Reproducible Features of Congested Highway Traffic

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Abstract

Observation of a 4-mile long, inhomogeneous, congested traffic stream revealed that vehicle accumulations between detectors vary with flow in a predictable way, and that a macroscopic kinematic wave with a reproducible speed exists in queues despite unusual traffic behavior. As a result, time-dependent vehicle trip times and accumulations inside long queues (and the queue length itself) can be predicted from readily available data without using any "degrees of freedom" to fit the parameters of a model. Experimental vehicle counts were within 20 vehicles of the predictions for over 2 hours.

KEY WORDS:

Traffic flow theory; congestion prediction; traffic spillovers; bottleneck effects; experimental verification

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Scientists and engineers have known for a long time that congested traffic streams exhibit unstable "stop-and-go" behavior [1], and that this behavior is inconsistent with the simplest and earliest theories of traffic flow, such as the car-following (microscopic) theories in [2] and the kinematic wave (KW) continuum theory of [3] and [4]. As a result, more complicated theories that allow for traffic instabilities were soon proposed (e.g., [5], [6], and [7]), but these theories had limited success in explaining driver behavior in detail. This led to a proliferation of new theories, which has accelerated in recent years (e.g., [8] and [9]). Today the number of theories exceeds the number of experiments and the former usually have to be adjusted to fit the data. The inability of traffic scientists to find a satisfactory description of driver behavior should not be surprising because drivers are different and idiosyncratic, and because highway inhomogeneities can affect drivers in site-specific ways.[1] This suggests complimentary efforts directed at finding macroscopic and site-dependent properties of the traffic stream on a scale of measurement where statistical fluctuations can be ignored. This paper reports on early successes in this direction; it shows, among other things, that the time series of vehicular accumulations between detectors in queued traffic is quite predictable, strongly suggesting that there is order within the complexity of traffic phenomena. The findings in this paper will allow engineers to improve traffic control methods so as to avoid backups and spillovers.

[1] The only theories that have been developed for inhomogeneous highways seem to be continuum models in the KW family (e.g., [3], [10], and [11]).

1 Background

Recent evidence from observations on two continents ([12], [13], and [14]) suggests that large disturbances in average flow propagate through space quite steadily and predictably. This has been confirmed quantitatively at other locations where researchers have been able to replicate the time series of average flows over a detector reasonably well with the KW model from knowledge of the time series at a neighboring detector [15], [16]. These limited successes do not indicate, however, what happens when the separation between observation points is large enough for small disturbances to grow large and/or when small highway inhomogeneities disrupt the traffic stream. This paper examines the character of the traffic stream under these conditions with data in [17], stressing aspects of practical importance such as the time series for vehicular accumulation, trip times, and cumulative counts.[2]

The site in question is a long southbound lane with slight grade changes that feeds a congested traffic signal; see Fig. 1(a). The vertical arrows in the figure indicate the observation points. Observations were made on two separate days for 2+ hour periods including the morning rush. The site is good for an experiment because the flow through the Wildcat Canyon intersection varies substantially within and across days, and because the queue often grows beyond 2 miles from the intersection, with a growth pattern that changes considerably from day to day.

As reported in [17], oscillations in traffic flow directly upstream of the traffic signal at location 8 traveled upstream toward detectors 7 and 6 as waves, but were quickly damped.

[2]These data have been posted at "http://www.ce.berkeley.edu/∼ daganzo/spdr.html".

This can be seen from the 2-minute pulses in the curve of cumulative vehicle count versus time observed at 8, curve N(8,t) of Fig. 1(b), which are largely absent in the curves for observers 7 and 6, N(7,t) and N(6,t). Reference [17] also noted that oscillations with longer amplitudes were observed further upstream within the queue, as exemplified by the wavy pattern of curves 2, 3, 4 and 5.[3]

