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SIMULATION OF FREEWAY MERGING AND DIVERGING BEHAVIOR

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ABSTRACT

Simplified theory of kinematic waves was proposed by Newell and uses cumulative arrival and departure counts to describe kinematic waves of freeway traffic. The original paper deals only with traffic on freeway mainline. It is of great interest, at least practically, to investigate whether the simplified theory can be used to simulate freeway traffic merging and diverging behavior. In his paper, Newell assumed that on-ramp traffic always has the priority and can bypass queues, if any. This assumption will be released so that traffic from the mainline and the on-ramp will have to compete for downstream supply. For off-ramps, Newell assumed that all vehicles that want to exit can always be able to do so. Again, this assumption is also released so that queues from either downstream can build up and block upstream traffic.

1 INTRODUCTION

In a macroscopic sense, highway traffic is often viewed as a one-dimensional compressible fluid which is characterized by kinematic waves, i.e., moving traffic with the same state (such as traffic flow, speed, and density). When kinematic waves representation different traffic states intersect, a shock wave forms. The above behavior is summarized in L-W-R theory (Lighthill et al, 1955; Richards, 1956) which provides description of highway traffic evolution in a continuous time-space domain. Based on this, traffic states at any point in the time-space domain can be solved if boundary conditions are known. However, solving such a problem is often much involved and various simplified procedures are proposed. Among which is Newell's simplified theory of kinematic waves (Newell 1993a, 1993b, and 1993c). It combines kinematic wave theory with deterministic queuing theory, and keeps track of the cumulative numbers of vehicles past a set of specific points on a freeway. Shock condition is then interpreted as the minimum of cumulative traffic counts when viewed from both sides of the traffic.

Hurdle and Son (Son 1996; Hurdle and Son 2000) tested the accuracy of Newell's theory and the adequacy of its underlying assumption, the triangular flow-density relationship, with real data collected from freeways in the San Francisco Bay Area. The test results support the validity of Newell's theory, and show that the theory works best under over-saturated conditions. Leonard (1997) coded Newell's theory into software GTWaves, which bridges the theory and its application.

Though Newell confined his theory to freeway mainline, it is possible to describe freeway merging and diverging behavior after relaxing some of its assumptions. This has important practical implications because the extension would allow analysis of alternate diversion strategies (in case of incidents on the freeway) and ramp metering strategies (to minimize the overall system-wide delay) if a queuing model computing delays on ramps is incorporated.

2 SUMMARY OF THE SIMPLIFIED THEORY

Newell assumes that the underlying flow-density relationship is a triangular one, i.e., there are only two constant wave speeds: a forward wave speed in under-saturated flow, and a backward wave speed in congested flow. When dealing with on-ramps, Newell assumes that ramp entering flow could always bypass the queue, if any, at the merging point, and thus experiences no delay. Travel time of all vehicles in a section is independent of their destinations. Therefore, exiting vehicles experience the same trip time as through vehicles in this section.

The simplified theory keeps track of cumulative arrival and departure curve at interested points along a freeway, and works as follows:

- Upstream arrival, which is actually a horizontal translation of the departure curve vs. time at its upstream point by a free trip time.
- Downstream queue, which is actually a horizontal translation of the departure curve at a downstream point and then a vertical translation of the resulting curve by a jam storage of the section.

- Capacity constraint to the left of the point.
- Capacity constraint to the right of the point.

The cumulative departure curve at a point on the freeway is determined by the lower bound of the above. In case of multiple-destination flows, link travel times are found by comparing cumulative departure curves at this point and its upstream point for the same destination such that the last vehicle seen at this point is identified on the curve of the upstream point. The horizontal distance of these two points is the trip time for this section and it is applied to all the current vehicles in the same link regardless of their destinations. This trip time is then used to advance cumulative departure curves for other destinations at this point, and the procedure proceeds until all lattice points in the time-space domain are traversed.

To represent a freeway, link-node structure is employed, and a general node is sketched in Figure 1. The notation in this paper is summarized as follows.

- X_i, X_j, X_n, X_p, X_q – Nodes. Nodes are sorted and indexed such that all potential origins of a node bear lower indices and all potential destinations of a node bear higher indices. On the other hand, a node keeps track of its adjacent upstream and downstream nodes as well as its potential destinations.
- $A_{in}{}^{-}{}_{-p}(t)$, $A_{jn}{}^{-}{}_{-p}(t)$, $A_n{}^{+}{}_{p-p}(t)$, $A_n{}^{+}{}_{q-q}(t)$ – Cumulative arrivals. For example, $A_{in}{}^{-}{}_{-p}(t)$ denotes the cumulative number of vehicles on link X_iX_n waiting to pass the left of X_n destined for X_p and beyond at time t.
- $D_{in}{}^{-}{}_{-p}(t)$, $D_{jn}{}^{-}{}_{-p}(t)$, $D_n{}^{+}{}_{p-p}(t)$, $D_n{}^{+}{}_{q-q}(t)$ – Cumulative departures. For example, $D_n{}^{+}{}_{q-q}(t)$ denotes the cumulative number of vehicles on link X_nX_q past the right of X_n destined for X_q and beyond at time t.
- Q_{in}, K_{in}, V_{in}, N_{in}, L_{in}, U_{in} – Capacity, jam density, free flow speed, number of lanes, length, and backward wave speed for link X_iX_n, respectively. Other links follow the same convention.

