Merging and Diverging Effects on Freeway Traffic Oscillations: Theory and Observation

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ABSTRACT

Continuum theory is used to explain why stop-and-go oscillations in congested freeway traffic change their amplitudes when they encounter the vehicular merging and diverging maneuvers that take place near ramps. The theory describes how oscillations diminish in amplitude when they propagate past a queued (and un-metered) on-ramp; and how they grow when they propagate past an off-ramp. The premise is that merging (diverging) flows change in response to freeway oscillations and that these changes in flow dampen (amplify) oscillations. The theory's descriptions are simple and rational; all of its inputs and outputs are directly observable; and its predictions are shown to match real data. The theory is tested against real data collected over multiple days from congested merge and diverge sites via videos and inductive loop detectors. For merges, predictions are found to agree with observation to within 10 percent, and for diverges, to within 12 percent. The paper thus resolves in a simple way a puzzling traffic feature reported in previous studies.

1. INTRODUCTION

The stop-and-go oscillations that arise in congested roadway traffic have been a long-standing puzzle. Traffic scientists have often conjectured that these oscillations are due to driver car-following behavior. Numerous car-following models reflecting this view have been developed, including *(1-5)*, to cite but a few examples. For certain values of their parameters, these models exhibit instabilities; i.e., the models predict that driver responses (accelerations and decelerations) amplify in magnitude as each driver passes through a disturbance *(6)*. These instabilities are commonly thought to explain and describe oscillating traffic. Though oscillations have been observed in the absence of vehicle lane-changing maneuvers (e.g. on single-lane roads and test tracks and in tunnels where lane changing was prohibited, see *(7-9)*), studies suggest that in freeway traffic, oscillations are not strictly a consequence of car-following, but are also affected by vehicle lane changing, merging and diverging activities.

In one such study *(10)*, data collected from inductive loop detectors and from videos showed that the disruptions caused by lane changing (made on freeway segments that were free of ramps) can both trigger oscillations to form; and cause oscillations that have already formed to grow in amplitude as they propagate backward through queues. Simulations in *(11)* support this finding. Another empirical study used loop detector data to show that freeway oscillations frequently form or grow near ramps, suggesting that merging and diverging can play a role *(12)*. The three above-cited works have not, however, offered theory to explain cause-and-effect mechanisms.

To their credit, higher-order kinematic wave models have replicated the formation of oscillations and their growth over time and space via numerical analysis and simulation *(13-16)*. These models are rather complex, however, and their numerical schemes are not as well established as those of the simpler, first-order kinematic wave theory *(17-22)*. And tests of higher-order models against real-world data are limited by comparison. Though the first-order model cannot generate the formation of oscillations, it has been shown to reproduce many other key traffic features, such as the propagation of congestion *(23-25)*, and oscillations once they become fully formed *(12, 26)*. Through extensions, moreover, the first-order model has been shown to predict other complex phenomena, such as the capacity drop at freeway bottlenecks *(27)*.

In light of the above, the present paper solves part of the puzzle regarding oscillations via simple extension of the first-order theory. The resulting model describes how merging and diverging near freeway ramps impact oscillation growth. The theory shows that merging traffic from a queued and un-metered on-ramp causes oscillations to diminish in amplitude as they propagate past the ramp; and that the extent of amplitude reduction is proportional to the so-called merge ratio (the ratio of flow entering the merge from the on-ramp and from the freeway). Analogously, the theory describes how diverging maneuvers near an off-ramp increase oscillation amplitudes in proportion to the fraction of flow that exits via that ramp. The theory has the advantage of requiring few parameters, all of which can be observed in real data; and this makes testing the theory a relatively straightforward task.

The theory is described in the following section. Its predictions are tested against real data in section 3. Implications of our findings are briefly discussed in section 4.

2. THE THEORY

We define oscillations as positive or negative deviations in flow from the longer-run averages due to disturbances (e.g. lane-changing maneuvers). When backward-moving oscillations arrive at a congested merge or diverge, they induce changes in the ramp's flow. It is the changing ramp flows that, in turn, cause oscillation amplitudes to diminish (at an on-ramp) or amplify (at an off-ramp). The mechanism can be described as a set of evolving freeway traffic states on the congested branch of a fundamental diagram. All inputs and outputs of the theory are observable. The theory as it applies to merges is presented in section 2.1; and application to diverges is in section 2.2.

2.1 Merges

Fig. 1(a) illustrates a hypothetical merge where both the freeway and the un-metered on-ramp are congested. We assume that freeway traffic conditions all along the merge are described by a Fundamental Diagram (FD) shown in Fig. 1(b). We use a triangular-shaped FD in the figure purely for illustrative purposes. The theory can be applied with a FD of any reasonable form. Since we are concerned only with the congested branch of the FD, even discontinuous, or so-called reverse-lambda forms *(3, 28-31)* can be used. We hasten to add, however, that our use of a triangular-form to test the theory (in sec. 3) is consistent with empirical evidence *(24, 32-35)*; and ultimately produced good agreements between prediction and observation, as will be shown in sec. 3. Further, the precise form of FD is a greater concern when one is predicting how oscillations change in terms of both density and flow. Here, however, we seek only to predict changes in oscillatory flows.