The cumulative counts of Fig. 1(b) were started with the passage of a reference vehicle across all observers; thus a horizontal line representing a particular vehicle intercepts the curves at the times when the vehicle in question passes the various observers. As a result, horizontal separations between two lines are trip times between observers, and vertical separations between lines are vehicle accumulations between observers.[4] Visualizing traffic flow in this way, one can determine at a glance when and where queues start and dissipate, and whether traffic is queued at any given time. This is important for the purposes of this paper which focuses on queued traffic. Fig. 1(c) illustrates this idea with the curves for the early part of the day. The onset of queuing at a particular location (e.g., at observers 6 and 7 as denoted by the arrows) is marked by the divergence of the corresponding N-curve from its companion to the left. When traffic is not queued between two observers their N-curves are nearly parallel and separated horizontally by a minimum trip time, as occurs with curves

[3]Both effects could be due to inhomogenieties [18]. The dissipation of pulses could be caused by drivers' ability to see the signal, and the longer period oscillations by changes in grade and the occasional drivers of heavy vehicles who allowed long gaps in front of them.

[4]For problems involving 1-dimensional flow, cumulative curves such as those in Fig. 1(b)–called N-curves here– are often preferred by engineers to time series of average flow because the latter conceal information about trip times and vehicle accumulations.

1-5 [12]. (The wider separation between curves 1-2 is simply due to the fact that segment 1-2 was longer.) These diagnostics were used to determine the queued intervals at each location because our final objective was to see what could be said about the queued portion of the N(j,t) curves from knowledge of downstream data, N(8,t).

2 KW Theory revisited

The KW theory was applied directly to the cumulative curves for queued traffic, as suggested in [19], with a method proposed in [20]. This method, which must be applied to piecewise linear approximations of the input N-curves, allowed us to determine the best fitting "flow-density" relation from a wide family of relations.[5]

The KW theory consists of three basic postulates, but only two play a role here. In the context of cumulative curves, the first postulate states that vehicle accumulations between two detectors ("U"-upstream and "D"-downstream) should be replicable within a queue for any (long) time interval in which the average flow, q, for the interval is the same; this accumulation-flow relationship is denoted, $m_{UD}(q)$. The postulate holds approximately if curves N(U,t) and N(D,t) fluctuate within reasonable bounds about two parallel straight lines, A(U,t) and A(D,t), with slope q that are $m_{UD}(q)$ vehicles apart, and if this separation

[5] One is justified in using piecewise linear approximations because the KW model is a contraction mapping in the space of N-curves; i.e., if the KW procedure is applied to two input N-curves, then the maximum separation between the two predicted N-curves will be at most equal to the maximum separation between the two input curves. [20]

only depends on q. Note that the postulate can be satisfied approximately even if there are stop-and-go oscillations. Further, this postulate applies to inhomogeneous road sections and does not require one to define a "density" for every point on the road. Vehicle accumulation (an observable number with no ambiguity) becomes the fundamental variable to be predicted. Here, the relationship $m_{UD}(q)$, shown in Fig. 2(a), replaces the conventional "flow-density" curve of KW theory. If one believes that the accumulation $m_{UD}(q)$ between any points U and D on a road depends only on these points through the distance that separates them and that the dependence is proportional (i.e., the road is homogeneous) then one can normalize the accumulation-flow relation by distance between points.

The second postulate states that the transition between two queued stationary states "q_1" and "q_2" propagates as a wave from D to U; i.e., that the actual N-curves are close to idealized curves such as A(D,t) and A(U,t) of Fig. 2(b) during the transition.[6] Note from the geometry of this figure that the wave trip time, w_{12}, is uniquely determined by the separations, $m_{UD}(q_1)$ and $m_{UD}(q_2)$, arising from postulate 1. In fact, the wave trip time is simply equal to the negative slope of the line passing through the two states in Fig. 2(a). These postulates suggest that upstream curves A(U,t) can be obtained easily by shifting the piecewise linear segments of A(D,t) as per $m_{UD}(q)$ and connecting the points where they intersect.

[6]This statement is only strictly true for transitions that can be characterized as "shocks". A third (stability) postulate is needed to fully describe all possible transitions, and to complete the theory [20], but this refinement plays no significant role when the linear segments of A(D,t) are long compared with wave trip times, as is the case in this paper.

