Capacity Analysis of a Semi-Automated Highway

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Abstract

Urban traffic congestion presents challenges for which no easy solutions are in sight. In this regard, advanced technologies and highway automation have been receiving considerable attention as potential congestion management tools. This paper analyzes the gains in capacity that can be achieved through highway automation. Fundamental theories of traffic flow and vehicle motion are applied to a "multi-lane semi-automated" highway where one or more automated lanes co-exist with one or more non-automated lanes. Dynamics of vehicle movements are simulated to assess capacity benefits that can be accrued under various speed scenarios on a semi-automated highway.

Introduction

Every year, urban traffic congestion costs the U.S. economy billions of dollars in lost productivity and delay. In an effort to tackle this ubiquitous problem, the Intermodal Surface Transportation Efficiency Act (ISTEA, 1991) has mandated the development of comprehensive congestion management systems (CMS). In this regard, advanced technologies in transportation including Intelligent Vehicle Highway Systems (IVHS) and other automated highway technologies have been receiving considerable attention as potential congestion management tools.

Highway automation has been motivated by the conjecture that the principal factor limiting the capacity of any travel mode is the degree of control which can be exercised over individual vehicles. It was then postulated that the automatic control of vehicles (say, by a central computer system) on existing roadways could relieve traffic congestion by increasing vehicle speeds while reducing headways (Barwell, 1977).

This paper is concerned with quantifying the capacity benefits that can be obtained through highway automation. The paper considers a partially automated highway where one or more automated lanes co-exist with one or more non-automated lanes. This highway configuration will be referred to as a "semi-automated highway" in this paper. An analysis of the semi-automated highway is performed by simulating vehicle dynamics and platoon formations to determine highway capacity after automation. Various merging movements, speed transitions, and lane changes are modeled using fundamental theories of traffic flow to quantify capacity gains through automation.

The next section of this paper provides a detailed description of the semi-automated highway and its operational assumptions. Theoretical models are derived and illustrated in the following section. In Section 4, numerical simulations of traffic flow leading to estimates of capacity gains through automation are presented. Finally, conclusions and suggestions for future research are presented in Section 5.

2. The Semi-Automated Highway

This section describes the configuration of the semi-automated highway and the operational assumptions that underlie the analysis presented in following sections. A four-lane semi-automated highway is considered (two lanes in each direction). In each direction, the left lane is automated while the right lane is not. The speed of traffic flow on the automated left lane is considerably higher than that on the non-automated right lane. The non-automated lane is mainly provided for smooth highway entry and exit. It could also be used by elderly or handicapped drivers who may not wish to travel at high speeds on the automated left lane, drivers whose vehicles do not have automated controls, or drivers whose vehicle's control systems are malfunctioning. Indeed, this configuration may represent an intermediate step on the road to full automation.

Vehicles in the automated left lane are clustered into groups of vehicles called "platoons". Within a platoon of vehicles, the headway between any two vehicles is negligibly small, thus contributing to an increase in capacity. Necessary headways are maintained between platoons to allow vehicles in the right lane to change to the left lane. Similarly, vehicles in the automated lane may disengage from a platoon and change to the right lane. Two assumptions are made in this paper regarding lane change maneuvers. First, a vehicle will change from the non-automated to the automated lane at the speed of the non-automated lane. Conversely, a vehicle changing from the automated to the non-automated lane will do so at the speed of the automated lane.

The considerable difference in speeds between the left and right lanes in a semi-automated highway makes analysis of lane change movements considerably more complex than for a conventional highway. Under the assumptions outlined in the previous paragraph, a vehicle merging from the non-automated lane to the automated lane will have to increase its speed within the headway available between platoons. Similarly, a vehicle merging from the automated to the non-automated lane will have to decrease its speed within the headway available between vehicles.

Speed transitions involved in changing lanes in a semi-automated highway may have serious capacity and safety implications. For example, consider the case where the automated lane is considerably faster than the non-automated lane. Then, the headway required between vehicles in the

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non-automated lane would be considerably larger than that required on a conventional highway. Thus, in the semi-automated highway, there is a reduction in capacity for the non-automated lane when compared with the conventional highway. This reduction in capacity needs to be compensated by suitably increasing the capacity in the automated left lane. This can be achieved by increasing the speed of traffic flow and/or the platoon size in the automated lane. This study computes the minimum platoon size required at various speed configurations so that the overall capacity of the automated highway is greater than that of the conventional highway. This is accomplished by evaluating headways required in each lane to ensure smooth lane change and merging movements. Fundamental theories of traffic flow and equations of motion are used to perform this analysis.

Several other assumptions are also made to ensure robustness of the analysis presented in the following sections. It is assumed that the entire highway system is controlled by a centralized computer system which adjusts headways and platoon sizes based on the demand for service. In the event of an emergency (such as a failure of the centralized computer system), all drivers will be warned to switch to manual operation.