Suppose that the upstream and downstream locations labeled X_U and X_D in Fig. 1(a) are initially characterized by traffic states labeled U and D on the FD; i.e. freeway traffic is fully congested both upstream and downstream of the on-ramp. The queued freeway flow at location X_D, q_D, is the sum of its upstream counterpart, q_U, and the on-ramp flow, q_{on}. These latter two inflows are determined by the so-called merge ratio, $\alpha = q_{on}/q_U$, which describes how (queued) freeway and on-ramp drivers take turns when entering a fully congested merge *(36)*. The ratio is assumed constant, independent of q_D, as per the empirical findings in *(37)*. Thus,

$$q_U = \frac{1}{1+\alpha} q_D \text{ and } q_{on} = \frac{\alpha}{1+\alpha} q_D .$$

Assume now that merge outflow is perturbed by an oscillation that arrives at X_D from downstream. Fig. 1(b) depicts the case of a positive perturbation in which merge outflow is increased by Δ_D. Thus, q_D increases to q_D' and the traffic state at X_D moves from D on the fundamental diagram to D'. Fig. 1(b) further shows that queued inflows to the merge (from both the freeway and the on-ramp) increase to q_U' and q_{on}'. They do so in such way that α remains constant: $q_{on}' / q_U' = q_{on} / q_U$. Since

$$q_D' = q_D + \Delta_D ,$$

and since at X_U the perturbation in freeway inflow, Δ_U, is

$$\Delta_U = q_U' - q_U = \frac{1}{1+\alpha} q_D' - \frac{1}{1+\alpha} q_D.$$

Its absolute value can be expressed as

$$|\Delta_U| = \frac{1}{1+\alpha}|\Delta_D|. \quad (1)$$

Since α is non-negative, $|\Delta_U| \le |\Delta_D|$. In summary, a positive perturbation in freeway flow is partially consumed by an increase in on-ramp inflow, and thus the amplitude of the freeway oscillation fractionally diminishes by $\frac{\alpha}{1+\alpha}$ as it propagates backward through the merge. A negative freeway flow perturbation would be damped by the same fraction, as the reduction in freeway flow is partially absorbed by a diminished on-ramp inflow.

The above logic can be applied to on-ramps that are metered, as well as to those that are not queued. In the former case, the ramp inflow(s) would merely equal the (possibly time-varying) metering rate. When there is no queue on the ramp, analysis would be performed using the ratio of the inflows from the ramp and the freeway approach, rather than the merge ratio, α.

2.2 Diverges

Analogous logic can be applied to a diverge that is fully engulfed in a freeway queue, like the hypothetical one shown in Fig. 2(a). In this case, oscillations increase in amplitude as they propagate past the off-ramp, as explained below.

Note that since part of the outflow from the diverge goes to the ramp, queued freeway flow at location X_U exceeds that at X_D. State D thus lies below state U on the fundamental diagram, as in Fig. 2(b). The vertical difference between these states, q_{off}, is the flow exiting via the off-ramp.

If the freeway flow perturbation at the downstream end of the diverge, Δ_D, is positive as in Fig. 2(b), the new off-ramp flow q_{off}' grows larger than the initial ramp flow, q_{off}. This growth, in turn, magnifies the freeway flow perturbation, such that $\Delta_D < \Delta_U$. Assuming that the fraction of vehicles that are destined for the off-ramp, β, is fixed,

$$\Delta_U = q_U' - q_U = \frac{1}{1-\beta}q_D' - \frac{1}{1-\beta}q_D = \frac{1}{1-\beta}\Delta_D. \quad (2)$$

Since $0 \le \beta \le 1$, then $|\Delta_U| \ge |\Delta_D|$; i.e. for both positive and negative perturbations, the oscillation's amplitude fractionally increases by $\frac{\beta}{1-\beta}$ as it propagates past the off-ramp. Since the fraction of exiting vehicles depends on the characteristics of origin-destination demand, β may not be constant over time. This can be remedied by identifying periods of nearly constant β and predicting oscillations' amplitude for each period. We will test this theory in this fashion; see sec. 3.3.

3. EMPIRICAL TESTS

We now test the theory against real observations. In section 3.1, video data of a merge are used to (i) confirm the theory's premise that oscillations in freeway flow induce, and as a result are partially consumed by, changes in ramp flows; and (ii) compare the theory's predictions of Δ_U (given Δ_D) against measured values. In section 3.2, predictions are tested for a second merge site using less detailed (but more plentiful) loop detector data. In section 3.3, tests of this latter kind are presented for a diverge location.

3.1 Tests Using Video Data from a Merge

The merge shown in Fig. 3(a) is examined first. Individual vehicle arrival times at the locations labeled X_0, X_D and X_U (including the arrival times of on-ramp vehicles at X_U) were measured from videos. These were taken from atop a nearby tall building for a 50-min period (on Aug 19, 2002) when both the freeway stretch and on-ramp were fully queued. These data reveal that flows from the ramp rise and fall in concert with oscillating freeway flows. To demonstrate this, Fig. 3(b) presents curves of $N(t)-\overline{N}(t)$, the vertical deviations between the cumulative vehicle count by time *t*, *N(t)*, and the 5-minute moving average of the counts spanning that *t*, $\overline{N}(t)$ = [N(t + 2.5 mins) + N(t – 2.5 mins)]/2. The 5-min (moving) time window was chosen so as to be comparable with an oscillation's period, as recommended in *(38)*. These curves are drawn as piecewise linear interpolations between consecutive vehicle arrivals, such that a curve's slope at any *t* is the flow difference at that *t* from a longer-run (5-min) average. Thus, the wiggles clearly evident in these deviation curves are oscillations, with positive (negative) slopes revealing periods of positive (negative) flow perturbations. As in previous studies *(10, 12)*, the curves in Fig. 3(b) show that the periods of high and low flows (as seen by fixed detectors) typically persisted for several minutes.