3 Estimation of $m_{UD}(q)$

A separate piecewise linear approximation A(D,t) of the downstream-most observer data (for D=8) was used for each day. On both days, N(8,t) was approximated to within 20 vehicles using linear segments of many minutes (long relative to the wave trip time). To control the statistical degrees of freedom, data from the first day of observation were used to estimate $m_{UD}(q)$ when predictions were made for the second day, and vice versa. By controlling the degrees of freedom in this way, the tests would indicate unambiguously whether the gross variations in N-curves propagate as kinematic waves, and whether vehicle counts can be usefully predicted as a result.

Ideally, the $m_{UD}(q)$ should be estimated separately for each observer pair, (D,U) = (8,j) for j=7,6,..., by plotting each queued stationary state observed at "j" as a point on an accumulation versus flow diagram, such as that in Fig. 2(a). (Flow would be the slope of one of the linear segments of A(8,t), and accumulation the vertical separation between said segment and a best-fit parallel line passing through the corresponding queued portion of N(j,t); see [18] for more details.) Although seven episodes of stationary traffic were observed at D = 8 on day 1, many of these occurred when the queue was short, reaching only the closest observers. Thus, the study site was initially treated as a homogeneous highway; accumulation could then be normalized by distance and pooled for all observer pairs. The pooled data for day 1 are included in Fig. 3. Part (a) of the figure displays the fit obtained with a straight line, and part (b) with a piecewise linear curve; the two curves have been extrapolated to the flow levels observed on day 2. The average kinematic wave speed implied by Fig. 3(a) is 10.7 mph. The best-fit lines for day 2 were very similar to those in Fig. 3 even though traffic evolved differently on that day (see Fig. 8 of [18]). The kinematic wave speed was 11.7 mph. The best-fit piecewise linear curve did not bend in the same way, however. Therefore, although the data suggest that there is a reproducible relation between accumulation and flow, they do not suggest that the relation is significantly curved in the range of flows observed.

4 Prediction

The day-1 curve of Fig. 3(a) was then used to construct the A(j,t) curves ($j < 8$) for day 2 with the KW procedure of Fig. 2, using the A(8,t) curve of day 2 as an input.[7] Fig. 4 displays the result. The light wiggly lines in this figure are raw data, and the piecewise linear curves predictions. The latter are only shown for those detectors (7, 6, 5 and 4) within the first mile from detector 8, and only during times when traffic was queued at these locations.[8] Qualitatively similar results are obtained when the process is repeated for day 1 with the accumulation-flow curve of day 2; see [18].

As shown in Fig. 4, the true N-curves track the predicted N-curves closely; discrepancies between predicted and observed N-curves were not, in general, greater than the input deviations between A(D,t) and N(D,t). For the most part, the predicted and observed curves

[7] Recall that the vertical shifts, $m_{j8}(q)$, applied to A(8,t) are in our case the product of normalized accumulation and distance.

[8] The predictions obtained with the curve in Fig. 3(b) differ from those in Fig. 4 only by a few vehicles in a few places; the discrepancies would be indistinguishable to the eye on the scale of Fig. 4.

remained within 10 vehicles of each other, even for the most distant of the four observers, and the accuracy did not deteriorate significantly with distance. Note in particular that the change in trend between states (positive or negative) seems to propagate cleanly and sharply from observer to observer; i.e., the theory seems to work similarly well during the transitions between states as it does during periods of stationary flow.

Predictions for the third observation point at 1.5 miles (not shown in Fig. 4) exceeded N(3,t) and this also occurred on day 2. That is, for any given flow, drivers spaced themselves more widely (and traveled faster) upstream of observer "4" than downstream on both days. This can be due to a number of location-specific reasons, such as a change of grade in the road, better pavement or prettier scenery as speculated in [18], which suggests that the road should be treated as an inhomogeneous facility upstream of observer 4.

In view of this, the A(3,t) curve for day 1 was reconstructed with a separate $m_{38}(q)$ relationship determined with day-2 data from detector 3, as explained in [18]. A similar but reversed process was used to obtain the A(3,t) curve for day 2. The new predictions, which can be found in Fig. 10 of [18], remained within similar error bands as the curves of Fig. 4.[9] This suggests that the effects of inhomogeneity are reproducible and that traffic counts and their subsidiary measures can be estimated with the KW theory despite location-specific traffic behavior.

