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Merging lanes—fairness through communication

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ABSTRACT

The merging of two lanes is a common traffic scenario. In this paper we derive a formal model for the behavior of vehicles in this scenario. We discuss the question of how fairness of a merging process can be defined and introduce the notion of free-flow fairness. We first show how optimal fairness could be achieved if all vehicles were omniscient and willing to follow a given strategy. We then move to a more realistic setting, where only a subset of vehicles participates in our merging scheme and where wireless communication is limited and unreliable. By means of analysis and simulation we show that a simple beacon-based approach yields very good fairness even if only 1% of the vehicles participate.

1. Introduction

On-ramps are a particular critical part of any road network. Congestion or even a complete breakdown of traffic may occur, if the traffic on on-ramps is not managed properly [1,2]. The conventional approach to solve this problem is ramp metering [3]: the inflow from the on-ramp is limited by traffic lights to prevent breakdown and to maximize the flow on the main road.

Not only has the principle of operation of common on-ramp metering algorithms recently been criticized [4,2], this approach also has another main disadvantage. The restricted inflow from the on-ramp often causes congestion on the on-ramp which may propagate upstream into the subsequent road network. Moreover, depending on the main road's traffic flow, vehicles in the on-ramp may have to wait for a considerable and unfair amount of time before they are allowed to enter the main road. It is very hard to take the effects into account properly, when designing conventional ramp metering.

In this paper we investigate the use of car-to-car communication to manage the traffic on on-ramps while avoiding the drawbacks of conventional ramp metering. Prior work in this area, e.g., [5,6] has focused on optimizing throughput. In the work presented here we go one step further and look at the fairness of traffic management on on-ramps when using car-to-car communication.

In a first step we will propose a fairness metric for merging algorithms based upon waiting times. We will show that zipper merge can result in arbitrarily unfair merge orders. We will then reason that, when vehicles are allowed to exchange information, fairness is achievable. We present a specific algorithm that ensures this property even when communication is restricted to unreliable single-hop beacons (e.g., via IEEE 802.11p) and under the constraint that only 1% of the vehicles participate.

The main contributions of the work presented here are:

1) The formal definition of a model describing the behavior of vehicles when two lanes merge.
2) The specification of a fairness criterion for this behavior, which we call *free-flow fairness*.
3) A distributed algorithm which results in good fairness under real-world conditions.
4) Simulation results analyzing the impact of the percentage of participating vehicles.

This paper is structured as follows. The next section discusses related work on lane merging. Section 3 describes the terms of the formal model and specifies a fairness criterion. The fairness of the zipper merge strategy is discussed in Section 4. In Section 5, we show how the vehicles should behave ideally, in order to reach a fair merge order. We then move to a real-world setting, where we drop unrealistic assumptions such as the omniscience of the involved vehicles. We propose a merging algorithm that coordinates the vehicles through unreliable beaconing. The algorithm has been implemented in the simulator ns-3 [7]; the simulation results are

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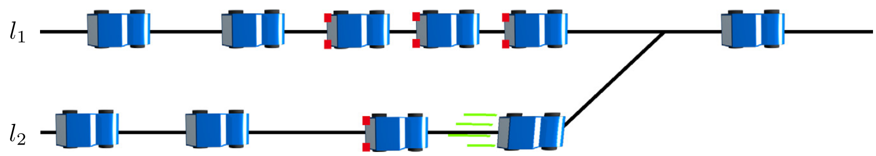

Fig. 1. A sketch of a merging of two lanes.

described in Section 6. Our findings on communication scheme design for merging scenarios are concluded in Section 7.

2. Related work

Related work on inter-vehicle communication for on-ramp traffic control can be grouped in three categories: (1) enhancing efficiency and safety through communication, (2) adapting or evaluating communication algorithms and radio channel properties in the context of lane merging support, and (3) experiments with cars or robots that perform merging. We give examples for each of those three categories in the following.