Fig. 3(b) further reveals that the oscillations in ramp traffic (shown by the lower of the two curves drawn in bold) have small amplitudes as compared with the oscillations measured across all freeway lanes (shown by the three other curves). This was to be expected: the on-ramp's contributions to the time-varying (oscillating) flows that depart the merge are rather small (see Fig. 4). The key point is that the on-ramp's deviation curve is strongly correlated with the freeway's curves with a small time lag that can be explained as the wave trip time from X_D to the on-ramp location. The cross-correlation between the ramp's curve and the freeway curve at X_D is estimated to be 0.78. (Note that the time lag used here corresponds to a backward-moving wave speed of 23 km/hr, a speed comparable to those reported in earlier-cited empirical studies; and that dotted arrows in Fig. 3(b) trace the motion of some of these waves). The strong correlation, combined with the reasonable value of backward moving wave speed, supports the premise that ramp flows change in response to the freeway's oscillating flows that arrive from downstream.

We will next show that the theory's prediction for Δ_U closely matches the measured value. We start by discussing the measured one. We will use the Root Mean Squared Errors (RMSEs) of the deviation curves at X_D and at X_U as proxies for a Δ_D and Δ_U. (Note that RMSE = $\left[\sum_{t=0}^{n}\left(N(t)-\overline{N}(t)\right)^2/n\right]^{1/2}$, where *n* is the number of observations in the study period.) With this metric, we are in effect using a proxy for *an average* of the flow deviations generated by a sequence of oscillations. Using an average of the deviations is consistent with the macroscopic nature of kinematic wave theory, which describes average trends in traffic, and not the details of individual vehicles. The metric considers both the positive and negative flow perturbations brought by these oscillations; and as we show below, provides a means of factoring-out effects of vehicle lane-changing maneuvers (not linked to merging or diverging) that would otherwise produce measurement errors. The reader will further note that Δ_D and Δ_U can be expressed per (single) unit time, and can therefore be compared with (dimensionless) RMSE.

The circular-shaped data points in Fig. 3(c) display the RMSE for each (50-min) curve measured at freeway locations X_0, X_D and X_U. The first two of these points reveal that amplitudes increased as freeway oscillations propagated from X_0 to X_D: the RMSE grew from

19.6 to 20.1 vehicles, a trend of 3.6 vehs/km. This positive trend is consistent with previous observations on queued freeway segments that are free from ramps *(4)*; and trends of this kind were shown in *(10)* to be caused by lane changing.

We thus assume that as the freeway oscillations further propagated from X_D to X_U, they were subject to both this lane-changing effect and a merging effect; and that these combined effects produced the RMSE of 17.7 measured at X_U; see the third circular data point in Fig. 3(c). The theory, of course, does not explain the increasing trend in amplitude caused by lane changing; in a sense, the theory assumes that X_D and X_U are so closely spaced that lane changing over the short intervening freeway segment is negligible. To eliminate (approximately) this discretionary lane-changing effect from our data, we extrapolated the measured trend from X_0 to X_D (3.6 vehs/km) to X_U. This extrapolation produced an estimated RMSE that is 0.4 in excess of the value measured at X_D (note the square-shaped data point in Fig. 3(c)). This value was then subtracted from the RMSE actually measured at X_U (17.7) to produce an adjusted estimate for Δ_U of 17.3. Note that this measured average (reflecting both the positive and negative flow perturbations) diminished as the oscillations propagated through the merge, as per the theory's description.

We turn our attention now to the prediction of a Δ_U, and focus first on the needed estimate of merge ratio, α, as specified in (1). To obtain this estimate, queued on-ramp and freeway inflows at X_U were jointly measured for each prolonged period characterized by nearly stationary outflows at X_D. These near-stationary periods were identified using N-curves measured at X_D; outflows were judged to be nearly stationary when deviations from the N-curve and a best-fit (straight) line remained less than 20 vehicles. To smooth fluctuations, the data were extracted only from nearly stationary periods that persisted for 2 mins or more (and only during periods when queues persisted both on the ramp and on the freeway segment spanning X_U and X_0).

The joint inflows collected in the above manner are plotted in Fig. 4. Notwithstanding the naturally-occurring fluctuations evident in these data, they indicate a linear relation, as was also observed at other merges studied in *(37)*. For the present merge, the estimated α (the slope of the best-fit line in Fig. 4) is 0.176. Thus the Δ_U predicted by Eq (1) is 20.1/(1+0.176) = 17.1 vehicles. The prediction differs from the observed value (17.3) by just 1 percent.