[9] Predictions for observation point j=2 could not be tested in a similar way because the queue only reached that point on one of the days.

5 Summary

The overall results suggest that it is possible to predict N-curves in queued traffic quite accurately over distances comparable with one mile and for time periods encompassing several hours without the need for calibrating a model on the day of the predictions.[10] While it appears that the finer details of the N-curves do not propagate as a simple KW wave at this site, their gross behavior does. Fortunately, it is this gross behavior that is the most important determinant of traffic backups and the necessary control responses.

Because the test site was a single lane road with no passing, the results do not necessarily extend to multi-lane freeways. However, given that individual drivers can have quite a significant impact on the following stream on a no-passing road, it is not unreasonable to expect similar (or perhaps even better) results on multi-lane facilities.

Acknowledgements

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[10]Reference [18] shows that the transitions between queued and unqueued traffic at this site also occurred as expected in KW theory.

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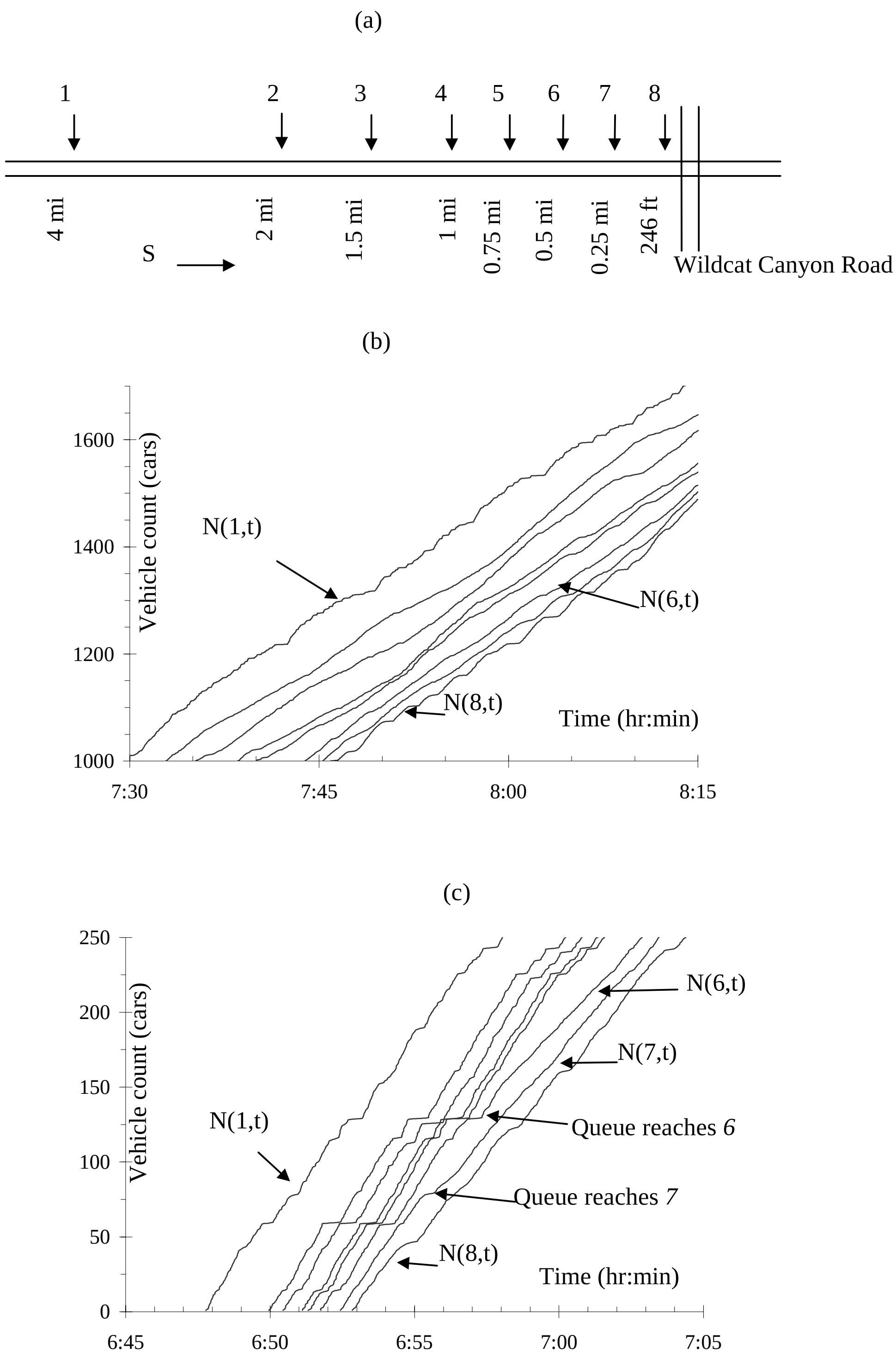
Figure Captions

