Feedback Control Speed Harmonization Algorithm: Methodology and Preliminary Testing

Hao Yang[a] and Hesham Rakha[b]
(a) Toyota Info Technology Center, (b) Center for Sustainable Mobility, Virginia Tech Transportation Institute

Introduction

The rapid growth of both traffic and freight volumes increases the pressure of transportation systems significantly. Recently, most urban transportation systems experience congested conditions on a regular basis and provide increasingly unreliable services, such as heavy delay of daily trips, capacity drops, high emissions and fuel consumption, high risk of incidences, etc. Aimed to mitigating traffic congestion, proactive operation strategies, a fully integrated, multimodal, and multi-jurisdictional manner, have been widely implemented on a corridor-wide or region-wide basis. Intelligent transportation system (ITS) is one effective tool to implement proactive operation strategies. ITS can deploy various dynamic actions/strategies based on prevailing and anticipated conditions to prevent, delay, and/or minimize breakdown conditions thereby optimizing the effectiveness, efficiency and safety of the transportation systems.

The capacity drop phenomenon, which reduces the maximum bottleneck discharge rate following the onset of congestion, is a critical restriction in transportation networks that produces additional traffic congestion. Consequently, preventing or reducing the occurrence of the capacity drop not only mitigates traffic congestion, but can also produce environmental and traffic safety benefits. In addressing this problem, the study develops a novel bang-bang feedback control speed harmonization (SH) or Variable Speed Limit (VSL) algorithm, that attempts to prevent or delay the breakdown of a bottleneck and thus reduce traffic congestion. The novelty of the system lies in the fact that it is both proactive and reactive in responding to the dynamic stochastic nature of traffic. The system is proactive because it uses a calibrated fundamental diagram to initially identify the optimum throughput to maintain within the SH zone. Furthermore, the system is reactive (dynamic) because it monitors the traffic stream directly upstream of the bottleneck to adjustment the metering rate to capture the dynamic and stochastic nature of traffic. The steady-state traffic states in the vicinity of a lane-drop bottleneck before and after applying the SH algorithm is analyzed to demonstrate the effectiveness of the algorithm in alleviating the capacity drop. We demonstrate theoretically that the SH algorithm is effective in enhancing the bottleneck discharge rate. A microscopic simulation of the network using the INTEGRATION software further demonstrates the benefits of the algorithm in increasing the bottleneck discharge rate, decreasing vehicle delay, and reducing vehicle fuel consumption and CO2 emission levels. Specifically, compared with the base case without the SH algorithm, the advisory speed limit increases the bottleneck discharge rate by approximately 7%, reduces the overall system delay by approximately 20%, and reduces the system-wide fuel consumption and CO2 emission levels by 5%.

Research Objectives

- The objective of speed harmonization is to dynamically adjust maximum appropriate vehicle speeds in response to downstream congestion caused by bottlenecks to maximize the discharge flow rates of bottlenecks as well as reducing travel delay, fuel consumption, and emissions. The strategy makes use of the frequently collected and rapidly disseminated multi-source data drawn from connected travelers, roadside sensors, and infrastructure.

Our Work

1. Develop a SH algorithm based on a feedback control system and V2I communications to provide advisory speed limits for connected vehicles to prevent capacity drop at bottlenecks;
2. Investigate the effect of the SH algorithm on improving the discharge flow rates of bottlenecks, reducing delay, fuel consumption, and emissions.

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Methodology

Speed harmonization is implemented to improve the discharge flow rates of bottlenecks as well as reduce traffic delay and emissions and fuel consumption. Fig. 1 illustrates the structure of a lane-drop bottleneck. To develop a speed harmonization algorithm, we place three sets of detectors: one in the SH zone, one directly upstream of the bottleneck, and one directly downstream of the bottleneck. If on- and/or off-ramps exist between the SH zone and the bottleneck, detectors are needed on the on- and off-ramps to record the traffic flow. The detectors gather traffic volume, speed and occupancy data for use in the algorithm. Equipped vehicles in the SH zone receive advisory speed limits from the TMC to control the flow arriving at the bottleneck.