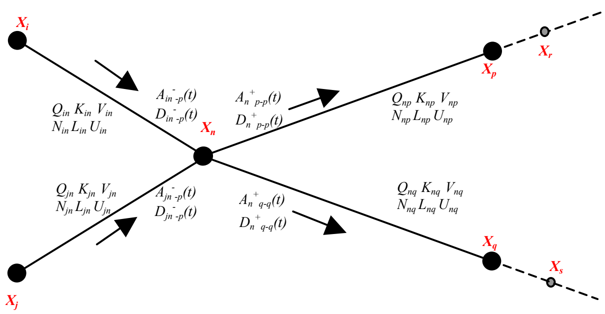

Figure 1: A General Junction of a Freeway System.

It is reasonable to assume that entrance-exit (E-E) flows can somehow be estimated from link traffic counts and, hence, are known. With a well-defined freeway network and some simple synthesis, it is possible to obtain flows from each entrance to its potential destinations (E-D flows), and this is the starting point of the simulation. The goal of this simulation is to keep track of cumulative arrivals and departures at every node because they tell virtually everything about the freeway traffic evolution.

3 SIMULATION OF FREEWAY MERGING BEHAVIOR

In freeway merging scenario, we consider a point on freeway where an on-ramp or a merging freeway joins. Therefore, there are two upstream links and one downstream link. Unlike Newell's procedure, queuing on both upstream links are now also of interest, so it is reasonable to assume that ramp entering traffic from both upstream links have the priority. This scenario corresponds to Figure 1 when the branch of X_nX_q is totally absent. Cumulative departure curves past X_n can be determined by the following procedure.

1. **Departure to the right.** The cumulative departure curve on link X_nX_p to the right of X_n destined for X_p and beyond, $D_n{}^{+}{}_{p-p}(t)$, is constrained by the following:
    a. **Upstream arrival.** The cumulative arrival curve on link X_iX_n to the left of X_n destined for X_p and beyond, $A_{in}{}^{-}{}_{-p}(t)$, can be obtained by translating the cumulative departure curve on link X_iX_n to the right of X_i destined for X_p and beyond, $D_i{}^{+}{}_{n-p}(t)$, by a free link travel time. Similarly, $A_{jn}{}^{-}{}_{-p}(t)$ can be obtained from $D_j{}^{+}{}_{n-p}(t)$. The demand to the right of X_n, $A_n{}^{+}{}_{p-p}(t)$, is the sum of $A_{in}{}^{-}{}_{-p}(t)$ and $A_{jn}{}^{-}{}_{-p}(t)$, i.e.,

    $$A_n{}^{+}{}_{p-p}(t) = A_{in}{}^{-}{}_{-p}(t) + A_{jn}{}^{-}{}_{-p}(t)$$
    $$= D_i{}^{+}{}_{n-p}(t - L_{in}/V_{in}) + D_j{}^{+}{}_{n-p}(t - L_{jn}/V_{jn})$$

    b. **Right capacity**

    $$D_n{}^{+}{}_{p-p}(t - \tau) + \tau \times Q_{np}$$

    Where τ is time increment.

    c. **Downstream queue, if any:**

    $$D_{np}{}^{-}{}_{-p}(t - L_{np}/U_{np}) + L_{np} \times K_{np}$$

    d. **Left capacity:** The difficulty here is that we have two upstream links (rather than one in Newell's procedure), and it is not so convenient to determine how left capacities constrain $D_n{}^{+}{}_{p-p}(t)$. However, it would be easier to take care of this constraint later on when we determine cumulative departures to the left of X_n. For now, $D_n{}^{+}{}_{p-p}(t)$ is simply the minimum of a, b, and c.
2. **Departure to the left.** Now, we are interested in knowing, of $D_n{}^{+}{}_{p-p}(t)$, how much is contributed by X_iX_n and how much by X_jX_n. There could be many

