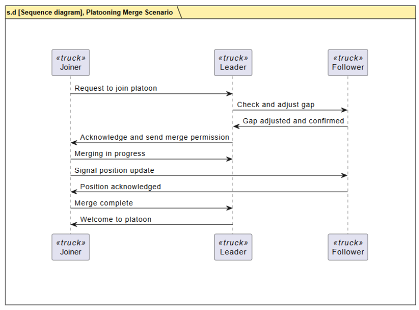

Fig. 4: Sequence Diagram

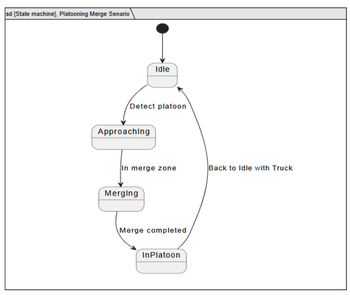

Fig. 5: State Machine Diagram

6 Formal Modeling with UPPAAL

To ensure correctness under timing constraints, we use **Timed Automata** as our formal modeling framework. The truck platooning scenario is specified as a network of automata where states represent vehicle behaviors (e.g., cruising, preparing to merge, merging), and transitions are triggered by timed events or message exchanges.

We implement the model in **UPPAAL**, a model-checking tool designed for real-time systems. The model verifies properties such as:

- Safety: Ensuring no collisions during the merge.
- Liveness: Ensuring a truck can eventually complete the merge.
- Timing: Ensuring the merging occurs within allowed time windows.

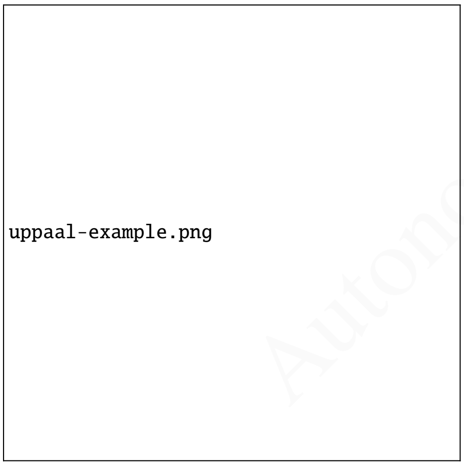

Fig. 6: Timed Automaton Model for Merging Truck in UPPAAL

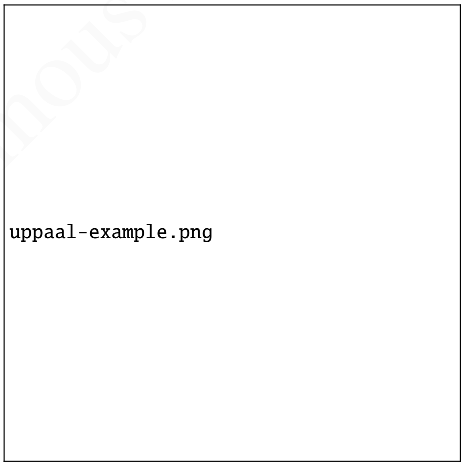

Fig. 7: Another View of Timed Automaton

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7 Conclusion

Merging in truck platooning presents significant challenges requiring coordinated control, real-time communication, and strict adherence to timing constraints. A formal model, such as a network of timed automata, can be used to verify the correctness of merging protocols under worst-case scenarios using tools like UPPAAL. Future work should focus on integrating sensor redundancy and infrastructure assistance to further enhance safety and scalability.

8 Abbreviations

Abbreviation	Description
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
CACC	Cooperative Adaptive Cruise Control
HMI	Human-Machine Interface
CV	Connected Vehicle
DSRC	Dedicated Short Range Communication
GPS	Global Positioning System
UDP	User Datagram Protocol
ITS	Intelligent Transportation Systems
UML	Unified Modeling Language
SysML	Systems Modeling Language
TA	Timed Automata

Tab. 1: List of abbreviations used in this study.

9 Declaration of Originality

I am Mohamed Abdo, herewith declare that I have composed the present paper and work by myself and without the use of any other than the cited sources and aids. Sentences or parts of sentences quoted literally are marked as such; other references with regard to the statement and scope are indicated by full details of the publications concerned. The paper and work in the same or similar form have not been submitted to any examination body and have not been published. This paper was not yet, even in part, used in another examination or as a course performance. I agree that my work may be checked by a plagiarism checker.

03/04/2025 Lippstadt Mohamed Abdo

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