FIG. 1. Queue evolution along single lane road. (a) Segment of San Pablo Dam Road, California, USA. (b) Cumulative curves from 7:30-8:30 a.m., day 1. (c) Cumulative curves from 6:45-7:05 a.m., day 1.

FIG. 2. (a) Flow - accumulation relationship. (b) Transition between states.

FIG. 3. Normalized accumulation-flow relationship. Data from day 1. (a) Linear approximation. (b) Piecewise linear approximation. Circle sizes represent duration of episode corresponding to data point.

FIG. 4. Predicted N-curves, day 2. (a) Vehicles 200-1300. (b) Vehicles 1300-2400. Light lines represent true N-curves, Dark lines represent predicted A-curves. Missing portions of some N(j,t) correspond to instances of experimental glitches, see [17].



"Reproducible Features of Congested Highway Traffic"
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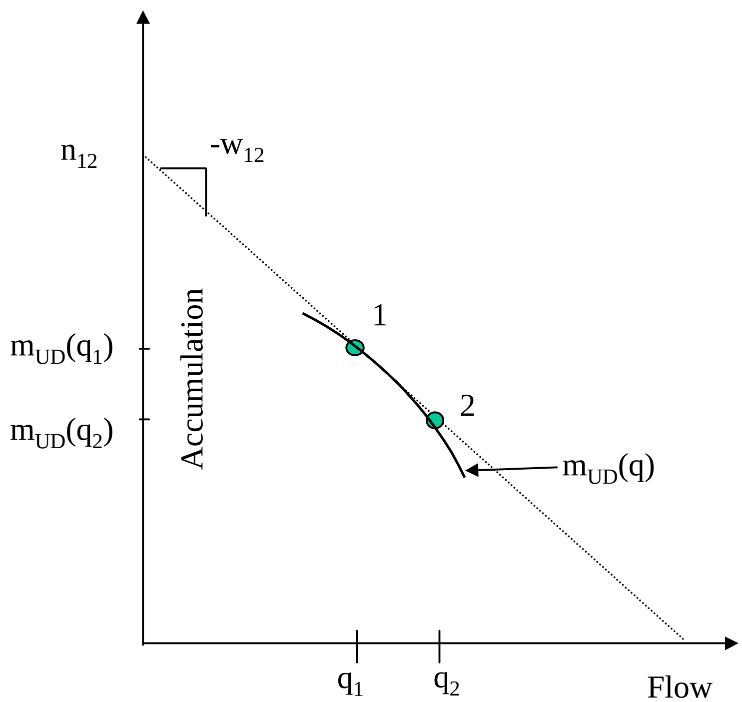
Figure 1

(a)



(b)