3.2 Repeated Tests Using Detector Data from a Second Merge

We next test the theory against data from another merge shown in Fig. 5(a). Here vehicle counts were measured (over 10-sec sampling intervals) by freeway loop detectors at the locations labeled in the figure as X_0, X_D and X_U. In total, these data were collected for 50-min periods on each of six afternoons in 2002 and 2003. It was known (from previous work in *(37)*) that both the on-ramp and the freeway segment tend to be congested during the time periods chosen. Regrettably, however, the continued presence of on-ramp queues could not be confirmed because the ramp did not have a detector, and more will be said about this momentarily.

Deviation curves measured at each of the three freeway detector locations are presented for one of our observation periods (on June 10, 2003) in Fig. 5(b). The circular data points in Fig. 5(c) are the RMSE's for the three curves. Once again, the RMSE increased (from 17.1 to 22.0) as oscillations propagated from X_0 to X_D, and we again attribute this to lane changing. To estimate this discretionary effect upstream, between X_U and X_D, the trend was extrapolated as before: the difference between the resulting value at X_U (26.5) and the RMSE measured at X_D (22.0) was subtracted from the measured value at X_U (20.3). This produced an adjusted estimate (for the average Δ_U) of 15.8 vehicles. Note again how the measured average of the amplitudes diminished as the oscillations propagated past the on-ramp. Amplitude reductions of this kind were observed for all six of our study days.

Table 1 shows for each of these days the measured and predicted values of RMSE, our proxy for Δ_U. The estimated α for each day is shown in the table as well. (To obtain this latter estimate, differences in cumulative freeway counts at X_D and X_U were taken to be the on-ramp inflows.) Note as an aside that *(37)* estimated α for this same merge location to be 0.371; the estimate was made for a 1-hour period when the merge was seen (from video) to exhibit persistent queueing on both the ramp and freeway. (This relatively high estimate is reasonable, given the added lane on the on-ramp; see Fig. 5(a).) Each day's α shown in Table 1 is lower than the earlier estimate; and this may indicate that the on-ramp's queue sometimes vanished during our six observation periods.Nonetheless, all predictions of Δ_U match observed values rather well. Table 1 reveals that prediction errors were always less than 10%.

3.3 Repeated Tests Using Detector Data from a Diverge

We end this section by testing the theory against data from the diverge site shown in Fig. 6(a). Vehicle counts were measured (over 20-sec intervals) by freeway detectors at the locations labeled X_D, X_U and X_0. These were collected over seven mornings in September 1999 while freeway queues spanned locations X_0 to X_D. Because the off-ramp did not have a detector, its exit flows were taken to be the differences in freeway counts at X_U and X_D. Lastly, the data were partitioned into periods characterized by nearly constant exit flow fractions, β. (These periods were identified using time series of these fractions; we selected each period for which the 20-min moving average values of the β did not deviate from a best-fit horizontal line by more than 0.05.) Our seven mornings collectively yielded twelve periods of near-constant β.

Fig. 6(b) displays deviation curves for one such period (on September 13, 1999), and the RMSE of each curve is shown in Fig. 6(c). A 10-minute time window was used for moving averages because cumulative count curves revealed that oscillations exhibited periods of around 10 minutes. The reader will note again the tell-tale signs of lane-changing on the freeway section not spanning the ramp: Fig. 6(c) shows that from X_U to X_0, the RMSE displayed an increasing trend of 1.5 vehs/km. This trend was used to estimate the lane-changing effect from X_D to X_U in the way previously described; and produced an adjusted estimate for Δ_U of 34.5 vehicles.

Thus for the period shown in Fig. 6(c), average measured amplitude increased (from 32.8 to 34.5) as the oscillations propagated from X_D to X_U, in qualitative agreement with the theory. This type of growth was observed for all twelve of our observation periods.

Table 2 presents for each of these twelve periods the measured proxy for Δ_U and the corresponding prediction from Eq (2). In all cases, differences never exceeded 12%.

4. CONCLUSIONS

The present findings indicate that a continuum theory can explain previous reports linking vehicle merging and diverging activity to oscillation growth. The premise that ramp flows change in concert with oscillating freeway flows was found to hold at the merge for which ramp counts were available from video; and tests at all three of our study sites (including tests made over multiple days) indicate that predicted changes in oscillation amplitudes matched the measured values quite well.

The theory has the distinct advantage of simplicity: it is not always possible to predict the detailed behavior of individual drivers, or even to obtain values for all the parameters needed by higher-order kinematic wave theories of traffic. Thus, it makes sense to model general features of oscillation formation and growth using the simple, first-order continuum theory advocated here. This theory is parsimonious (it has few inputs); and both its inputs and outputs are directly observable from data.

Very importantly, the present findings are further evidence that, in congested freeway traffic, oscillations are not solely a consequence of car-following behavior. Rather, they are also affected by vehicular interactions across lanes. We suspect that remaining puzzles concerning oscillations, including for example the reason(s) behind their lengthy periodicities, can also be traced back to inter-lane interactions. Research in this realm continues since, after all, the accurate prediction of oscillations could have significant impacts on real-time control strategies. One can envision, for example, freeway on-ramp metering algorithms that adjust metering rates to dampen oscillations as they arrive at each on-ramp. Such strategies might produce a more homogeneous flow with lower engine emissions and fossil fuel depletion.