3. Models for Capacity Analysis

This section develops the theory and equations necessary to evaluate the capacity of automated and non-automated lanes in a semi-automated highway. A discussion on the capacity of a conventional highway is also included for completeness.

A) Semi-Automated Highway: Non-automated Lane

Consider a stretch of automated highway as shown in Figure 1A. The left lane is automated while the right lane is not. Vehicles in the automated lane proceed in platoons while those in the non-automated lane proceed in a conventional manner.

Consider a vehicle B in the automated left lane that desires to change to the non-automated right lane. Vehicle B must change lanes at the speed of the automated lane as slowing down is not permitted in this lane. Figure 1A shows vehicle B changing from the automated to the non-automated lane at the speed of the automated lane, V_1. The speed of the non-automated lane, V_2, is presumably smaller than V_1. Let vehicle B merge into the non-automated lane just in front of vehicle C. The headway between two vehicles A and C in the non-automated lane should be such that vehicle B can slow down to speed V_2 without having a rear-end collision with vehicle A. Figure 1B shows the completion of the maneuver.

In a conventional highway, vehicle B would have been able to slow down considerably in the left lane before performing the lane-change maneuver. However, in this case, vehicle B requires an additional slow-down distance to be provided between vehicles in the non-automated lane. In this section, the total headway required so that vehicle B can change lanes smoothly is derived using equations of motion.

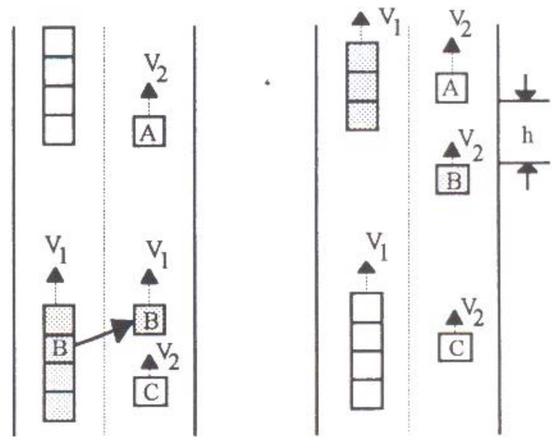

Figure 1A Figure 1B
Merging from Automated (Left) to Non-Automated (Right) Lane

The total headway required between vehicles A and C may be written as:

$$H_r = h + (S_B - S_A) + L \quad (1)$$

where h is the headway required between vehicles A and C in a conventional highway, S_B is the distance traveled by vehicle B in slowing down from speed V_1 to V_2, S_A is the distance covered by vehicle A during that time, and L is the average length of a vehicle.

S_B may be derived from equations of motion as,

$$S_B = \frac{V_2^2 - V_1^2}{2a_m} \quad (2)$$

where a_m is the comfortable rate of deceleration for vehicle B. The time required by vehicle B to cover this distance is,

$$T_B = \frac{V_2 - V_1}{a_m} \quad (3)$$

During this time, vehicle A moving at a speed of V_2 would travel a distance given by,

$$S_A = V_2 T_B = \frac{V_2^2 - V_1 V_2}{a_m} \quad (4)$$

Substituting equations (2) and (4) into equation (1) gives the total headway in the non-automated lane as,

$$H_r = h - \frac{(V_2 - V_1)^2}{2a_m} + L \quad (5)$$

It is to be noted that a_m is negative as it constitutes a deceleration rate. Also, length L is added to the total headway as headways are being measured in this paper with reference to the front ends of vehicles. Values for conventional highway lane headways, h, will be discussed in a later section.

Finally, the capacity of the non-automated lane would be,

$$C_r = \frac{V_2}{h - \frac{(V_2 - V_1)^2}{2a_m} + L} \tag{6}$$

B) Semi-Automated Highway: Automated Lane

The evaluation of capacity of the automated left lane is similar to that described by Whiteside (1988) and closely parallels the evaluation of the non-automated lane. Figures 2A and 2B show the lane-change maneuver of a vehicle B from the non-automated to the automated lane that is going to govern the capacity of the automated lane.

