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Predicting travel time to limit congestion at a highway bottleneck

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ABSTRACT

A new method is proposed to predict the travel time on a highway route with a bottleneck caused by an on-ramp. The method takes advantage of the slow variation of the bottleneck throughput when congestion exists. The predicted travel time for a vehicle leaving the origin is given by the current number of vehicles on the route divided by the estimated throughput. The latter is an average of N/T recorded as each vehicle reaches the destination where N is the number of vehicles at the start of the trip and T is the time to complete the trip. Drivers divert to an off-ramp when the predicted travel time exceeds a target value. The target could be historical average travel times of alternative routes or chosen to limit the amount of congestion. Simulations employing three-phase traffic theory show that the travel time converges to the target value and remains close to or below it with the proposed prediction strategy. Strong oscillations in travel time obtained when other strategies are used for diversion do not develop with the new method because the inherent delay is effectively removed.

1. Introduction

It is anticipated that vehicle-to-vehicle communications and/or an advanced travel information system (ATIS) will be readily available in the future to improve traffic speeds and reduce congestion. Such systems provide real-time information so that drivers can choose among alternative routes to find the shortest travel time [1–9]. Thus it is important to provide optimal information. In addition to the societal benefits, the problem is of interest because it is fundamentally a question of the stability of a dynamical system with delay. The challenge is to determine an accurate prediction of the time to reach the destination—a better estimate than the travel time of the last car to complete the route.

Here I analyze a highway (freeway) with a bottleneck caused by vehicles merging from an on-ramp. Since the alternative routes are usually slower, but not necessarily highly variable and up-to-date travel times might not be available, I suggest setting a target value for the highway travel time and providing information for drivers to attain the target. The target value could be the historical average of travel times on alternative routes, for example. I propose a new method to predict travel time based on the number of vehicles on the highway. The prediction makes use of the notion that the throughput of a bottleneck is often slowly varying (roughly constant at the so-called bottleneck capacity) [10,11]. If drivers faithfully follow the guidance to divert to an alternative route when the predicted transit time exceeds the target, the actual highway travel time is maintained at or below the target.

As simulations will demonstrate, using the current travel time on a route containing a bottleneck does not work for reasons previously discovered. In 2000 Wahle et al. [12] published an analysis of a two-route model in which drivers chose their routes according to current travel times. Because the routes were identical, the system optimum was for each route to have the same flow. However, simulations showed that flow rates on the two routes oscillated out-of-phase due to travel-time delay. Although the information provided was instantaneous, it could only be as up to date as the travel time of the last car reaching the destination.

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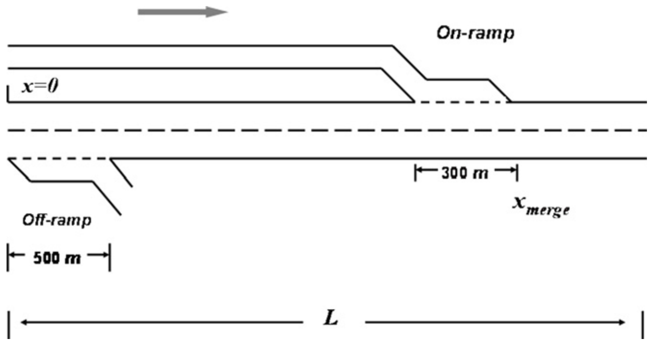

Fig. 1. Highway bottleneck due to on-ramp at $x_{\text{merge}} = 6$ km. The route is from the origin $x = 0$ to the destination $x = L = 8$ km. The incoming flow increases from 2400 vehicles/h to 4800 vehicles/h over 800 s (1200/lane/h to 2400/lane/h). The flow to the on-ramp is a steady 800/h (Figs. 2–10) or 500/h (Figs. 11–14). Drivers may choose to divert to alternative routes at the off-ramp at $x = 0$. Speed limits are 32 m/s and 25 m/s on the highway and on-ramp respectively.

Lee et al. [13] showed that using the instantaneous average velocity of vehicles on each route, rather than travel time, improved performance. Their method resulted in a steady state with nearly equal flow and travel time on each route. For the bottleneck analyzed in the present work, however, the average-velocity approach does not work well. The resulting travel time oscillates about the target value and does not converge to a constant value. This differing result most likely occurs because I use three-phase theory, specifically the Kerner–Klenov model [10,11,14–17], to describe congested flow rather than the Nagel–Schreckenberg cellular automaton model [18] used by Wahle et al. [12] and by Lee et al. [13]. The Kerner–Klenov model reproduces empirical data near an on-ramp accurately and has been validated in numerous studies [10,11]. Pertinent criticism of the model is discussed in Section 10.3.7 of Ref. [11].

Wang et al. [19] suggested another method in which a congestion coefficient was computed for each route and used as the basis for choosing the better route. They claimed their algorithm had advantages over the travel-time and average-velocity algorithms. They also employed the Nagel–Schreckenberg cellular automaton model of traffic flow, but did not indicate how their method should be implemented in three-phase theory or with empirical real-time data. Also see Ref. [20].

The theory of predicting travel times through a bottleneck is presented in Section 2. Simulations demonstrating the efficacy of the proposed method are presented in Section 3. Conclusions are given in Section 4. The Kerner–Klenov model used for simulations is described in the Appendix.

2. Theory

A two-lane highway with an on-ramp is a prototypical traffic bottleneck (Fig. 1). When the rate of flow is large, vehicles merging onto the highway can induce congestion near the ramp. Depending on the incoming flow rate, the congestion (synchronous flow) can be localized or can expand up the highway [21]. If the density of vehicles becomes sufficiently high, jams nucleate and propagate upstream as well [10,11].

To reduce congestion various strategies to control the on-ramp flow by metering or to adjust the speed limit on the highway have been investigated [10,11]. In this paper, I examine congestion reduction at a bottleneck from a different perspective—that of dynamical traffic assignment [22–27]. Conventional assignment approaches seek to apportion a given amount of flow to alternative routes so that travel times from the same origin to the same destination are equal. Assignment can de done on the basis of historical demand data or real-time information [28–30].

I suggest a modified assignment procedure where the objective is to keep the travel time on the highway from exceeding a target time T_{target}. The time to complete the highway route can be altered by diverting a portion of the incoming flow to an alternative route. The target T_{target} could be set at an average of the historical travel times on the alternative route (or routes) or according to a desired societal criterion, such as guaranteeing that the highway travel time will not exceed a maximum acceptable value.

Even this simple objective is not straightforward to realize. Suppose an up-to-date travel time, $T_{\text{path}}(t)$, is known for the highway. The path over which $T_{\text{path}}(t)$ is measured extends from a point ($x = 0$) before an off-ramp (Fig. 1), where vehicles can be diverted, to a point ($x = L$) beyond the bottleneck (Fig. 1). If all the flow in the right lane is diverted to the on-ramp whenever

$$T_{\text{path}}(t) > T_{\text{target}}, \quad (1)$$

the result is a strong oscillation in $T_{\text{path}}(t)$. The oscillation is caused by delay, namely the time to travel the path. An example of oscillating $T_{\text{path}}(t)$ is denoted "T_{path} Strategy" in Fig. 2 (discussed more fully later). Likewise, if the average velocity of vehicles on the highway v is used so that flow is diverted whenever $v < L/T_{\text{target}}$ the travel time also oscillates as demonstrated in Fig. 3. In two hours of simulated time, the velocity does not appear to converge and consequently $T_{\text{path}}(t)$ does not either. The conclusion of Lee et al. [13] that average velocity improves performance compared to using travel time