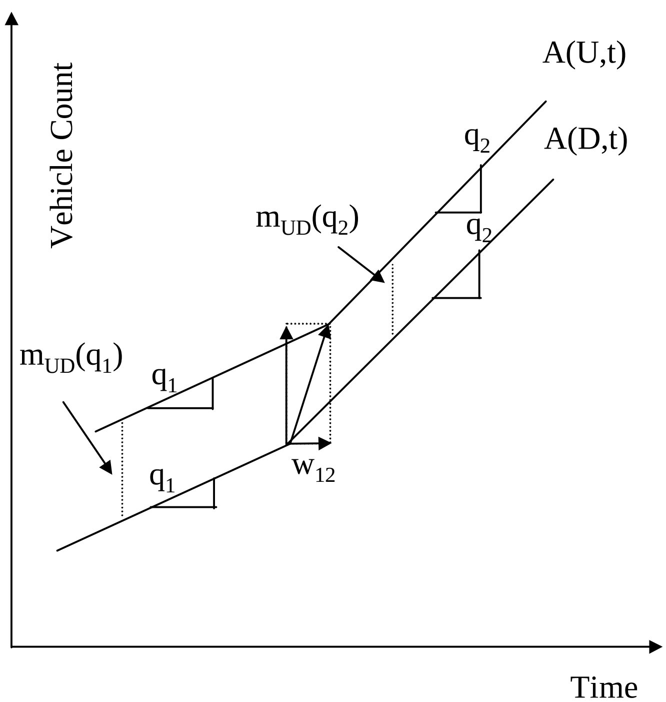


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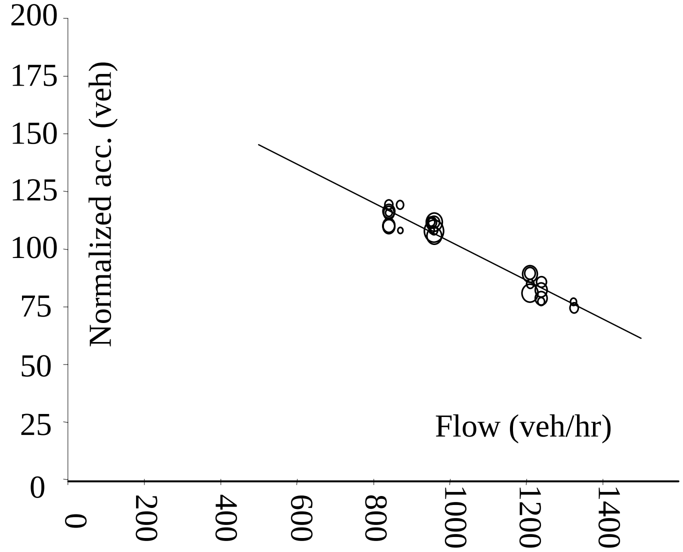
Figure 2

(a)



(b)