In the mean time, it seems that any comprehensive theory of freeway traffic oscillations should consider vehicle merging and diverging maneuvers near ramps, along with the lane changing that takes over the entire freeway. So-called hybrid models in which traffic is treated as a continuum with lane-changing vehicles modeled as particles *(27)* offer a potentially useful framework. Within a framework like this, our present findings indicate that simple continuum theories can be used to describe oscillation growth near ramps quite well.

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TABLE 1 The Performance Results of the Theory of Merging Effect

Date	Measured Merge Ratio	Observed RMSE (vehs)	Predicted RMSE (vehs)	Prediction Error (%)
6/10/2003	0.36	15.8	16.2	2.5
6/11/2003	0.31	9.3	10.1	8.5
6/12/2003	0.31	12.4	11.9	-4.6
7/18/2002	0.29	13.8	12.9	-6.8
7/23/2002	0.30	19.3	19.7	2.1
7/31/2002	0.30	14.2	13.3	-5.9
8/22/2002	0.30	20.0	20.0	0.2

TABLE 2 The Performance Results of the Theory of Diverging Effect

Date	Time period		Fraction of Outflow	Observed RMSE (vehs)	Predicted RMSE (vehs)	Prediction Error (%)
	From	To				
9/13/1999	7:05	7:55	0.10	34.5	36.6	6.1
9/13/1999	7:55	8:35	0.12	41.8	45.3	8.4
9/13/1999	8:35	9:15	0.11	26.1	27.8	6.6
9/15/1999	6:55	7:45	0.08	30.6	33.3	8.8
9/15/1999	8:10	9:00	0.09	31.6	34.9	10.3
9/16/1999	7:45	8:55	0.13	32.7	30.8	-5.8
9/17/1999	6:45	7:25	0.09	31.9	33.1	3.6
9/17/1999	7:25	8:25	0.12	28.6	30.0	5.0
9/21/1999	6:55	7:55	0.10	27.6	28.2	2.1
9/22/1999	7:30	8:30	0.11	26.3	29.4	11.9
9/23/1999	6:40	7:40	0.09	22.5	22.2	-1.2
9/23/1999	7:40	8:40	0.12	24.4	23.7	-3.0

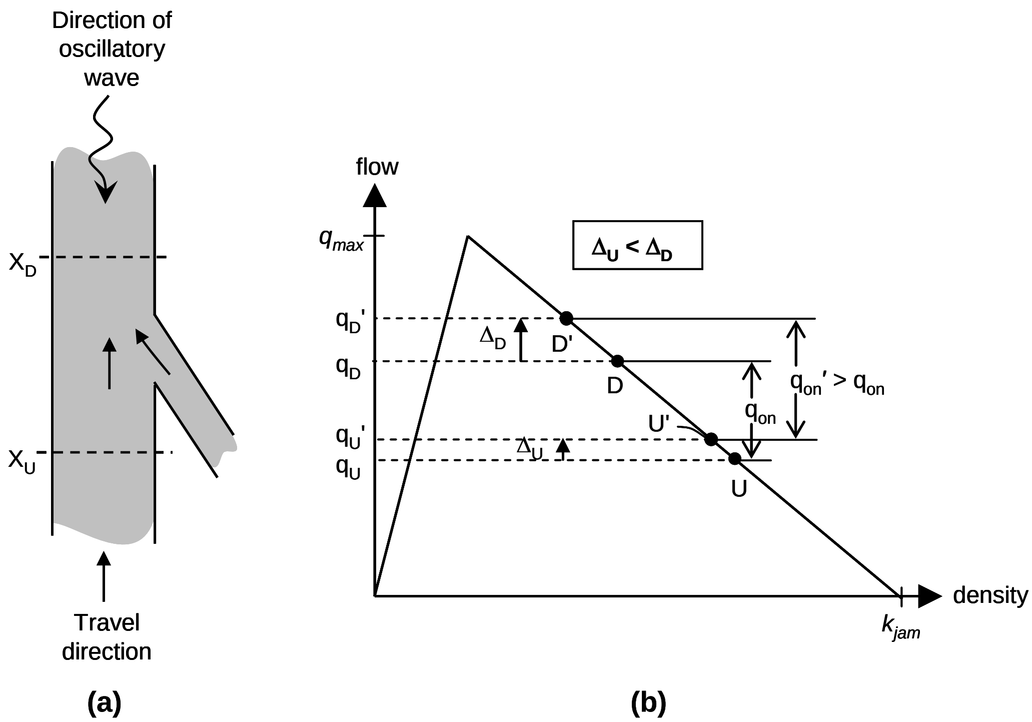
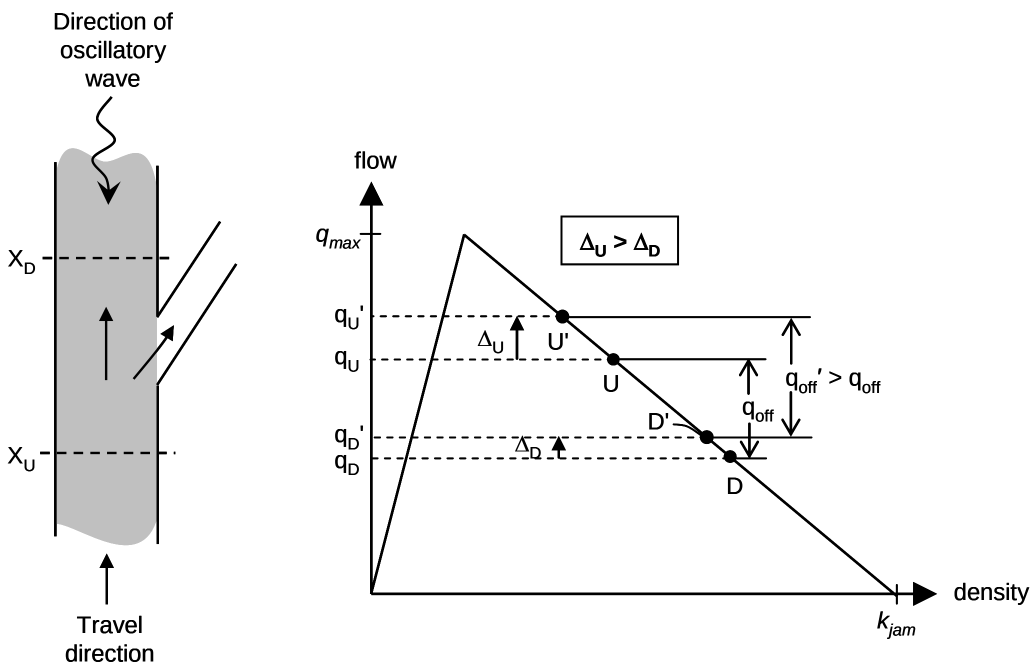