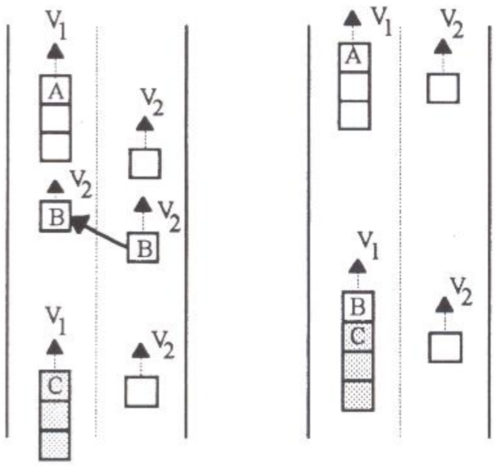

Figure 2A Figure 2B

Merging from Non-automated (Right) to Automated (Left) Lane

The headway to be provided in the automated lane should be such that vehicle B merging just behind platoon A will be able to accelerate and attain the speed of the automated lane, V_1, without being subject to a rear-end collision by platoon C. On completion of the lane-change maneuver, vehicle B will become the lead vehicle of platoon C. This is shown in Figure 2B.

Let n be the platoon size, i.e., the number of vehicles in one platoon before the merge. Then, the total headway required between platoons A and C is,

$$H_l = S_C - S_B + L + nL \tag{7}$$

where S_B is the distance traveled by vehicle B in accelerating from a speed V_2 to V_1, S_C is the distance traveled by platoon C during this time, and L is the average length of a vehicle. The length of one vehicle, L, is added to account for the length of vehicle B. It is to be noted that the total headway is being measured from the front-end of the lead vehicle in platoon A to the front-end of the lead vehicle in platoon C.

Again, equations of motion are applicable to the computation of various quantities. S_B is given by,

$$S_B = \frac{V_1^2 - V_2^2}{2a_n} \tag{8}$$

where a_n is the rate of acceleration of vehicle B. The time required by vehicle B to accelerate from speed V_2 to V_1 is,

$$T_B = \frac{V_1 - V_2}{a_n} \tag{9}$$

During this time, platoon C moving at a speed of V_1 would travel a distance given by,

$$S_C = V_1 T_B = \frac{V_1^2 - V_1 V_2}{a_n} \tag{10}$$

Substituting equations (8) and (10) into equation (7) yields,

$$H_l = \frac{(V_1 - V_2)^2}{2a_n} + (n+1)L \tag{11}$$

Then, the capacity of the automated lane would be,

$$C_l = \frac{V_1 n}{\frac{(V_1 - V_2)^2}{2a_n} + (n+1)L} \tag{12}$$

Finally, combining capacities of the non-automated and automated lanes provides the total capacity of the semi-automated highway, i.e., $C_s = C_r + C_l$.

C) Conventional Highway

The Highway Capacity Manual (TRB, 1985) provides values of maximum service flow (MSF) rates for various freeway speeds. These values are adopted in this paper as estimates of conventional highway capacities. Also, the maximum value of highway capacity is taken to be that which occurs at level of service E (V/C ratio equal to 1).

It is noted that equation (6) requires estimates of h (space headway on a conventional highway) to compute the capacity of the non-automated lane in a semi-automated highway. Space headway at capacity is given by (May, 1990):

$$h + L = \frac{V}{C} \tag{13}$$

where V is speed and C is capacity.

4. Simulation Results

This section presents results of numerical simulations to analyze capacity benefits that can be accrued through semi-automation. Minimum platoon sizes required in the automated lane so that the overall capacity of the automated highway is greater than that of the conventional highway are computed.

Table 1 shows capacity calculations for conventional and semi-automated highways under various speed scenarios.

Table 1. Capacity Analysis of a Semi-Automated and Conventional Highway

Conventional Highway			Semi-Automated Highway					
Lane Speeds		Total	Lane Speeds		Platoon	Left Lane	Right Lane	Total
Left Lane mph	Right Lane mph	Capacity* vph	Left Lane mph	Right Lane mph	Size veh	Capacity vph	Capacity vph	Capacity vph
40	30	4000	75	30	3	4091	553	4644
			100	30	5	3757	273	4030
			125	30	8	4080	158	4237
50	40	3700	75	40	2	4508	881	5390
			100	40	4	4091	437	4528
			125	40	6	3822	247	4069
60	50	3100	75	50	1	4418	1127	5545
			100	50	2	2945	619	3565
			125	50	4	3273	354	3626
70	60	2000	75	60	1	12273	932	13205
			100	60	1	2301	659	2960
			125	60	2	2179	423	2601

*These capacities are based on an assumed 70 mph design speed.
*Source: Transportation Research Board (1985) Highway Capacity Manual.

Several assumptions were made to facilitate the numerical simulations. First, a design speed of 70 mph was assumed. Conventional highway capacities were obtained from the Highway Capacity Manual (TRB, 1985) based on this assumption. Second, in a conventional highway, it was assumed that the left lane is approximately 10 mph faster than the right lane. Third, for the semi-automated highway, an acceleration rate (for accelerating in the automated lane) of 7.5 ft/sec^2 and a deceleration rate (for decelerating in the non-automated lane) of 10.5 ft/sec^2 are assumed. These values are recommended by Barwell (1977) and are in agreement with those provided by May (1990). In reality, acceleration and deceleration rates vary with speed; however, for the analyses presented here, it was considered sufficient to assume the same average acceleration and deceleration rates for all speed scenarios. Finally, the average length of a vehicle is assumed to be 12 ft.