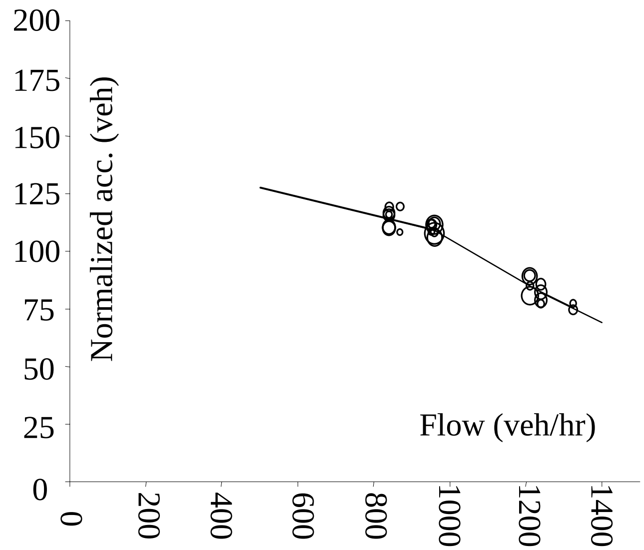


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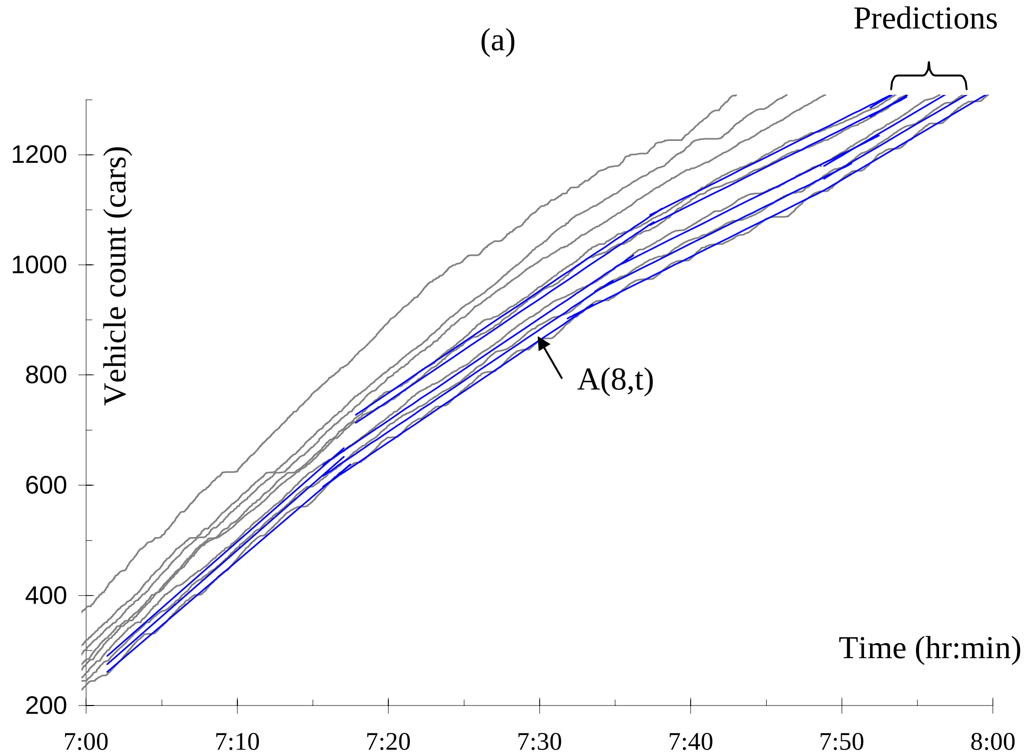
Figure 3

(a)



(b)

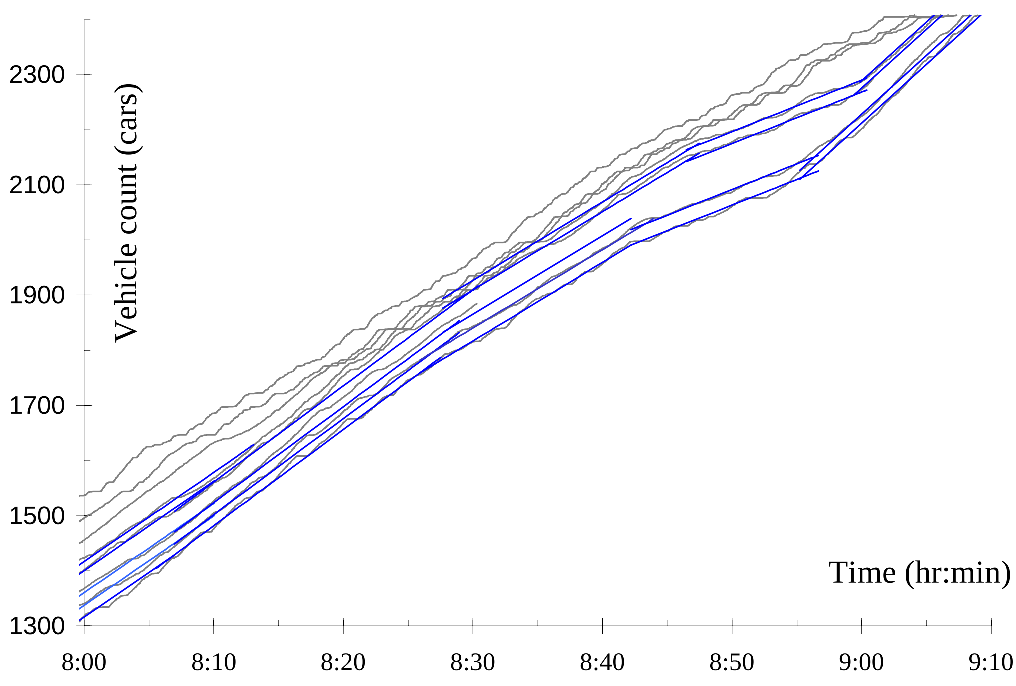


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Figure 4