recipes to split $D_n^+{}_{p\text{-}p}(t)$. A reasonable interpretation of "equal opportunity to depart" is that traffic flows from upstream links compete to depart, constrained by their shares of downstream supply. Let $a_{in}^-{}_{\text{-}p}(t)$ be the current arrival on link X_iX_n to the left of X_n destined for X_p and beyond, $a_{jn}^-{}_{\text{-}p}(t)$ be the current arrival on link X_jX_n to the left of X_n destined for X_p and beyond, d_{np} be the current departure at link X_iX_n, $d_{i\text{-}np}$ be the downstream capacity share for link X_iX_n, and $d_{j\text{-}np}$ be the downstream capacity share for link X_jX_n. Obviously, we have:

$$a_{in}^-{}_{\text{-}p}(t) = A_{in}^-{}_{\text{-}p}(t) - D_{in}^-{}_{\text{-}p}(t - \tau)$$
$$a_{jn}^-{}_{\text{-}p}(t) = A_{jn}^-{}_{\text{-}p}(t) - D_{jn}^-{}_{\text{-}p}(t - \tau)$$
$$d_{np} = D_n^+{}_{p\text{-}p}(t) - D_n^+{}_{p\text{-}p}(t-\tau)$$
$$d_{i\text{-}np} = d_{np}{\times}Q_{in}/(\, Q_{in}+ Q_{jn})$$
$$d_{j\text{-}np} = d_{np}{\times}Q_{jn}/(\, Q_{in}+ Q_{jn})$$

There are 4 possible cases:

a. $\mathbf{a_{in}^-{}_{\text{-}p}(t) < d_{i\text{-}np}}$ **and** $\mathbf{a_{jn}^-{}_{\text{-}p}(t) < d_{j\text{-}np}}$

In this case, all vehicles get their chances to depart without delay, if the capacity of each link permits, i.e.,

$$d_{in}^-{}_{\text{-}p}(t) = min\{a_{in}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{in}\}$$
$$d_{jn}^-{}_{\text{-}p}(t) = min\{a_{jn}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{jn}\}$$

where, $d_{in}^-{}_{\text{-}p}(t)$ is the current departure count on link X_iX_n to the left of X_n destined for X_p and beyond. $d_{jn}^-{}_{\text{-}p}(t)$ is the current departure count on link X_jX_n to the left of X_n destined for X_p and beyond.

b. $\mathbf{a_{in}^-{}_{\text{-}p}(t) \geq d_{i\text{-}np}}$ **and** $\mathbf{a_{jn}^-{}_{\text{-}p}(t) < d_{j\text{-}np}}$

In this case, vehicles on link X_jX_n depart without delay if the link capacity permits, while vehicles on link X_iX_n depart constrained by the link capacity and the remainder of downstream capacity, i.e.,

$$d_{jn}^-{}_{\text{-}p}(t) = min\{a_{jn}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{jn}\}$$
$$d_{in}^-{}_{\text{-}p}(t) = min\{a_{in}^-{}_{\text{-}p}(t),\ d_n^+{}_{p\text{-}p}(t) - d_{jn}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{np} - d_{jn}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{in}\}$$

where,

$$d_n^+{}_{p\text{-}p}(t) = D_n^+{}_{p\text{-}p}(t) - D_n^+{}_{p\text{-}p}(t-\tau).$$

c. $\mathbf{a_{in}^-{}_{\text{-}p}(t) < d_{i\text{-}np}}$ **and** $\mathbf{a_{jn}^-{}_{\text{-}p}(t) \geq d_{j\text{-}np}}$

Similar to b, we have:

$$d_{in}^-{}_{\text{-}p}(t) = min\{a_{in}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{in}\}$$
$$d_{jn}^-{}_{\text{-}p}(t) = min\{a_{jn}^-{}_{\text{-}p}(t),\ d_n^+{}_{p\text{-}p}(t) - d_{in}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{np} - d_{in}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{jn}\}$$

d. $\mathbf{a_{in}^-{}_{\text{-}p}(t) \geq d_{i\text{-}np}}$ **and** $\mathbf{a_{jn}^-{}_{\text{-}p}(t) \geq d_{j\text{-}np}}$

In this case, vehicles on both links depart proportionally to their respective capacities, i.e.,

$$d_{in}^-{}_{\text{-}p}(t) = min\{a_{jn}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{in},\ d_n^+{}_{p\text{-}p}(t){\times}Q_{in}/(\, Q_{in}+Q_{jn})$$

and

$$d_{jn}^-{}_{\text{-}p}(t) = min\{a_{jn}^-{}_{\text{-}p}(t),\ \tau{\times}Q_{jn},\ d_n^+{}_{p\text{-}p}(t){\times}Q_{jn}/(\, Q_{in}+Q_{jn})\}$$

