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Effects of variable speed limits on traffic operation characteristics and environmental impacts under car-following scenarios: Simulations in the framework of Kerner's three-phase traffic theory

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HIGHLIGHTS

- The advantage of investigating VSL under Kerner's three-phase traffic theory is discussed.
- A modified VSL control algorithm is proposed.
- The effects of the VSL on traffic operation and environmental impacts are studied.

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ABSTRACT

Variable speed limits (VSL) strategies have been demonstrated to successfully improve traffic dynamics characteristics. However, the effects of the strategies on overall traffic performance from the perspective of Kerner's three-phase theory has yet to be needed. This paper attempts to present a comprehensive simulation study on this topic. The study investigates the effects of VSL strategies on traffic operation characteristics and environmental impacts by combining the Kerner–Klenov car-following model and a practical VSL control algorithm. Simulations have been carried out for different control scenarios. The simulation results quantitatively indicate how and to what extent the VSL strategies affect overall traffic performance, including fundamental diagram, local speed variance, VSP distributions and average exhaust emission rates. It is revealed that the implemented VSL strategies cannot either improve maximum flow rate or prevent from the occurrence of the F→S transition. However, VSL lead to a significant extension of occupancy range for synchronized flow phase and suppress speed variability in traffic stream in congested traffic state, especially in the jam phase and the transitional state S → J. Moreover, the VSL strategies is able to reduce traffic emissions by improving VSP distributions and average emission rates in the synchronized and jam phases. These findings suggest that the perspective of Kerner's three-phase theory can be added to the development of VSL control algorithms which aim to achieve high traffic efficiency with minimum traffic environmental impacts.

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1. Introduction

Road traffic system attracts a lot of attention due to its strong correlation with urban operation and development. With the increasing number of vehicles traveling on road, serious congestion are emerging. In addition, more and more concerns focus on environmental impacts of road traffic operation, including fuel consumption, greenhouse gas emissions and particulate matter emissions.

Nowadays, many efforts have been devoted to solving problems related to traffic congestion and environment problems by applying advanced traffic management and control approaches. Variable speed limits (VSL) strategies are widely implemented around the world [1,2]. Combined with a specific control algorithm, VSL strategies act with showing different speed limits information based on time-variation local traffic operation measures (e.g. flow rate, occupancy and speed). The main objectives of VSL are to improve traffic operation efficiency and decrease traffic accident rates by reducing differences in traffic operation measures. Previous works showed that an overall decrease in major accident rates ranged between 20% and 30% was achieved after the implementation of VSL [3–6]. Moreover, VSL systems are also able to ease traffic congestion by reducing average free flow speed, resulting in larger occupancy range during high flow periods [7]. In recent years, some existing works pay attention to the effects of VSL strategies on environmental benefits using traffic simulation models combined with emission models [8,9]. These simulation results indicated that VSL could provide environmental benefits as a result of homogenizing traffic flow.

The control algorithms for VSL systems were usually developed on the basis of empirical features of traffic operation. According to recent observations, traffic breakdown is a phase transition from free flow to congested traffic, and its probability is an increasing function of flow rate. Congested traffic can be further categorized into two phases as they have different dynamic features. However, generally accepted fundamentals and models of traffic theory (e.g. LWR theory) are not consistent with the set of the fundamental empirical features of traffic phase transitions at highway bottlenecks [10,11]. Such classical developments regard the capacity of traffic as a particular value, and they cannot identify the differences in congested traffic pattern features. It should be noted that the reliability of traffic optimization is determined by whether optimization methods can prevent from phase transitions which deteriorate traffic operations (such as the occurrence of breakdown) [12]. Then the impacts of VSL systems on traffic performance are still need to be investigated by theories and methods which are able to explain and reproduce the set of empirical findings of traffic operation.

Kerner's three-phase traffic theory is a modern approach which breaks through the traditional fundamental diagram approach [12]. The theory has been developed to solve the puzzle of empirical spatiotemporal features of traffic discussed above [13]. In the late 1990s, Kerner compiled traffic data measured for several years on freeways and investigated empirical features of traffic [14–18]. He discovered several macroscopic spatiotemporal features as fundamental elements of Kerner's three-phase traffic theory. They are as follows:

(i) There are three distinct steady phases [19,20], including (1) free flow phase (F), in which the average speed is around drivers' expected speed; (2) synchronized flow (S), which is characterized by a two-dimensional area in the flow-density plane. The average speed is noticeably lower while the density is significantly higher, which results in relatively high flow rate, and (3) wide moving jams (J), in which the average speed and flow rate are very low. A wide moving jam moves through any traffic states or bottlenecks, which maintains a constant mean velocity of downstream jam front.

(ii) Two phase transitions can be observed during the formation of jams [21–24]. Free flow firstly transit to synchronized flow (F→S) with probability, which indicates the occurrence of traffic breakdown. This probabilistic breakdown (i.e. the F→S transition) can be either spontaneous or induced. Note that the return transition S→F often occurs at lower flow rate. When the traffic density continuously increases, synchronized flow evolves into wide moving jams (S→J) later.

Despite the fact that Kerner's three phase traffic theory was originally proposed to understand the physic mechanisms of complex traffic phenomena, it also has potential to develop traffic optimization methods and evaluate the effects of control strategies on freeway traffic. Kerner has studied speed limit control by using the Kerner–Klenov microscopic traffic model [25]. However, the control algorithm in his study was not able to adjust the value of speed limit in accordance with changes in traffic conditions. Our work is an extended effort following previous research on traffic flow and speed limit control. More specially, the study aims to quantify the effects of a candidate VSL strategy on traffic operation characteristics and its environmental impacts from the perspective of Kerner's three-phase traffic theory. The control algorithm in the paper can make the speed limit value adapt to the dynamic traffic conditions. The results of this research help us better understand the effects of VSL strategies on traffic phases and phase transitions. Furthermore, the simulations embedded with traffic emission models can provide quantitative results about the environmental impacts of VSL strategies associated with different traffic phases. Note that this study focuses on the car-following scenario, which forms the basis of traffic flow dynamics. Moreover, the simulation findings are useful for the development and implementation of VSL systems.

The remainder of this paper proceeds as follows. Section 2 introduces the Kerner–Klenov car-following model which is presented for Kerner's three-phase traffic theory and the VSL control algorithm and the emission model which are embedded in the Kerner–Klenov model. Section 3 reports the simulation results, including the effects of the VSL strategy on traffic operation and environmental impacts. Finally, the conclusions from the study are discussed in Section 4.