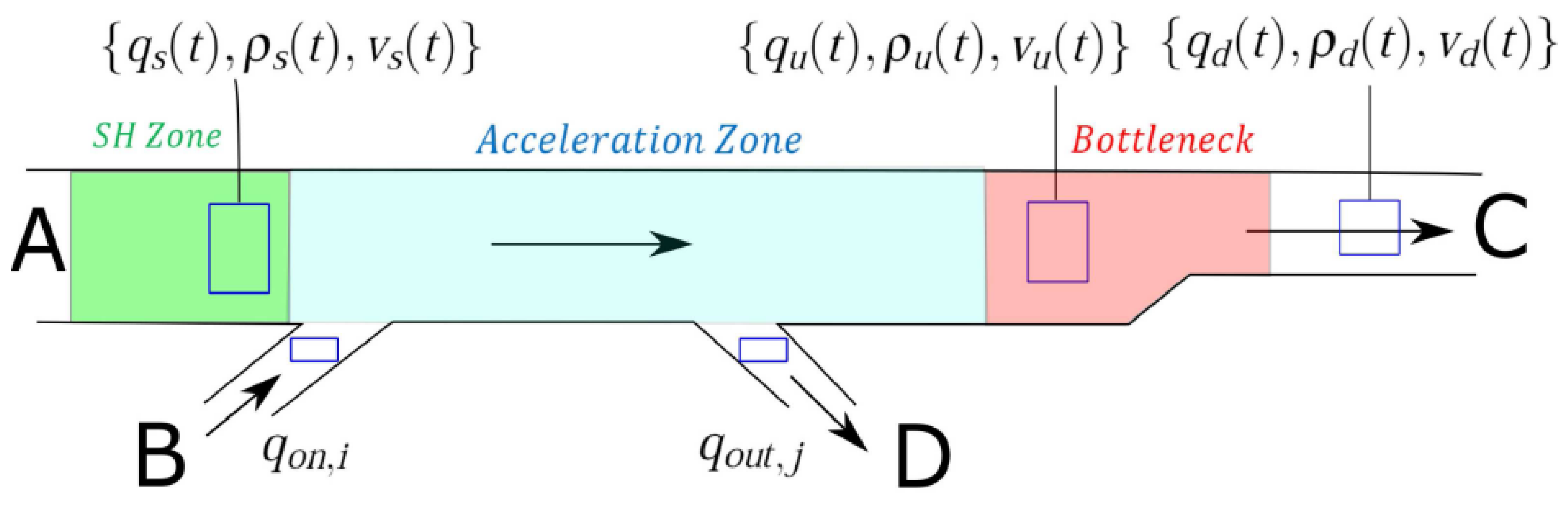


Fig.1. Illustration of lane-drop bottleneck

Capacity Drop at Bottleneck

$$Q_b = \begin{cases} q_{d,c} & \rho_u(t) < \rho_{d,c} \\ (1-\delta)\cdot q_{d,c} & \rho_u(t) \geq \rho_{d,c} \end{cases}$$

Q_b : capacity of the bottleneck;
$q_{d,c}$: density at capacity of the bottleneck;
δ : capacity drop factor;

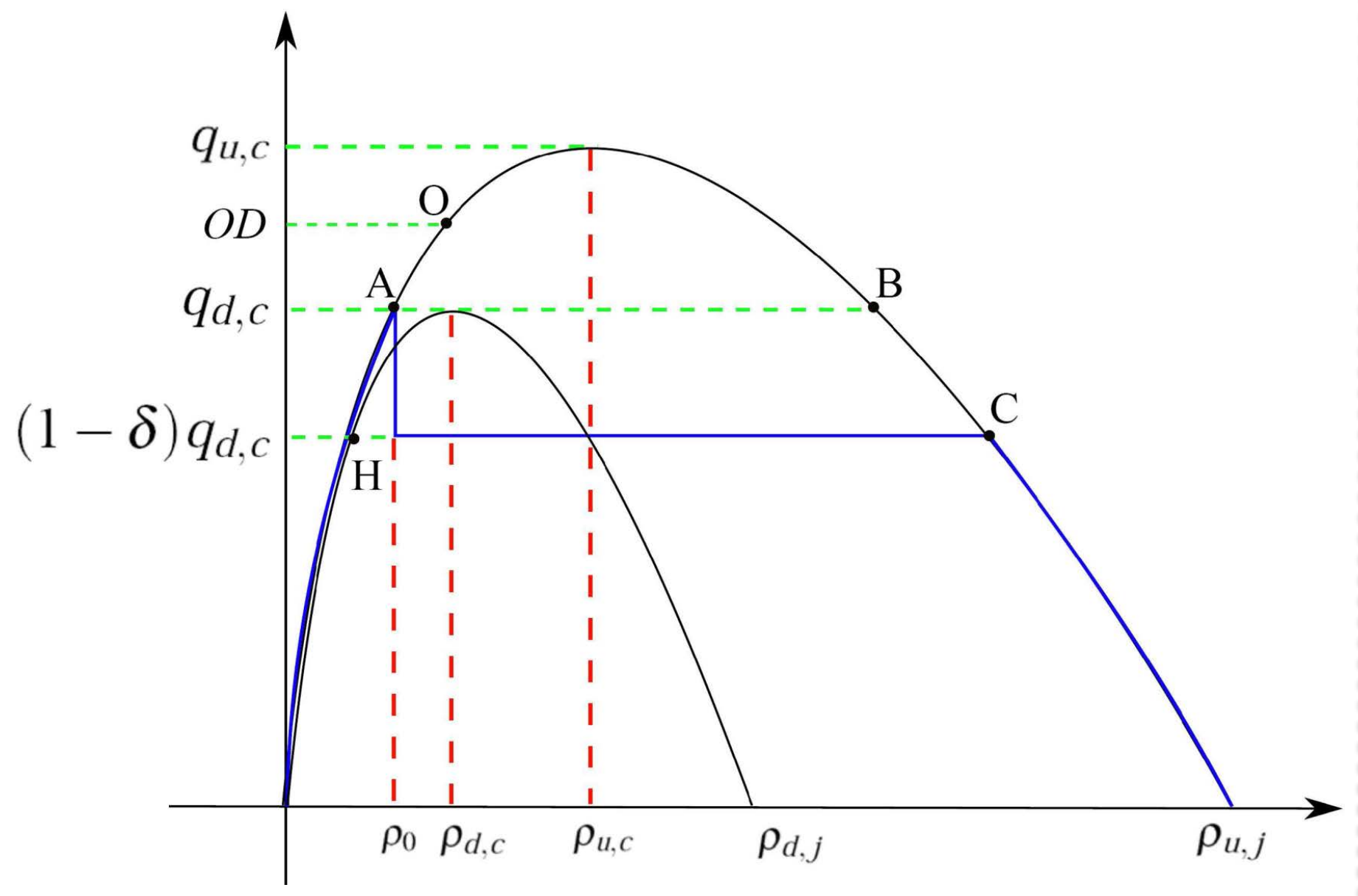


Fig.2. Fundamental Diagram at bottleneck

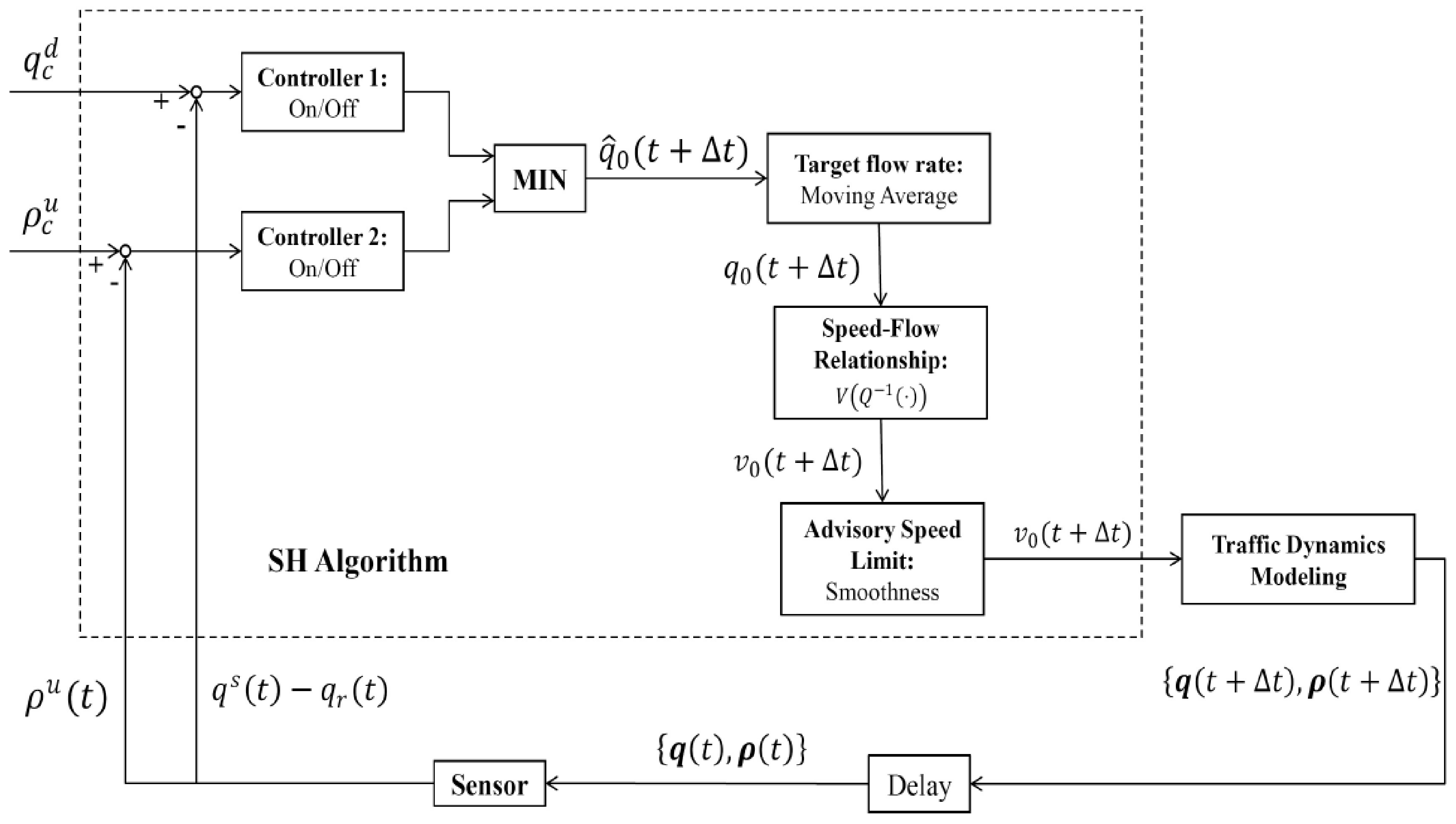
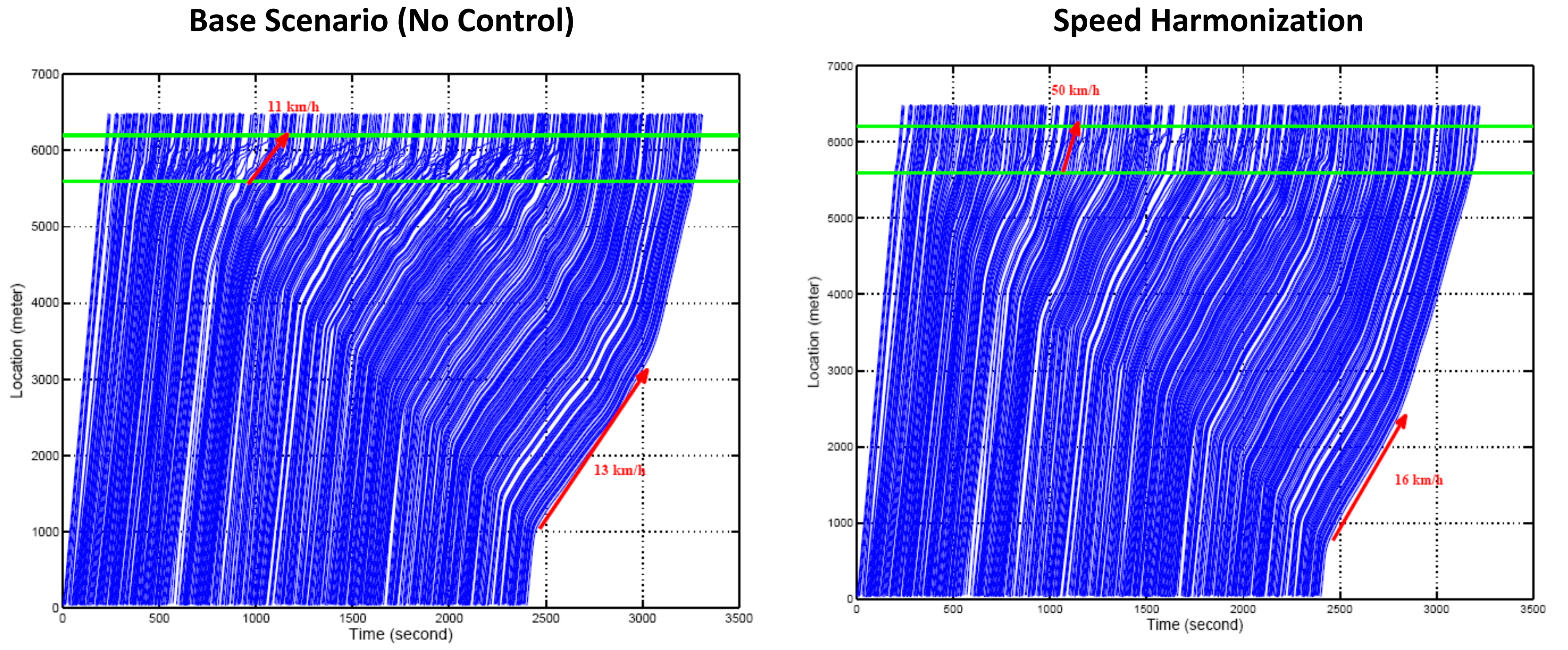


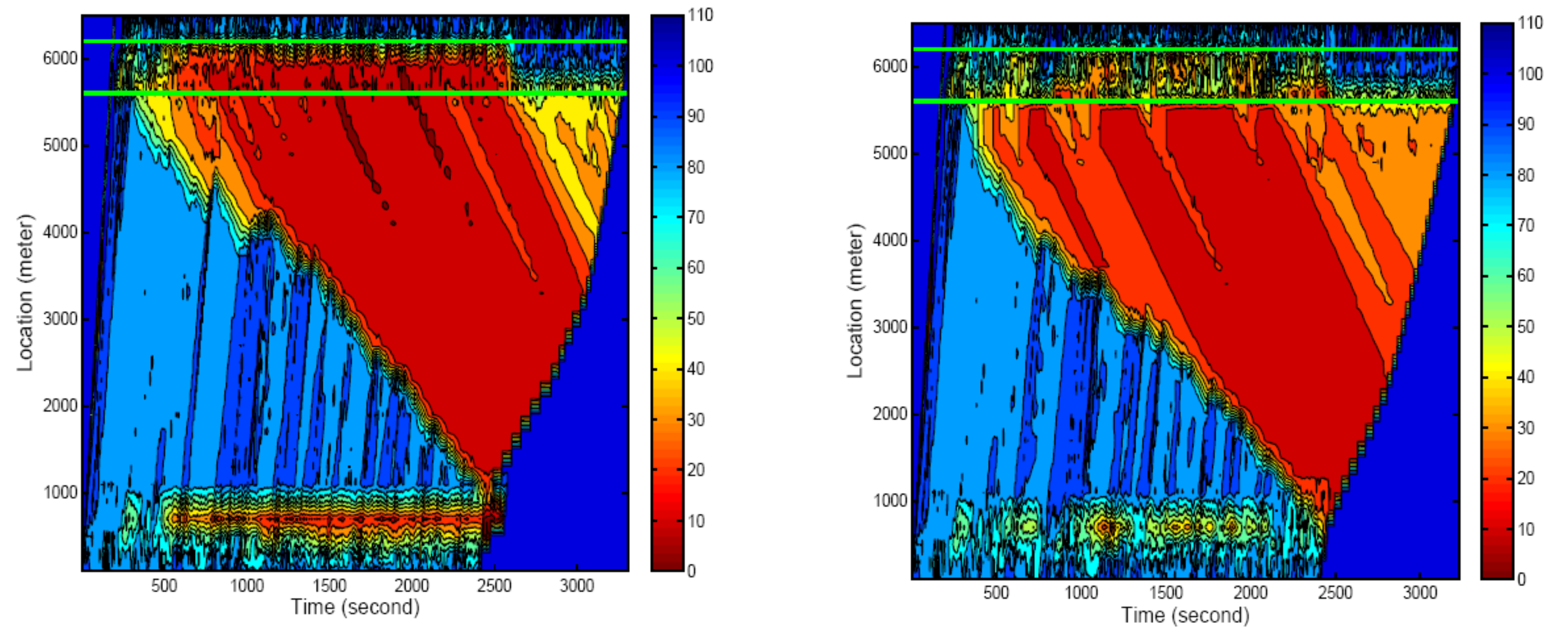
Fig. 3. SPD-HARM algorithm feedback control schematic

The algorithm is activated either when the out-flux of the SH zone is larger than the target flow rate or when the upstream of the bottleneck is congested. The advisory speed limit is introduced to move the state of traffic at the upstream of the bottleneck to the steady state. The limit is also smoothed to reduce the risk of car crashes.