Based on the above rules, the departure counts of both upstream links at current time step can be obtained. The cumulative departure counts are simply:

$$D_{in}^-{}_{\text{-}p}(t) = D_{in}^-{}_{\text{-}p}(t-\tau) + d_{in}^-{}_{\text{-}p}(t)$$
$$D_{jn}^-{}_{\text{-}p}(t) = D_{jn}^-{}_{\text{-}p}(t-\tau) + d_{jn}^-{}_{\text{-}p}(t)$$

3. **Link travel time.** According to Newell, link travel time is obtained by comparing upstream cumulative departure and downstream cumulative departure of a link. Therefore, link travel time on X_iX_n, $T_{in}(t)$, can be found by comparing curve pair $D_i^+{}_{n\text{-}p}(t)$ vs. $D_{in}^-{}_{\text{-}p}(t)$ such that the former is traced backwards to a prior time t' when $D_i^+{}_{n\text{-}p}(t')=D_{in}^-{}_{\text{-}p}(t)$. Then $T_{in}(t)=t\text{-}t'$.

   In a similar fashion, link travel time on X_jX_n, $T_{jn}(t)$, can be found.
4. **Departure to the left–multi-destinations.** Based on Newell's assumption that vehicles on the same link experience the same link travel time regardless of their destinations, the cumulative departure curve on link X_iX_n to the left of X_n destined for other destinations, $D_{in}^-{}_{\text{-}r}(t)$, can be obtained by simply translating $D_i^+{}_{n\text{-}r}(t)$ to the right by $T_{in}(t)$ and $D_{jn}^-{}_{\text{-}r}(t)$ can be obtained by translating $D_j^+{}_{n\text{-}r}(t)$ to the right by $T_{jn}(t)$, i.e.,

$$D_{in}^-{}_{\text{-}r}(t) = D_i^+{}_{n\text{-}r}(t - T_{in}(t))$$
$$D_{jn}^-{}_{\text{-}r}(t) = D_j^+{}_{n\text{-}r}(t - T_{jn}(t))$$

5. **Departure to the right – multi-destinations.** The cumulative departure curve past the right of X_n destined for other destination X_r, $D_n^+{}_{p\text{-}r}(t)$, is simply:

$$D_n^+{}_{p\text{-}r}(t) = D_{in}^-{}_{\text{-}r}(t) + D_{jn}^-{}_{\text{-}r}(t)$$

4 SIMULATION OF FREEWAY DIVERGING BEHAVIOR

In the diverge scenario, we consider a point on the freeway where an off-ramp or a diverging freeway leaves the freeway. Therefore, there is one upstream link and two downstream links. Unlike Newell's procedure, exiting flow (for either of the downstream links, the same thereafter) is no longer always able to exit, and queue is possible on both downstream links. If a downstream queue backs up exceeding the diverging point, we assume that the delay is imposed on all vehicles rather than on vehicles to that link alone.

A diverge scenario corresponds to Figure 1 when the branch X_jX_n is totally absent. Let X_r denotes any potential destinations of X_p and X_s denotes any potential destinations of X_q. Again, the cumulative departure curves past X_n can be determined as follows.

1. **Departure to the right.** There are two links to the right of X_n, X_nX_p and X_nX_q, so cumulative departure curves $D_n^+{}_{p\text{-}p}(t)$ and $D_n^+{}_{q\text{-}q}(t)$ are evaluated individually. According to Newell, the cumulative departure curve on link X_nX_p to the right of X_n destined for X_p and beyond, $D_n^+{}_{p\text{-}p}(t)$, is constrained by the following:
   a. **Upstream arrival**

   $$A_n^+{}_{p\text{-}p}(t) = A_{in}^-{}_{\text{-}p}(t) = D_i^+{}_{n\text{-}p}(t - L_{in}/V_{in})$$

   b. **Right capacity**

   $$D_n^+{}_{p\text{-}p}(t - \tau) + \tau \times Q_{np}$$

   c. **Downstream queue:**

   $$D_{np}^-{}_{\text{-}p}(t - L_{np}/U_{np}) + L_{np} \times K_{np}$$

   d. **Left capacity:** There is a problem here. Obviously the capacity to the left of X_n is always enough to handle traffic destined for X_p and beyond. However, this capacity is, at the same time, shared by traffic destined for X_q and beyond. The question is, how much of the capacity can be utilized by the former? We leave this question to later steps. For now, $D_n^+{}_{p\text{-}p}(t)$ is simply the minimum of a, b, and c.

   Similarly, we can obtain $D_n^+{}_{q\text{-}q}(t)$.