Work on efficiency and safety focuses on metrics like disturbances in traffic flows [5] and the time cars need to drive to an intersection [8] but the merge order is not a matter in the discussions. The queue lengths upstream of a merge with and without communication are evaluated by Xu et al. [9] and the performance of cooperative autonomous cruise control (C-ACC) systems compared to non-cooperative ACC systems is discussed by Xu and Sengupta [6]. Criteria for robust merging, sets of different merging strategies, and algorithms for communicating cars are proposed by Wang, Kulik, and Ramamohanarao [10]. Further research is done on the coordination at intersections by supporting traffic light switching through communication [11]. A key term here are virtual traffic lights which are only visible to communicating cars: they help to increase intersection capacity [12,13]. Another approach presented in a paper by Morla envisions a slot-based road usage where slots are maintained by cooperating vehicles [14]. This idea is exemplified with a road merging scenario. The paper's high-level discussion does not include details of the merge order or the communication scheme, and it is suggested that the cooperation should fail if the inbound flows are high enough that jams will emerge. In contrast, we argue that a merging coordination scheme is particularly relevant in face of a traffic jam.

The second category of related work is about communication algorithm enhancements and radio channel properties. The impact of the antenna radiation pattern with regard to the line of sight in merging scenarios is discussed by Abbas et al. [15]. Uno, Sakaguchi, and Tsugawa propose a merging control algorithm that uses communication for reserving merging space with virtual vehicles [16]. The authors evaluate the algorithm's communication delays using simulations. Wolterink, Heijenk, and Karagiannis analyze a geocast algorithm in a merging scenario and suggest to predict future positions of vehicles for enhancing the algorithm's performance in dense traffic [17].

The third category evaluates merging behavior by means of experiments. Sakaguchi, Uno, and Tsugawa conducted experiments to show the feasibility of their merging algorithm with autonomous mobile robots [18]. Experiments with vehicles that cooperate using communication in an intersection are described by Kolodko and Vlacic [19]. A more recent experimental study, part of the AUTOPIA project [20], showed that coordinated merging at an on-ramp is possible in a real setting with cars exchanging information with a road-side unit [21]. The authors created an automated merging system with the goal of fluidly merging to a congested main road and deployed it in three production vehicles.

In contrast to the previously described works, the paper at hand proposes fairness as a further goal for merging assistant applications. We introduce a formal model in order to understand and describe the meaning of "perfect" fairness in absolute terms. A decentralized algorithm is developed and evaluated for how close we can get to perfect fairness in simulations with realistic settings. To the author's best knowledge, there is no other approach that improves fairness in a merging with decentralized communication.

3. Merging order fairness

In order to analyze the behavior of vehicles when two lanes merge into one, we use a formal model. The focus of this paper is on the merging order. We therefore concentrate on this aspect in the model, and otherwise keep it as simple as possible. We consider a topology with a main lane l_1 and an on-ramp lane l_2 which merges into the main lane.

The on-ramp lane l_2 ends at a point which we call the merge point. Both lanes, as well as cars driving in the lanes, are one-dimensional. Fig. 1 depicts the scenario. The longitudinal movement of the cars is restricted by a maximum speed common to all cars and a minimum speed of zero. A further simplification is that all cars have the same acceleration capabilities and the same length. To keep track of the initial order of the cars before they pass the merge point, we consider them to be totally ordered in a lane by their time of appearance.

Car c_i (for $i \in \mathbb{N}$) appears in one of the lanes at t_i^0. Only one car appears at the same time in the same lane.

The cars pass the merge point in a certain order. Each car c_i therefore has a position index $k_i \in \mathbb{N}$ in the sequence of vehicles leaving the merge. The merging scheme that is applied determines the position indices for all cars in a given traffic scenario. Our fairness criterion will refer to the order of cars leaving the merge, as given by the sequence k_i.

3.1. Free-flow fairness

Our objective is to enable a fair merging order. In order to reach this goal we need a better understanding of the term "fairness" in this context. Consider two cars that approach the merge point and have to decide which one drives first. An intuitive approach would be to base that decision on the cars' distances to the merge. This is not a good solution, though: depending on the length of the queue on each line before the merge point, two cars may be similarly far from that point, while one of them has been waiting much longer than the other. It would clearly be unfair to let a car with shorter waiting time pass first. The decision should therefore be based on the time that the cars spend waiting: a car with longer waiting time should be given preference.

But how can the waiting time be measured? Or, more specifically, when does a car start waiting? We argue that the waiting time of the car should be measured starting from the point in time when the car would have arrived at the merge point if it was not hindered by any other car. This is the earliest point in time at which a given car could possibly arrive at the merge point; we term this point in time the car's *free-flow arrival time*.

A merge order based on the free-flow arrival time lets a car pass earlier if it has the earlier free-flow arrival time. Our definition of fairness is based on this concept: