Physica A 503 (2018) 491–502

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

An analysis on the traffic processing efficiency of a combination of serial and parallel bottlenecks

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HIGHLIGHTS

- Capacity of serial and parallel bottlenecks have been compared using full analytical solutions.
- Analysis shows that the difference in the constrained motion results in the difference in capacity.
- Novel combination of serial and parallel expansions was proposed.
- The efficacy of these bottlenecks in relevance of real-world traffic have been discussed.

ARTICLE INFO

Article history:
Received 12 July 2017
Received in revised form 21 January 2018

Keywords:
NaSch model
Cellular automaton
Multi-point tollbooth
Lane expansion
Fundamental diagram

ABSTRACT

By means of the Nagel–Schreckenberg model, we have investigated into the maximum vehicular flow rate of traffic processing bottlenecks. The evaluated analytical form of this flow rate is found to give quantitative insights into the underlying physics of collective vehicular motions constrained by these bottlenecks. Our analysis shows that for large-scale expansion, a new class of processing bottleneck known as the serial bottleneck is more efficient than the conventional parallel bottleneck in the absence of human driving behavior. When characteristics such as slow-to-start is considered in the model, the consequential delay due to human reaction time not only degrade the overall efficiency, it also diminishes the efficacy of serial processing such that a serial bottleneck is no longer tenable for traffic processing. These results point to the fundamental importance of optimizing traffic efficiency, which we illustrate by elucidating the detailed mechanisms with which vehicles interact collectively in the bottlenecks. In particular, we demonstrate that by constructing combinations of serial and parallel bottlenecks, optimal efficiencies are achieved via configurations with few (many) lanes of a large (small) number of serial units when the processing time is short (long). A direct implication of these results is that autonomous self-driving vehicles could serve to improve the transportation capacity for the densely populated urban cities of the future, due to the intrinsically more efficient collective vehicular motions through these bottlenecks.

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https://doi.org/10.1016/j.physa.2018.02.081

1. Introduction

The Nagel–Schreckenberg (NaSch) model [1] is a cellular automaton that had been used extensively for theoretical traffic modeling. While it is simplistic and does not describe the full spectrum of real-world traffic phenomenology, it does capture the essential aspect of the emergence of congestion when vehicular density increases past a critical value [2]. In particular, this transition is known as the absorbing-state phase transition [3] when the random deceleration parameter $p = 0$. Active research on critical transition in traffic system invariably employs the NaSch model due to its analytical tractability [4]. In fact, one example of such phase transition occurs at the presence of bottleneck, with a *plateau* exhibited in the fundamental diagram. Traffic states at the plateau are observed to display the characteristics of phase-segregation in the spatiotemporal trajectories of the vehicles, with a continuous change from the free flow to the congestion state as the traffic density increases. Interestingly, this change is similar to the separation of liquid phase and vapor phase in a van der Waals fluid, giving the study of NaSch model with bottleneck a direct relevance to statistical physics [2].

In real-world traffic system, the presence of traffic bottlenecks is fundamental and they are inevitable sources of congestion. Traffic bottlenecks appear in various forms: as accident sites, merging of lanes, or even slow moving vehicles. In general, traffic bottleneck is defined as a localized section of the road or highway at which vehicles experience reduced speeds, and vehicles may require more time to transverse through these sites. This reduction in flow rate results in an increase in vehicle density, which in turn leads to the instability of the free flow phase due to the collective vehicular interactions, eventually leading to traffic congestions at the bottlenecks [5].

While traffic bottlenecks can arise spontaneously and randomly such as in the case of a traffic accident, a vast majority of bottlenecks are fixed in their locations. Examples of these latter bottlenecks include tollbooths, highway's on/off-ramps, pick-up/drop-off points for public transport, and many more. Nowadays, such fixed-site bottlenecks are common sights in the traffic landscape of modern societies. Their purpose is to process the mobility of traffic flow, which is of interest in this paper. Since bottlenecks serve only to increase vehicular density which in turn destabilizes the free flow phase, an important conclusion is that the effects of a bottleneck on traffic flow is independent of the specific bottleneck mechanism [2,6–8]. The consequence is a maximum outflow through the bottleneck, which is known as the bottleneck capacity. Bottleneck capacity corresponds to the maximum value of the macroscopic traffic flow captured by the fundamental diagram in a closed, or sufficiently long stretch of road. Its universal feature enables a general study of bottlenecks by solving the maximal outflow through it, or by the time-headway approach adopted in this paper.

At present, there are numerous studies on traffic bottlenecks using NaSch model, such as the effects of time-delay bottlenecks [6], on- and off-ramps [9], and lane expansion at bottlenecks [10,11]. These studies have been further facilitated by full analytical solutions of the bottleneck capacity, and compared against the flow-density relation of the homogeneous NaSch model in the deterministic limit, or in the $v_{\max} = 1$ limit [12,13]. Solutions based on mean-field approximation have also been explored for general parameter range [14,15]. The analytical solutions from these studies allow for greater quantitative insights into the physical mechanisms underlying traffic bottlenecks, which are not tenable from empirically consistent traffic models since the complex parameterization and stochasticity within these models render such solutions almost impossible [2]. The analytical consequences of NaSch model as exhibited in these research give strength to the approach, and explains its continued relevance in current traffic studies even when there exist traffic models that are more empirically consistent [8,16,17].

In this paper, we examine into a new type of bottleneck whose function is to process the mobility and transportation needs of modern society. In order to sustain the rapid growth of traffic demands, these *processing* bottlenecks are required to function efficiently. Our idea is a bottleneck that comprises multiple processing units that serve the same function, with both serial and parallel processing occurring at the same time. In other words, our proposed processing bottleneck combines two configurations: processing in parallel; and in serial (see Fig. 1).

Parallel expansion of traffic bottleneck involves splitting a lane into multiple lanes in the vicinity of a processing site, with each lane supporting a single processing unit. This is the typical method used to increase the processing capacity of tollbooths and immigration counters. Several studies were performed to probe the effect of parallel expansions of bottlenecks on traffic flow [10,18,19]. Notably, the capacity of a highway is found to be fully recoverable through parallel expansion of bottleneck [10]. On the other hand, serial expansion of traffic bottleneck allows multiple processing units to be co-located along a lane such that two or more vehicles are simultaneously processed. As an example, a bus bay that extends over a length of two buses allows passengers from two buses to alight and board at the same time. This decreases the overall processing time of the two buses. Such an expansion of traffic bottleneck was explored in Ref. [20] to investigate the influence of manual versus electronic toll collection on traffic flow.

In the following sections, we first measure and compare the flow-density relation of a simplified NaSch model, modified with a parallel and a serial expansion of traffic bottlenecks. These values will be compared against the processing capacity of the different expansions, which would be solved analytically. Note that such characterization has yet to be achieved in the literature. Interestingly, the two expansions perform differently with each outperforming the other under certain conditions. One key advantage of a serial expansion is that it requires no expansion of lane to function. This raises the possibility of trading processing efficiency with the cost of lane expansion. For this, we examine into the mechanism underlying the discrepancy in efficiency of the two expansions. In addition, we quantify the difference between them in terms of various bottleneck parameters. After which, we proceed to analyze the performance of a traffic bottleneck that combines parallel and serial processing into a single multi-processing unit. In particular, we investigate into the conditions under which this combination bottleneck outperforms both the parallel and serial expansions in terms of traffic processing capacity.