2. **Departure to the Left.** The cumulative departure curve to the left of X_n destined for X_n and beyond, $D_{in}^-{}_{\text{-}n}(t)$, is simply the minimum of:
   a. **Upstream arrival**

   $$A_{in}^-{}_{\text{-}n}(t) = D_i^+{}_{n\text{-}n}(t - L_{in}/V_{in})$$

   b. **Downstream departure**

   $$D_n^+{}_{p\text{-}p}(t) + D_n^+{}_{q\text{-}q}(t)$$

   c. **Left capacity**

   $$D_{in}^-{}_{\text{-}n}(t - \tau) + \tau \times Q_{in}$$

Note here the destination is X_n, not X_p or X_q. It is implicitly assumed that, on link X_iX_n, the states of traffic destined for X_p and beyond and traffic destined for X_q and beyond are the same. For example, if downstream link X_nX_q is congested and the queue backs up past X_n, all traffic on link X_iX_n will be affected. This is reasonable because, in reality, the congestion on several of the outer-most lanes will eventually spread to all the lanes, leaving a triangular uncongested area to the end of this link. What remains is to identify the impact of triangular uncongested area when the whole link is viewed as congested. Another observation supporting this assumption is that, when the outer lanes (lead to X_q, for example) are blocked, traffic destined for X_p and beyond tends to change lane in advance to avoid excessive delay, and this tend to smooth out congestion over the whole link.

In response to the problem of left capacity posed above, this step guarantees that the cumulative departure destined for X_n (i.e., the sum of those destined for X_p and X_q) won't exceed the capacity to the left of X_n.

Now, a new problem arises. Of the amount $D_{in}^-{}_{\text{-}n}(t)$ determined above, how much is destined for X_p, i.e. $D_{in}^-{}_{\text{-}p}(t)$, and how much is destined for X_q, i.e., $D_{in}^-{}_{\text{-}q}(t)$? They might be the same as $D_n^+{}_{p\text{-}p}(t)$ and $D_n^+{}_{q\text{-}q}(t)$, respectively, if $D_{in}^-{}_{\text{-}n}(t)$ is constrained only by downstream departures. However, when $D_{in}^-{}_{\text{-}n}(t)$ is constrained by upstream arrival or left capacity, $D_{in}^-{}_{\text{-}p}(t)$ and $D_{in}^-{}_{\text{-}q}(t)$ are expected to be less than $D_n^+{}_{p\text{-}p}(t)$ and $D_n^+{}_{q\text{-}q}(t)$, respectively. In either case, $D_{in}^-{}_{\text{-}n}(t)$ is split based on the current contributions of the downstream links:

Let $d_n^+{}_{p\text{-}p}(t) = D_n^+{}_{p\text{-}p}(t) + D_n^+{}_{p\text{-}p}(t\text{-}\tau)$ and $d_n^+{}_{q\text{-}q}(t) = D_n^+{}_{q\text{-}q}(t) + D_n^+{}_{q\text{-}q}(t\text{-}\tau)$. Also let $d_{in}^-{}_{\text{-}n}(t) = D_{in}^-{}_{\text{-}n}(t) - D_{in}^-{}_{\text{-}n}(t\text{-}\tau)$. Then,

$$d_{in}^-{}_{\text{-}p}(t) = d_{in}^-{}_{\text{-}n}(t) \times d_n^+{}_{p\text{-}p}(t) / (d_n^+{}_{p\text{-}p}(t) + d_n^+{}_{q\text{-}q}(t))$$
$$D_{in}^-{}_{\text{-}p}(t) = d_n^+{}_{q\text{-}q}(t) + D_{in}^-{}_{\text{-}p}(t\text{-}\tau)$$
$$d_{in}^-{}_{\text{-}q}(t) = d_{in}^-{}_{\text{-}n}(t) \times d_n^+{}_{q\text{-}q}(t) / (d_n^+{}_{p\text{-}p}(t) + d_n^+{}_{q\text{-}q}(t))$$
$$D_{in}^-{}_{\text{-}q}(t) = d_{in}^-{}_{\text{-}q}(t) + D_{in}^-{}_{\text{-}q}(t\text{-}\tau)$$

If $d_n^+{}_{p\text{-}p}(t) + d_n^+{}_{q\text{-}q}(t) = 0$, no traffic discharges for either downstream links, i.e., $d_{in}^-{}_{\text{-}p}(t) = d_{in}^-{}_{\text{-}q}(t) = 0;$

3. **Link Travel Time**. Since traffic destined for X_p and beyond and traffic destined for X_q and beyond operates independent when they pass X_n. Multiple destination flows for each of the downstream link are determined individually, so do their link travel times.