In the table, capacities of conventional highways are presented first. Four possible speed scenarios are considered based on a right lane speed of 30, 40, 50, or 60 mph. The same speeds are used for the right lane of the semi-automated highway. However, for the left lane, speeds of 75, 100, and 125 mph are considered. This is because automation will presumably result in realization of speeds beyond the design speed.

From the table, it can be seen that the capacity of the right lane in an automated highway is considerably less than that in a conventional highway. This is consistent with the discussion earlier that additional headway is required to accommodate vehicles changing from the automated to the non-automated lane. However, this loss in capacity on the non-automated lane can be offset through capacity increases on the automated lane. The table shows *minimum* platoon sizes required in the automated (left) lane such that the overall capacity of the automated highway is greater than that of the conventional highway.

The results indicate that minimum required platoon sizes increase as speed differentials between automated and non-automated lanes increase. For example, when the automated and non-automated lane speeds are 125 mph and 30 mph respectively, a minimum platoon size of 8 is required to ensure that the automated highway has a capacity greater than that of the conventional highway. However, when the automated and non-automated lane speeds are 125 mph and 60 mph respectively, a platoon size of 2 vehicles is sufficient to ensure capacity increases through automation. In fact, when speed differentials are reduced further, (say, at 100 mph and 60 mph speeds), platoon sizes of 1 are sufficient to ensure capacity increases. This implies that each vehicle may individually constitute one platoon.

In general, it is found that reasonably small platoon sizes are sufficient to ensure capacity increases through automation. The small platoon sizes ensure that the frequency of acceptable gap occurrence (to accommodate vehicles changing lanes) will be considerably high. If highway automation required the deployment of long platoons, lane changing maneuvers would become cumbersome as acceptable gaps would occur rarely. The analysis presented in this section supports the notion that highway automation may provide capacity increases without having to make substantial compromises in vehicle maneuverability.

5. Conclusions

Automation and control in transport is increasingly being suggested as a means of mitigating urban traffic congestion. Highway automation may potentially increase highway speeds while reducing vehicle headways thereby providing for a more efficient use of existing infrastructure. Advanced transportation technologies have received further impetus through recent federal legislation, namely, ISTEA (1991) and The Clean Air Act Amendments (1990).

This paper aimed at analyzing the operation of a semi-automated highway where the inner left lane is automated and the right lane is non-automated. Vehicle headways and lane capacities were theoretically derived using fundamental theories of traffic flow describing vehicle dynamics. It was found that larger speed differentials between the left and right lanes in an automated highway required larger headways in the non-automated right lane. This reduced the capacity of the right lane when compared with that of a conventional highway. However, this loss in capacity could be adequately offset by increasing the speed and/or platoon size of vehicles in the automated left lane. In general, small platoons ranging in size from 1 through 8 were found to be sufficient to ensure that highway automation resulted in capacity increases.

The computation of minimum platoon size requirements has several important implications. First, small platoons ensure that acceptable gaps occur frequently enough to facilitate lane change maneuvers without delays. Second, geometric and pavement design considerations may place a limitation on the size of the platoon that can be accommodated. For example, the presence of sharp curves, hilly terrain, or bridges may necessitate small platoon sizes so that vehicles may be maneuvered safely at high speeds while ensuring passenger comfort. Third, safety considerations may warrant a restriction on platoon sizes. In case of a disastrous failure of the automated system, a smaller platoon size may entail fewer vehicles being involved in an accident. Finally, human factors need to be considered. Drivers may prefer small platoons so that they can see the lead vehicle of their platoon and be psychologically satisfied that they are fully aware of their vehicle's environment.

In summary, a semi-automated highway, which may constitute a first step towards full automation, exhibits tremendous potential for providing capacity benefits. This paper has quantified the capacity benefits that can be realized at various speed configurations.

Further research is warranted in the area of capacity analysis of automated highways. First, this paper has concentrated solely on the operational aspects of the highway. Human factors have not been explicitly considered. Driver behavior, perceptions, and attitudes are likely to significantly impact the effectiveness of advanced transportation technologies. Second, the analysis in this paper makes several assumptions regarding acceleration and deceleration characteristics of vehicles, speeds at and during lane change maneuvers, and other operational characteristics. These assumptions allow a convenient static analysis of the semi-automated highway system. It would be worthwhile to relax these assumptions and attempt to perform dynamic simulations of vehicle movements where platoons are in a constant state of transition. This would provide for more accurate replication of real-world conditions.

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