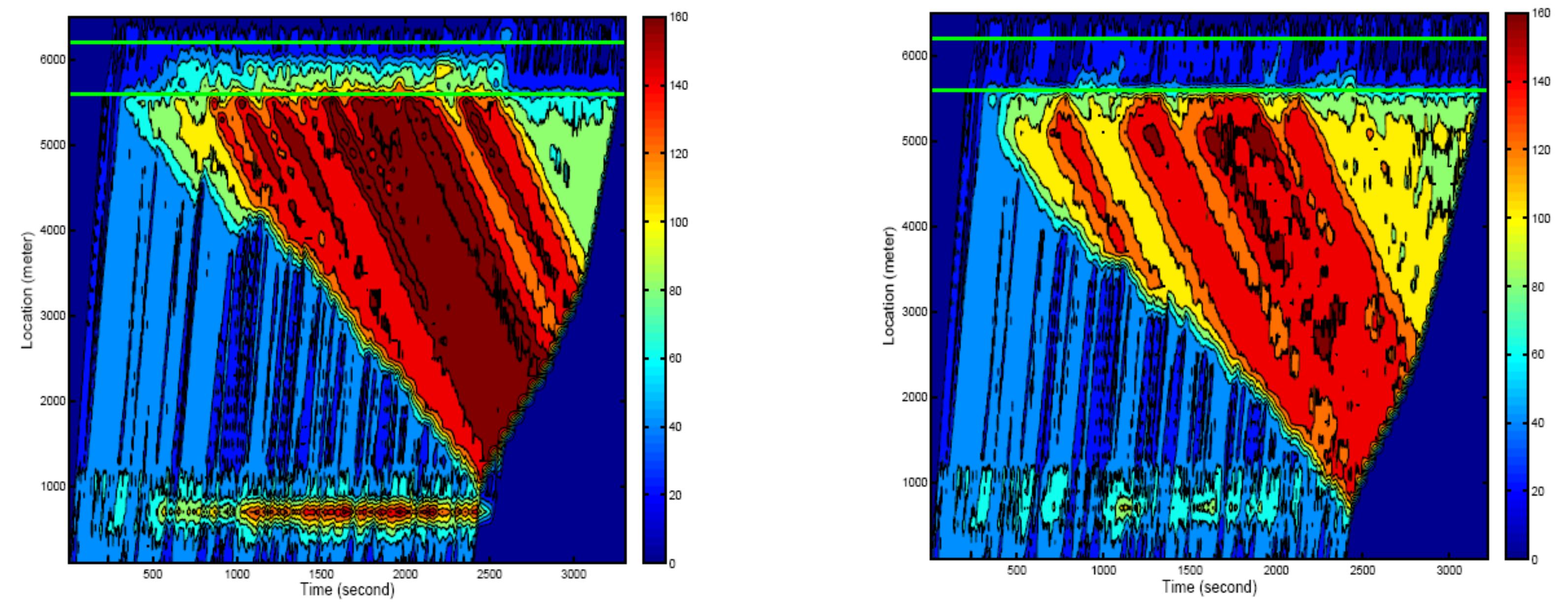
Simulation


Base Scenario (No Control)
Speed Harmonization

Vehicle Trajectories



Speed Profiles



Density Profiles

Table 1: Benefits of the SH algorithm

Measurement	No Control	SH algorithm	Diff (%)
Delay (s/km)	71.24	57.05	-19.92
Fuel (l/km)	0.125	0.119	-5.24
HC (g/km)	0.254	0.258	1.40
CO (g/km)	6.437	6.736	4.63
NOx (g/km)	0.307	0.301	-1.93
CO_2 (g/km)	281.2	265.5	-5.59

Conclusion

1. This study develops a dynamic SH algorithm to prevent the generation of capacity drop and to mitigate the existing capacity drop at bottlenecks;
2. The SH algorithm increases the discharge flow rate of bottleneck about 7% and reduces the delay by up to 20%;
3. Applying the algorithm can also reduce fuel consumption and emissions.