   For traffic destined for X_p and beyond, its travel time at link X_iX_n, $T_{in-p}(t)$,is determined by comparing departure curve pair $D_i^+{}_{n-p}(t)$ vs. $D_{in}^-{}_{-p}(t)$;

   For traffic destined for X_q and beyond, its travel time at link X_iX_n, $T_{in-q}(t)$,is determined by comparing departure curve pair $D_i^+{}_{n-q}(t)$ vs. $D_{in}^-{}_{-q}(t)$;
4. **Departure to the left–multi-destinations**. Based on the link travel times obtained above, it is a simple exercise to determine/update cumulative departure curves on link X_iX_n past the left of X_n destined for all destinations, i.e.,

$$D_{in}^-{}_{-r}(t) = D_i^+{}_{n-r}(t - T_{in-p}(t))$$
$$D_{in}^-{}_{-s}(t) = D_i^+{}_{n-s}(t - T_{in-q}(t))$$

5. **Departure to the right–multi-destinations.** Since this is a diverge scenario, no traffic enters from on-ramp. The cumulative departure curves past the right of X_n are the same as their counterparts past the left of X_n, i.e.

$$D_n^+{}_{p-p}(t) = D_{in}^-{}_{-p}(t),\ D_n^+{}_{p-r}(t) = D_{in}^-{}_{-r}(t)$$
$$D_n^+{}_{q-q}(t) = D_{in}^-{}_{-q}(t),\ D_n^+{}_{q-s}(t) = D_{in}^-{}_{-s}(t)$$

5 SIMULATION RESULTS

The proposed simulation procedures are tested using field observation from Georgia 400, a toll road in the north of Metro Atlanta. Two test sites are selected for this study. Since testing of merging and diverging don't require estimation of origin-destination flows, observed flows at entrance links are used directly as input to the simulation. The goal of the tests is to check how close the predicted traffic density approximates the observed density in the time-space domain.

5.1 Test Site and Test Data

Site 1 is for testing freeway merging behavior. It consists of 7 observation stations (all start with 400) and 7 links as labeled in circles. See Figure 2. Geometry and traffic characteristic data of this site is listed in Table 1. The merge, node 5008, might be a bottleneck because the capacity of its downstream link (5008-4000054) is less than the sum of its upstream links (4000053-5008 and 4005008-5008). Another potential bottleneck is the downstream of node 4000055 because queues might build up from further downstream and back up onto our test site.

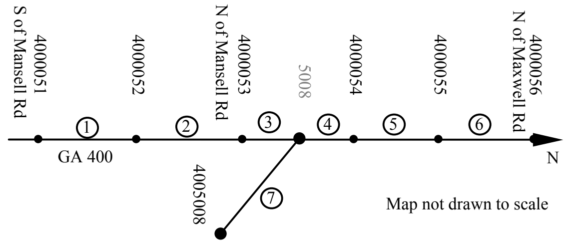

Figure 2: Test Site 1 - Merging Scenario

Table 1: Data of Test Site 1

Link	Length (mi)	Lanes	FFS (mi/h)	Capacity (veh/h/ln)	Jam Density (veh/mi/ln)
1	0.37	3	58	2200	180
2	0.28	3	63	2200	180
3	0.16	3	67	2200	180
4	0.17	3	57	2200	180
5	0.28	3	57	2000	180
6	0.31	3	61	2000	180
7	0.50	1	20	1800	180

Site 2 is for testing freeway diverging behavior. It consists of 9 observation stations (all start with 400) and 9 links as labeled in circles. See Figure 3. Geometry and traffic characteristic data of this site is listed in Table 2. The diverge, node 6006, might be a bottleneck because queues can back up from either of the downstream links.

Note that, coding of the test sites in simulation may not literally follow the above link structures. Two days, - Sept. 6, 2002 and Sept 12, 2002, are selected for testing, one for each site.

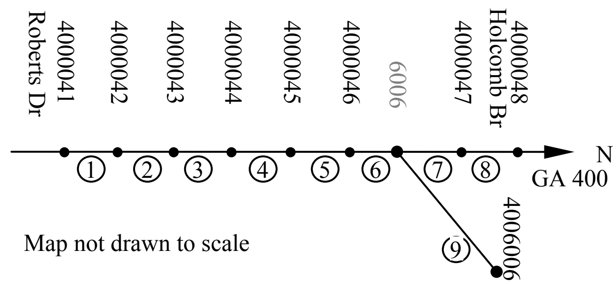

Figure 3: Test Site 2 - Diverging Scenario

Table 2: Data of Test Site 2

Link	Length (mi)	Lanes	FFS (mi/h)	Capacity (veh/h/ln)	Jam Density (veh/mi/ln)
1	0.28	4	68	2200	180
2	0.33	4	68	2200	180
3	0.32	4	68	2200	180
4	0.27	4	68	2200	180
5	0.35	4	68	2200	180
6	0.23	4	68	2200	180
7	0.24	4	60	2200	180
8	0.28	4	65	2200	180
9	0.50	1	60	2000	180

5.2 Qualitative Results

Qualitative evaluation of the model performance is based on visual examination of observed and predicted density. Figures 4 and 5 summarize simulation results of the test sites for freeway merging and diverging behavior.

In each part of the figures, the upper plot is flow vs. time curve, the middle one is a schematic map of the test site and the current link is highlighted in red. The bottom plot is density vs. time curve. for all plots, observed curves are solid lines in blue and predicted curves are dot dash lines in red. Simulation for site 1 starts at 00:00:40 and ends at 23:50:40. Simulation for site 2 starts at 00:01:00 and ends at 23::51:00.

For test site 1, there are two peaks originated from downstream of node 4000055 and they spill back to somewhere between nodes 4000051 and 4000053. The morning peak forms roughly from 07:00:00 to 08:30:00, and the afternoon peak lasts roughly from 15:05:00~18:03:20). Notice that there is much variation in flow and density at the on-ramp, and the peak, if any, is not so apparent.

For test site 2, there are also two peaks. The morning peak is originated from downstream of node 4000048, while the afternoon peak is caused by congestion at downstream of node 4006006. Notice that, in figure C and D, the morning peak and afternoon peak show up individually, while in figure B they both appear at the same place but in different time.

5.3 Quantitative Results

Quantitative evaluation is based on prediction mean absolute error (PMAE) as well as mean absolute percentage error (MAPE). Table 3 shows test result of site 1. The result suggests that prediction on freeway mainline is generally more accurate than that of the ramp, and the overall precision of prediction falls in the range of ± 9.6%. Table 4 shows the result for site 2. Again, the result suggests more accurate prediction on mainline than the ramp. The overall precision is ± 7.3%.

In conclusion, qualitative examination shows good fit of density curves, while quantitative comparison reveals that the predicted density varies within ± 9.6% of observed density. Considering that there are so many working factors affecting traffic operation that only a few major factors are considered in this macroscopic deterministic simulation model, the above results are quite satisfactory.

6 SUMMARY AND CONCLUSION

Freeway merging and diverging behavior plays an important role in freeway traffic operation, but research of this topic is limited in literature. This paper, based on Newell's simplified kinematic wave theory, proposed a set of procedures to deal with traffic on ramps. From the above discus-

