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Will a higher free-flow speed lead us to a less congested freeway?

Sheng-Xue He *

Business School, University of Shanghai for Science and Technology, Shanghai 200093, China

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ABSTRACT

An approach based on cell transmission model (CTM) is proposed to estimate the impact of variable free-flow speeds (FFS) on the performance of a freeway system. Based on the basic CTM, four typical freeway control strategies consisting of non control, local ramp metering, coordinated ramp metering and global control are first formulated. Then the method of adjusting model parameters to the changed free-flow speeds is presented. Among the adjustments, an experimental function based on Fan and Seibold (2014) is proposed to change the jam density. Several useful measures are defined to estimate and compare the performances of different freeways. The following three main observations are obtained from numerical experiments. (a) With the gradually increasing FFS, the throughput of freeway will increase at the beginning and then change to decrease. (b) With the increasing FFS, the average delay of vehicles will decrease at the beginning and then change to increase. (c) A series of free-flow speeds associate with the best performance of freeway. These observations are theoretically analyzed through investigating the location and capacity of bottleneck. Study shows that in general the actual bottleneck capacity will increase at the beginning and then change to decrease with the continually increasing FFS. In view of the positive correlation between traffic delay and bottleneck capacity, the theoretical analysis confirms the numerical observations. The findings of this study can deepen the understanding of freeway systems and help management agents adopt proper measures to improve the performance of the whole system.

1. Introduction

Free-flow speed (FFS) is the speed of traffic flow that is unaffected by upstream or downstream conditions. Ideally, free-flow speed is the speed that occurs when density and flow are zero. As a key index of traffic conditions, free-flow speed is influenced by many factors, e.g. by the performance of vehicles, the conditions of the roadway, and the posted speed limit. It is not always possible to measure the free-flow speed. In practice, methods are proposed to adjust the actual free-flow speed to the lane features, e.g. lane width and the number of lanes. But there are very limited researches about the impact of free-flow speeds on the performance of a freeway network. In view of the changeability of free-flow speeds, the impact of FFS on the performance of a freeway becomes relevant not only in theoretical field but also in practice. People wonder if the increase of FFS will lead to a less congested traffic state or not. In another word, is it true in reality that "more haste, less speed" when a freeway network is considered?

* Tel.: +86 21 18019495040.
E-mail address: lovellhe@126.com

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Generally speaking, the bottlenecks of urban traffic will commonly develop around the intersections due to limited road resources and the large traffic demand distributed unevenly. Different from the urban traffic network, a freeway generally has a more enjoyable driving environment with seldom interference once a vehicle enters the freeway mainline. Ramp metering can keep the mainline stream running under critical flow capacity so as to reach a high performance of the whole freeway system. This kind of demand management has been the focus of freeway control field since it was proposed. But note that there are some other aspects related to the behaviors of drivers and physical conditions of freeway that could also influence the final results. One concept could be adopted to synthesize these relevant aspects is free-flow speed. When a freeway system is considered, the related free-flow speed becomes a critical value embodying the system characteristic. So what is the impact of varying FFS on a freeway system with or without ramp metering? Intuition may lead us to the conclusion that a higher FFS would generate a better traffic state if the other possible negative results, e.g. the potentially more serious accidents, are overlooked. No matter what is the intuition, a reasonable answer based on scientific experiments is necessary to clarify this confusion.

It is not easy to answer the question asked in the title because no offhand method exists to facilitate us to carry out this task. Some specific experiments are required to investigate such an impact. The designed experiments should be able to cover the complex real traffic states. The fundamental relationships between flow, speed, and density should be embodied in the experiment. The different freeway control strategies widely used nowadays should be addressed with special attention. Except the difference of control strategies, many other factors should be addressed in a way so that the influence of these factors on the final performance of system is under control. To achieve the above goal, the Cell Transmission Model (CTM) is adopted as the modeling basis of this study. As is well known, CTM is a convergent numerical approximation to the Lighthill and Whitham (1955) and Richards (1956) – the LWR model. Since the LWR model covers the whole range of the fundamental relationships between traffic speed, flow and density, it is expected that the CTM based formulation will do the same. Through careful modification, proper formulations reflecting different control scenarios could be obtained. To reflect the impact of the variable FFS on the jam density, an experimental function based on the results of Fan and Seibold (2014) is proposed to adjust the allowable maximum number of vehicles in a cell. To properly estimate the performance of the whole freeway system, several relevant measures need to be defined, too. With the formulations and measures mentioned above, it becomes possible for us to observe the impact of the varying free flow speeds on the performance of a freeway system.

After checking the existing literature focusing on free-flow speed, it is found out that most of them pay close attention to the prediction models of proper free-flow speed using field data of speeds and many other data about the facilities in question (example, Hashim, 2011; Dhamaniya and Chandra, 2013; Eluru et al., 2013; Luca et al., 2012; Zhang et al., 2013). One focus of the existing literature is the impact of posted speed limits on the prediction model of free-flow speed and the other relationships related to free-flow speed (Aljanahi et al., 1999; Deardoff et al., 2011; Himes et al., 2013; Nitzsche and Tscharaktschiew, 2013; Saifizul et al., 2011). From these studies, three impressions about FFS that naturally lead to the main concern in this paper can be obtained. The first impression is that there is a large allowable range for the realized free-flow speeds. This will put this research on a strong and reasonable basis since from these existing studies the possibility of changing a free-flow speed can be ensured. The second impression is that free-flow speed plays a very important role in the field of traffic research and practice. Many macroscopic traffic flow models will use FFS as a given coefficient, e.g. CTM (Daganzo, 1994, 1995) and AMOC (Kotsialos and Papageorgiou, 2004). Many microscopic traffic flow simulation models also need FFS to realize the simulation of real traffic flow. These facts will naturally emphasize the importance of researches about FFS. The third impression is that there exists a gap mentioned in the first paragraph of this paper. As far as the author knows, efforts have seldom been made to investigate the impact of varying FFS on the performance of a freeway network. The effort made in this paper can be viewed as a trial to bridge the gap.

The main contributions of this paper are summarized as follows. (a) An approach based on CTM is proposed to investigate the impact of changed free-flow speeds on the whole performance of freeway system; (b) four typical control scenarios including non-control, local ramp metering, coordinated ramp metering and global control are formulated to investigate the impact of FFS with respect to different control schemes; (c) to facilitate the estimation and comparison of whole performances of different networks, several relevant measures that can be used independent of the specific topology and scale of the network in question are defined; (d) some useful observations obtained from numerical experiments will facilitate practitioners and researchers to choose proper measures to improve the whole performance of freeway system; (e) with the continually increasing FFS, the changes of location and capacity of actual bottleneck are analyzed to explain the numerical results.

The remainder of this paper is organized as follows. Section 2 is dedicated to formulating the proper models corresponding to different control schemes. Section 3 deals with the necessary changes of parameters with respect to the varying free-flow speeds and defines several relevant measures to estimate and compare the performances of various freeway systems. Section 4 does numerical experiments to illustrate the effectiveness of methods and to gain some useful insights into the impact of changed free-flow speeds on the performance of a freeway system. Section 5 analyzes the mechanism of the observed changing trends of measures of performance. Section 6 sums up the main conclusions and suggests several possible research directions for future researches.