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Optimization Based Merging for Connected Vehicles

By

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This is to certify that:

(i) the report comprises only my original work toward the course project,

(ii) due acknowledgment has been made in the text to all other material used

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October 17, 2023

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List of Abbreviations

CAVs	Connected and Automated Vehicles
MS	Merging Sequence
CACC	Cooperative Adaptive Cruise Control
AVS	Autonomous vehicles

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Chapter 1

Introduction

1.1 Smart transportation and autonomous vehicles

A new era of urban development known as ”smart cities” is being ushered in by the use of cutting-edge technology to improve resident quality of life while also advancing efficiency and sustainability. The idea of smart transport, a dynamic and networked system intended to completely transform the movement of people and products inside and between these cutting-edge urban environments, is at the core of this urban evolution. In this sense, smart transport represents a major change in the conception, planning, and operation of cities, offering safer, more convenient, and environmentally friendly mobility options for all. It goes beyond simply streamlining routes and easing traffic congestion. Autonomous vehicles (AVS) have become a game-changer in smart cities, offering revolutionary answers to persistent urban transportation problems. Their exceptional coordination and communication skills have been important in helping to reduce traffic congestion. Autonomously navigating highways, AVS may merge and manoeuvre with efficiency, interacting with infrastructure and other cars to maximise traffic flow. By doing this, bottlenecks are lessened and safety is improved. Because AVS can anticipate and adjust to traffic patterns, intersection management—which is frequently a cause of congestion and accidents—has improved. Wait times are shortened and traffic flow is improved as a result. Overall, by drastically lowering traffic, enhancing intersection management, and expediting highway merging and ramp operations, autonomous cars have transformed transportation in smart cities and, in the process, raised the prospect of a safer, more effective, and sustainable urban lifestyle. The way we travel on the roads of the world is changing due to connected vehicles, which are sometimes referred to as the keystone of the transportation industry to come. These sophisticated cars and other forms of transportation are outfitted with state-of-the-art technology that enables real-time communication between them and the traffic infrastructure. The data that linked cars exchange opens up a world of amazing opportunities. They can enhance safety by alerting drivers of accidents and traffic bottlenecks, allowing for speedier route adjustments. They give traffic management systems vital information that helps to improve traffic flow and lessen congestion. Furthermore, because they can share data to manage challenging road conditions and enhance overall road safety, linked vehicles open the door for the development of autonomous driving.

Figure 1.1: Autonomous vehicles

1.2 Merging vehicles in Highways on Ramps

Merging control of vehicles at highway on-ramps is a critical element in optimizing traffic flow and enhancing overall transportation efficiency. This process entails the seamless integration of vehicles entering the highway from an on-ramp with the existing traffic. Efficient merging is vital for reducing congestion, minimizing the potential for accidents, and ensuring the uninterrupted movement of vehicles on the highway. Advanced technologies, such as connected vehicles and autonomous driving systems, are poised to revolutionize this aspect of highway operations. Connected vehicles can communicate with each other and with the highway infrastructure in real-time, sharing information about their positions, speeds, and intentions. This enables a level of coordination and synchronization previously unattainable with traditional human drivers. AVS equipped with precise sensors, artificial intelligence, and instant communication capabilities, can anticipate traffic patterns and identify suitable gaps for merging onto the highway. These vehicles adjust their speed and trajectory in real-time, negotiating entry onto the highway with unparalleled precision. By removing human error and hesitation from the equation, these technologies not only make merging smoother but also enhance safety by reducing the risk of collisions and bottlenecks at on-ramps. Moreover, they enable a more efficient use of highway space and a more predictable traffic flow, ultimately improving the overall driving experience. As smart cities continue to evolve, the integration of merging control systems for vehicles at highway on-ramps holds great promise in reducing urban congestion and enhancing transportation sustainability. This technological advancement represents a critical step toward the realization of safer, more efficient, and more environmentally friendly mobility solutions in our increasingly interconnected and intelligent transportation networks.

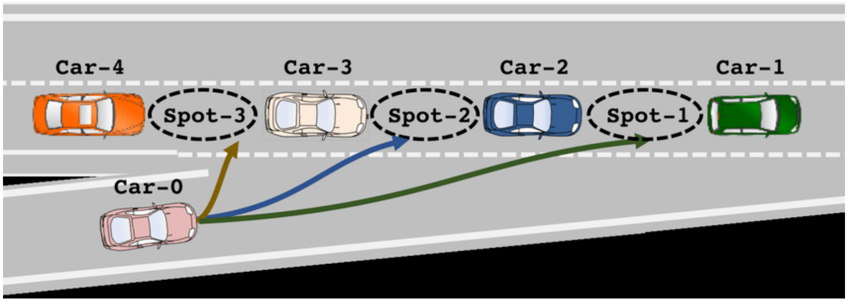

Figure 1.2: Merging vehicles

Chapter 2

Literature Review

There have been multiple research on the optimization of merging for connected vehicles. the study in [1] proposes a cooperative merging strategy for connected vehicles that uses a genetic algorithm to optimize traffic flow and minimize travel time. The strategy takes into account the inflow from on-ramps and uses wireless communication to improve traffic efficiency and fuel consumption. The paper presents simulation scenarios to verify the effectiveness of the proposed strategy and concludes with areas for future work.