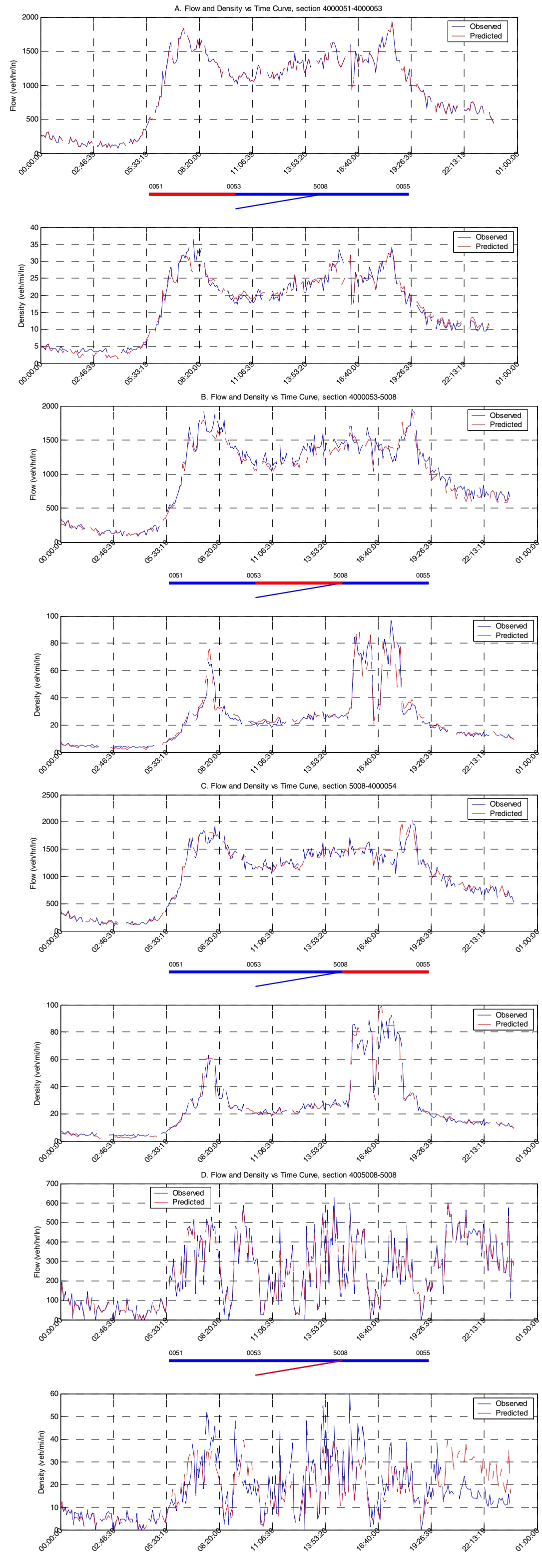

Figure 4: Simulation Result of Test Site 1

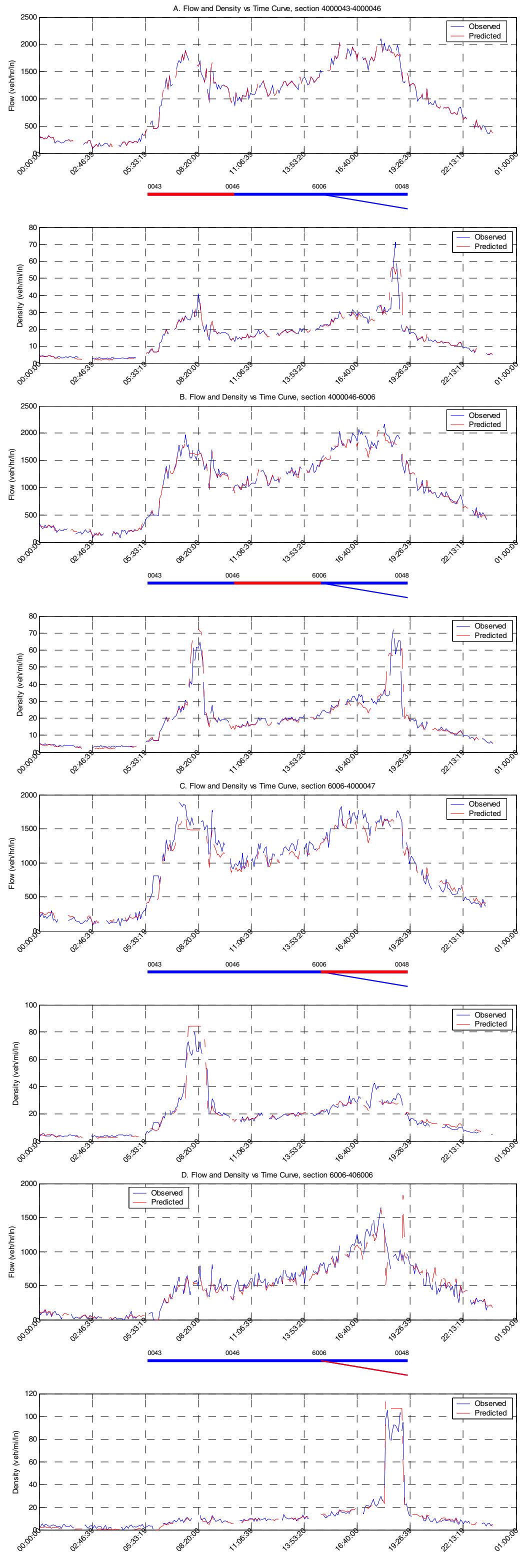

Figure 5: Simulation Result of Test Site 2

Table 3: Test Result of Test Site 1

Link	PMAE	MAPE
4000051-4000053	1.19	0.106
4000053-5008	2.77	0.131
5008-4000054	2.70	0.131
4005008-5008	5.92	0.396
Grand Mean	3.145	0.191

Table 4: Test Result of Test Site 2

Link	PMAE	MAPE
4000043-4000046	1.01	0.071
4000046-6006	1.74	0.100
6006-4000047	2.50	0.147
6006-4006006	2.01	0.260
Grand Mean	1.82	0.145

sion, it is self-evident that these procedures do not explicitly distinguish freeway mainline and ramps and their roles are exchangeable. This means that the procedures also applies to scenarios where two freeways merge or diverge such as that of I-75 and I-85 at downtown Atlanta.

The proposed merging scenario relaxes Newell's assumption that on-ramp traffic always has the priority and can bypass queues, if any. Traffic on both entering links now have the same priority and have to compete each other for downstream supply.

The proposed diverging scenario relaxes Newell's assumption that exiting traffic can always to do so without delay. This is no longer true because queues from either exit ramp or downstream mainline can build up and block upstream traffic. If there is any delay, it is experienced by all vehicles in the upstream link, not through traffic alone.

Empirical tests show that the proposed procedures are efficient and can predict traffic operation with reasonable accuracy. Visual examination suggests that the predicted and observed density in good agreement. In particular, the proposed procedures shows a good ability to capture the peaks, which are of great interest to traffic engineers, in both temporal and spatial domain. Numerical comparison shows that the procedures generally yield a prediction precision within ± 9.6%.

The modeling of merging and diverging has important practical implications. For example, it allow analysis of alternate diversion strategies, incident recovery strategies, and ramp metering strategies. It also enables the simulation of a regional freeway corridor and network, such as the one in metro Atlanta area, so that traffic management agency are at a better position to evaluate the overall performance of the system and thus assist in decision-making.

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