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Definition of a merging assistant strategy using intelligent vehicles

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A B S T R A C T

In the area of active traffic management, new technologies provide opportunities to improve the use of current infrastructure. Vehicles equipped with in-car communication systems are capable of exchanging messages with the infrastructure and other vehicles. This new capability offers many opportunities for traffic management. This paper presents a novel merging assistant strategy that exploits the communication capabilities of intelligent vehicles. The proposed control requires the cooperation of equipped vehicles on the main carriageway in order to create merging gaps for on-ramp vehicles released by a traffic light. The aim is to reduce disruptions to the traffic flow created by the merging vehicles. This paper focuses on the analytical formulation of the control algorithm, and the traffic flow theories used to define the strategy. The dynamics of the gap formation derived from theoretical considerations are validated using a microscopic simulation. The validation indicates that the control strategy mostly developed from macroscopic theory well approximates microscopic traffic behaviour. The results present encouraging capabilities of the system. The size and frequency of the gaps created on the main carriageway, and the space and time required for their creation are compatible with a real deployment of the system. Finally, we summarise the results of a previous study showing that the proposed merging strategy reduces the occurrence of congestion and the number of late-merging vehicles. This innovative control strategy shows the potential of using intelligent vehicles for facilitating the merging manoeuvre through use of emerging communications technologies.

1. Introduction

Emerging communication technologies open new management possibilities in the field of Intelligent Transport Systems (ITS). Particularly promising are technologies allowing vehicles to infrastructure (V2I) and vehicle to vehicle (V2V) communication. This new communication capability could enable cooperation among vehicles, opening a new research thread known as Cooperative ITS (NEARCTIS, 2009; Netten et al., 2011; COOPERS, 2010). Using cooperation, the current ITS can be improved, and a new generation of Intelligent Transport Systems can be developed. It is following these new challenges and opportunities that the present research takes place.

This paper proposes a merging assistant strategy for on-ramps using intelligent vehicles capable of V2I communication. The innovative strategy, called Cooperative Merging Assistant (CoopMA), rearranges vehicles on the main carriageway to

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create large gaps for facilitating the merging of on-ramp traffic. We introduce the control algorithm and present the governing equations based on both macroscopic and microscopic traffic flow theories. The control strategy describes the size, frequency, space and time needed to create useful gaps for merging. Then, we use microscopic simulation as "ground truth" to validate the gap formation dynamic derived by the theoretical considerations. This paper focuses on the algorithm definition. However, we report a brief summary of the traffic performance based on previous work for completeness (Scarinci et al., 2015).

Although researchers and practitioners have given much attention to the use of emerging technologies applied to ITS, new possibilities and challenges are constantly opening. For this reason, this research area is still largely unexplored and more studies are needed to understand all the possible opportunities given by these technological advances. The current study adds another input into the field of Cooperative ITS, suggesting an innovative application able to optimise further the use of motorways.

The paper is structured as follows. Section 2 reviews active traffic management algorithms for on-ramp merging using intelligent vehicles. The Cooperative Merging Assistant strategy is described in Section 3. We first introduce the control strategy, then, we present the equations governing the algorithm. The analytical formulation is validated against microscopic simulation in Section 4. A brief evaluation of the Cooperative Merging Assistant system traffic performance is given in Section 5. Finally, Section 6 summarises the main conclusions.

2. Literature review

A vast literature on merging assistant strategies is present. It ranges from the first work on autonomous vehicles on motorways, e.g. Mammano and Bishop (1992), to recent work on cooperative vehicles, e.g. Xie et al. (2016). We refer to Scarinci and Heydecker (2014) for a complete review of the control algorithms, evaluation methods and optimization strategies.

In the following, we review three main categories of control algorithms for facilitating motorway on-ramp merging. Each category uses a different type of intelligent vehicles to manage the merging process.

(i) **Automated vehicles**. Completely automated vehicles are capable to perform longitudinal and lateral movements without driver's interventions. In the 1990s, Yang et al. (1993) Yang and Kurami (1993) and Kachroo and Li (1997) started developing control algorithms with the main goal of providing a smooth merging. This is achieved by guiding on-ramp vehicles into existing gaps on the main carriageway. Antoniotti et al. (1997) and Ran et al. (1999) further extend the control capability of the merging procedure controlling also vehicles travelling on the main carriageway. First field tests are performed by Kato et al. (2002) and Lu et al. (2004). These tests evaluate both the technological requirement for communication and control and the theoretical algorithm capabilities. More recently, Marinescu et al. (2010, 2012) propose a centralized algorithm that detects when a control intervention is needed. Automated vehicles, when needed, are guided to slots available for merging. Xie et al. (2016) propose a merging control strategy optimizing the speed profile of vehicles close to the on-ramp. The authors also develop a simulation platform for testing and evaluating control strategies for cooperative vehicles.

(ii) **Cooperative Adaptive Cruise Control**. Vehicles equipped with Cooperative Adaptive Cruise Control (CACC) can maintain a fixed gap with the preceding vehicle and receive information to proactively change speed. Uno et al. (1999) suggest to place a "virtual vehicle" in front of a vehicle travelling in the main carriageway to create a suitable gap for merging vehicles. The impact of using CACC for facilitating merging in mixed traffic is evaluated by Xu and Sengupta (2003) and Davis (2007). In their tests, equipped vehicles on the main carriageway create merging gaps for on-ramp vehicles. In another study on mixed traffic, van Arem et al. (2006) evaluate the impact of CACC in lane changing manoeuvres. Also Pueboobpaphan et al. (2010) propose a merging assistant strategy for mixed traffic. The proposed algorithm aims to increase traffic flow stability. Wang et al. (2007) and Kanavalli et al. (2008) apply "proactive merging strategy" to merging algorithms. Thanks to the communication capability, intelligent vehicles can collect data of the surroundings vehicles and adjusting their speed.

(iii) **On-board display**. Vehicles equipped with an on-board display can receive suggestions of speed or lane changes from the infrastructure to which the driver should react. This topic is more recent, and less research has been done. Park et al. (2011) identify vehicles on the main carriages that performing a lane-change can facilitate the merging of on-ramp vehicles. The lane-changing suggestion, if performed, should be able to reduce merging conflicts. Daamen et al. (2011) test the traffic impacts of sending messages to single vehicles in case of a large speed difference between two vehicles is present, and a platoon conflicts with a merging vehicle.

The majority of the authors evaluate the performance of the presented algorithms using a microscopic simulation. The key performance indicators evaluated, such as gap creation dynamics, merging speed and total delay, show how the control strategies improve the traffic flow.

We now identify where the proposed Cooperative Merging Assistant (CoopMA) strategy is located within the review literature. The CoopMA strategy requests the cooperation of intelligent vehicles on the main carriageway. Instead, the on-ramp vehicles are controlled by a traffic light, as done by the ramp metering system (Papageorgiou and Kotsialos, 2002). Only one intelligent vehicle on the main carriageway is requested at each traffic cycle. The innovation is the