There has been another study in [2] that proposes an optimization framework and analytical solution for coordinating connected and automated vehicles Connected and Automated Vehicles (CAVs) at merging roadways to achieve smooth traffic flow without stop-and-go driving. The effectiveness of the proposed solution is validated through simulation, showing significant reductions in fuel consumption and travel time. The majority of research efforts in this area have focused on intersections and merging highways.

Also the study in [3] presents an optimization framework for cooperative merging of platoons of connected and automated vehicles at highway on-ramps. The problem is modeled as a job-shop scheduling problem, and an optimal scheduling algorithm is presented to derive the sequence and time for each platoon to enter the highway safely. An optimal control problem is also formulated to derive the optimal control input (acceleration/deceleration) in terms of fuel consumption of the platoons at the highway. Simulation results show that the proposed framework significantly reduces crossing time and fuel consumption of platoons at highway on-ramps. The paper contributes to the literature on scheduling theory-based control algorithms for optimizing vehicle coordination in various transportation scenarios.

Another study in [4] discusses a rule-based cooperative merging strategy for connected and automated vehicles at highway on-ramps. The authors derive a near-optimal merging sequence using a rule-based adjusting algorithm and an energy-efficient motion planning method. Simulation-based case studies are conducted to compare the effectiveness and robustness of their method with other control strategies. The proposed strategy consistently outperforms the other methods in terms of throughput and delay under unbalanced vehicle arrival rates. The paper provides a comprehensive review of related works on cooperative merging and identifies the differences of their work from the existing works. Overall, the paper presents an efficient and safe method for coordinating two strings of vehicles at highway on-ramps.

Finally, the paper in [5] presents a game-based approach to optimize merging behavior for connected and automated vehicles. The proposed approach improves traffic flow and fuel economy while reducing collision risks. The main contributions of the study are the mixed-strategy Nash equilibrium of the complete information static game for Merging Sequence (MS) allocation, the varying-scale grid search algorithm to numerically search for acceptable parameters in the cost function of the bi-objective optimization problem, and the adoption of a modified quick-sort algorithm to find the Pareto front. The paper also applies Pontryagin's minimum principle to calculate the optimal control law for the bi-objective optimization problem.

Ramp metering is an important concept for traffic management strategy used on highways and freeway systems to regulate the flow of vehicles entering the mainline traffic from on-ramps. It involves the use of traffic signals or control devices at the on-ramps to control the rate at which vehicles merge onto the mainline.

The metrics used to evaluate the performance of the proposed approach are average travel time, number of cars crossing the merging zone and average vehicle speed.

Chapter 3

Methodology

3.1 Problem Formulation

3.1.1 Objective Function

Given m number of vehicles traveling on the main road in a platoon formation and r number of vehicles traveling on the ramp towards the merging point, The aim is to discover the optimal merging sequence between vehicles from the on-ramp and those already on the main highway that maximizes the total number of vehicles successfully merging from the ramp 3.1, while minimizing the overall delay for vehicles already on the main road eq:3.2, where $r1$ is the number of vehicles that are left for the next merging decision.

$$f_1 = \frac{r - r_1}{r} \tag{3.1}$$

$$f_2 = \frac{-\sum_{i=1}^{m} t_i + \sum_{i=1}^{m} \frac{l_i}{v_{\min}}}{-\sum_{i=1}^{m} \frac{l_i}{v_{\max}} + \sum_{i=1}^{m} \frac{l_i}{v_{\min}}} \tag{3.2}$$

The final objective function is: subject to

$$0 \leq w_1 \leq 1$$
$$0 \leq w_2 \leq 1$$
$$\mathrm{w}_1 + w_2 = 1$$
$$\mathrm{a}_{\min} \leq a_i \leq a_{\max} \quad \text{for } i = 1, 2, \ldots, m$$
$$\mathrm{a}_{\min} \leq a_j \leq a_{\max} \quad \text{for } j = 1, 2, \ldots, r$$
$$\mathrm{v}_{\min} \leq v_i \leq v_{\max} \quad \text{for } i = 1, 2, \ldots, m$$