FIGURE 1
(a) Hypothetical freeway merge
(b) Theory of merging effect



(a) **(b)**

FIGURE 2
(a) Hypothetical freeway diverge
(b) Theory of diverging effect

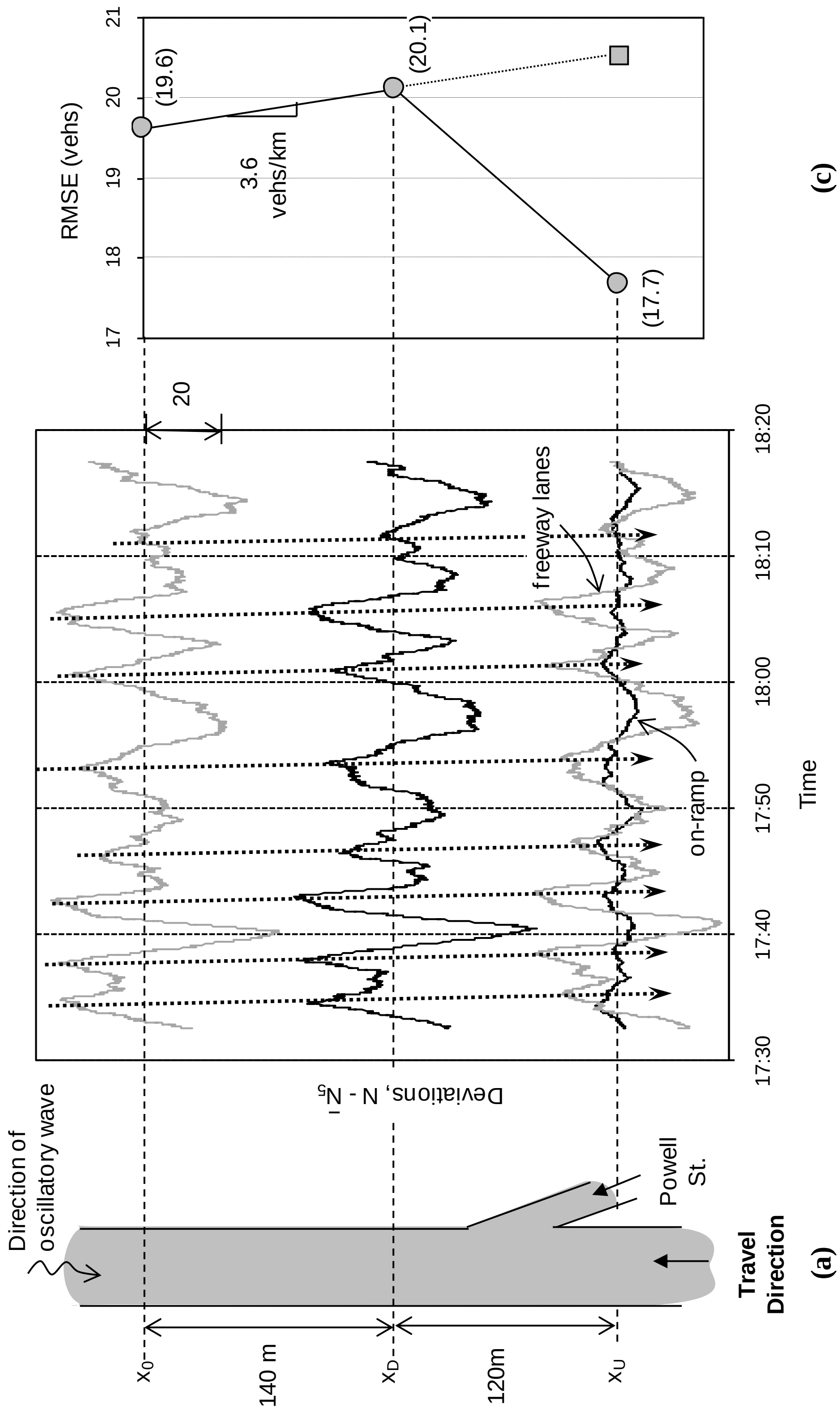


FIGURE 3

(a) Eastbound Interstate 80 near Powell St. on-ramp merge
(b) Deviation curves at the measurement locations (August 19, 2002)
(c) Root mean squared error computed at the measurement locations (August 19, 2002)

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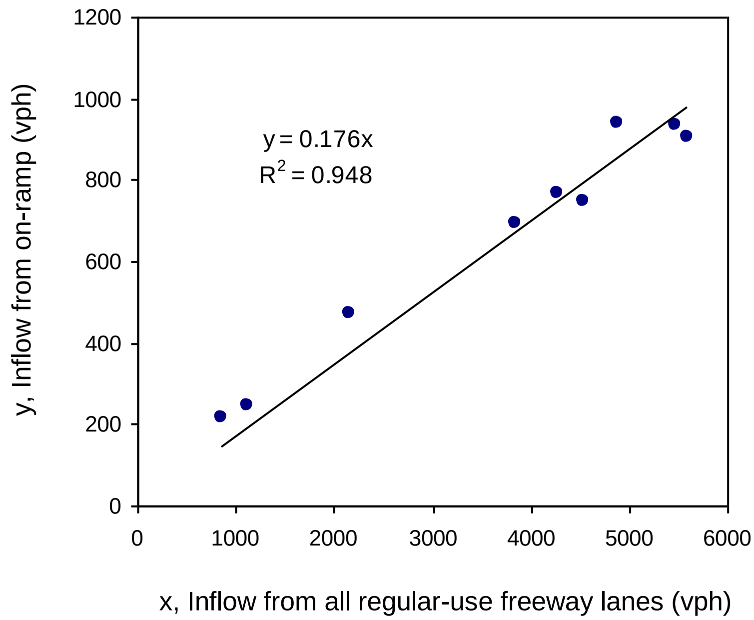

FIGURE 4 Inflows from all regular-use freeway lanes vs. inflows from Powell St. on-ramp

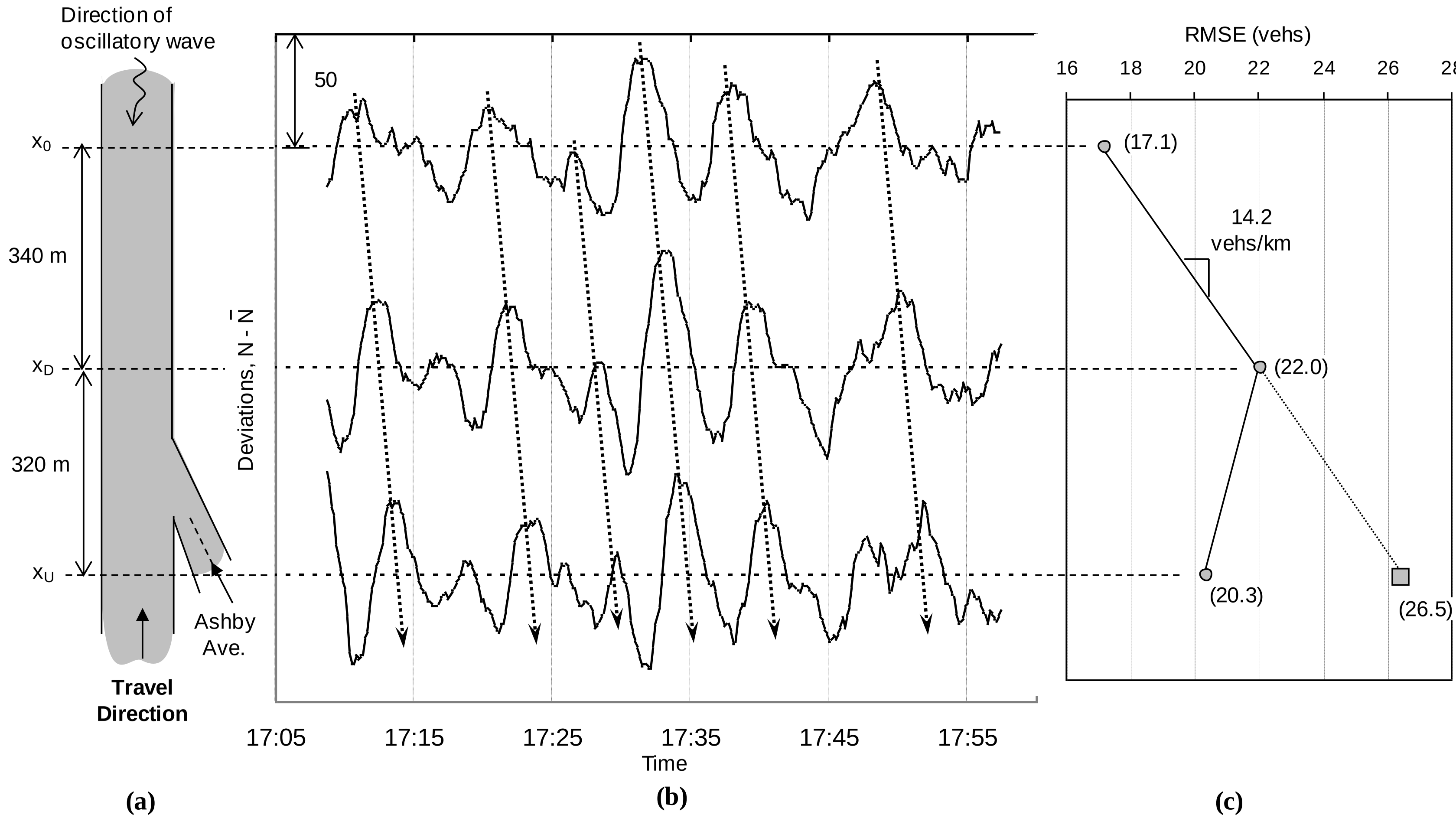

FIGURE 5

(a) Eastbound Interstate 80 near Ashby Ave. on-ramp merge

(b) Deviation curves at the measurement locations (June 10, 2003)

(c) Root mean squared error computed at the measurement locations (June 10,2003)

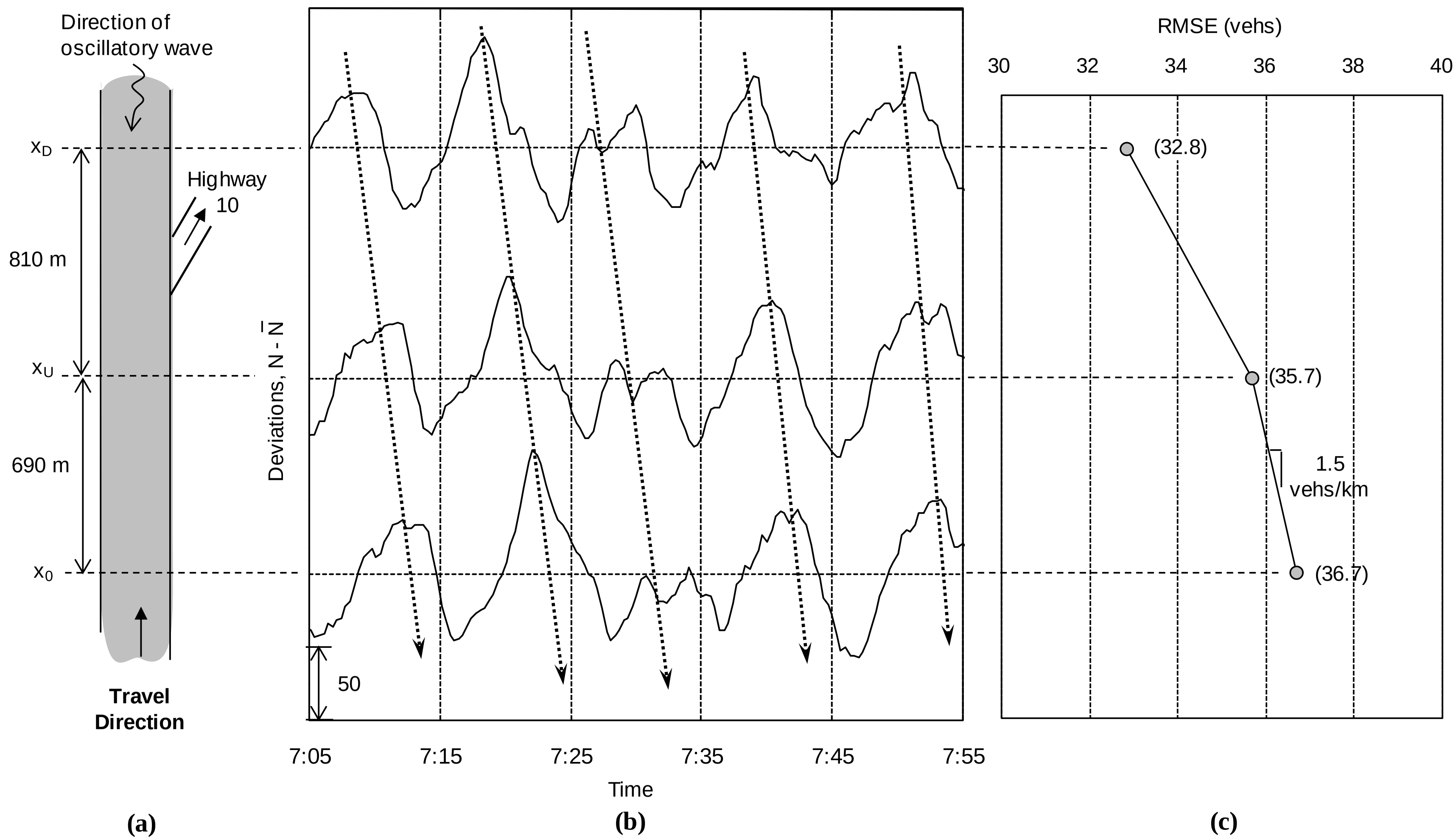

FIGURE 6

(a) Queen Elizabeth Way near Highway 10 off-ramp diverge

(b) Deviation curves at the measurement locations (September 13, 1999)

(c) Root mean squared error computed at the measurement locations (September 13, 1999)