$\mathrm{v}_{\min} \leq v_j \leq v_{\max} \quad \text{for } j = 1, 2, \ldots, r$

When a vehicle enters the control zone, all the the data regarding the vehicle motion is transmitted to a central unit having all the data for all the vehicles inside the control zone. For the main road vehicles. once a vehicle enters the control zone, its initial acceleration is maintained constant until it reaches the decision point. The an optimization problem is solved before the decision point is reached. After passing the decision point and the optimal sequence is obtained, Cooperative Adaptive Cruise Control (CACC) law 3.3 is applied to generate the trajectory for all vehicles in the solution on array, when an on ramp is scheduled to merge, the following vehicles in the sequence create a space for the vehicle to be merged in the future as the on ramp vehicle is virtually moving with the main line vehicle until it merges at the merging point.

$$a_f = \alpha \cdot a_l + \beta \cdot (v_f - v_l) + \gamma \cdot (s - sd) \tag{3.3}$$

where sd is the distance between the following vehicle and the preceding vehicle

The decision variable of this problem is the merging sequence between the on ramp and main road vehicles, the sequence matrix will have different number of inserted on ramp vehicles.

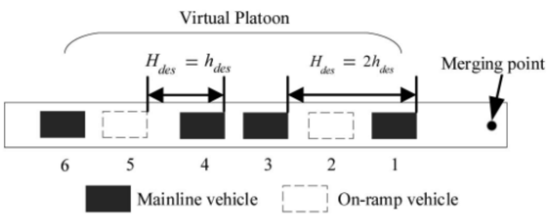

Figure 3.1: virtual platooning

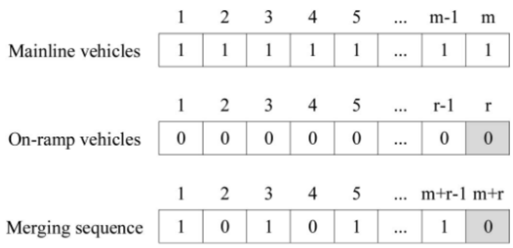

Figure 3.2: Solution Array

3.1.2 Assumptions

Several key assumptions are made to streamline the complexities of vehicle merging in a controlled environment. Firstly, the merging point of vehicles is assumed to be fixed upstream of the exit, ensuring a consistent location for merging. Lane-changing maneuvers are prohibited within the control zone, simplifying the scenario to include only the rightmost lane of the main road and a single lane on the on-ramp. Additionally, the focus is placed on longitudinal control of vehicles, disregarding lateral control, such as lane changes. The assumption of Cooperative Adaptive Cruise Control (CACC) vehicles, equipped with Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication, enables the exchange of state information and real-time merging instructions. The merging process is divided into short time intervals, with constant acceleration assumed within each interval, facilitating the modeling and analysis of vehicle behavior. These assumptions collectively provide a controlled and predictable merging environment, essential for the development and optimization of cooperative merging strategies.

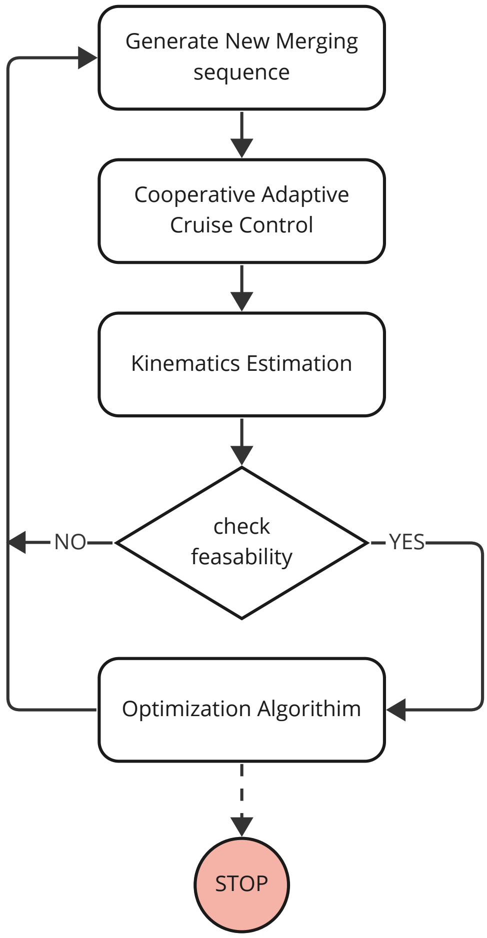

Figure 3.3: Proposed merging framework

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