Abstract

Knowledge of fundamental traffic flow characteristics of traffic simulation models is an essential requirement when using these models for the planning, design, and operation of transportation systems. In this paper we discuss the following: a description of how features relevant to traffic flow are currently under implementation in the TRANSIMS microsimulation, a proposition for standardized traffic flow tests for traffic simulation models, and the results of these tests for two different versions of the TRANSIMS microsimulation.

keywords: traffic simulation, traffic flow, intersections
I. INTRODUCTION

One could probably reach agreement that the traffic flow behavior of traffic simulation models should be well documented. Yet, in practice, this turns out to be somewhat difficult. Many traffic simulation models are under continuous development, and the traffic flow dynamics documented in a certain publication has probably been refined and extended until the paper gets actually published.

It makes thus sense to agree on a certain set of tests for traffic flow dynamics which should always be run and documented together with any “real” results. In this paper, we propose such a suite of traffic flow measurements. We are well aware of the fact that some of the results in this paper are arguably unrefined with respect to reality. Yet, as we stated above, we are continuously working on improvements, and this publication represents both a snapshot of where we currently stand and an argument for a standardized traffic flow test suite for simulation models. We hope that this publication will both open the way for a constructive dialogue on which standardized traffic flow tests should be run for traffic simulation models, and which of the features of our traffic simulation models may need improvement.

When designing a traffic microsimulation model, the first idea might be to measure all aspects of human driving and put them in algorithmic form into the computer. Unfortunately, such attempts cause many problems. The first is a data collection problem, because one can certainly not measure “all” aspects of human driving and is thus faced with the double sided problem that the necessary data collection process is extremely costly and still selective. Second, what if the macroscopic flow properties of such a model are clearly wrong, for example producing an hourly flow rate that is much too high or low? Since, in such a modeling approach, one does not know the connection between the many parameters of the model and the emergent properties (such as flow), one is left to random trial and error.

For that reason, the TRANSIMS (TRansportation ANalysis and SIMulation System [1]) microsimulation starts with a minimal approach. A minimal set of driving rules is used to simulate traffic, and this set of rules is only extended when it becomes clear that a certain important aspect of traffic flow behavior cannot be included with the current rule set. Besides the conceptual clarity, this also has the advantage that it is usually computationally fast – minimal models have few rules and thus run fast on computers. This argument also makes it clear that one wants to remain flexible with respect to refinements of the model: If certain refinements are unnecessary with respect to a certain question, one would want to switch them off both for conceptual clarity and for computational speed.

The questions that TRANSIMS is currently designed for are transportation planning questions. The most important zeroth order result of a transportation microsimulation should be the delays, since, once they occur, they dominate travel times, and also hinder discharge of the transportation system, thus leading to grid-lock. Delays are caused by congestion, and congestion is caused by demand being higher than capacity. This implies that the first thing the TRANSIMS traffic microsimulation has to get right are capacity constraints (and possibly their variance). Capacity constraints are caused by a variety of effects:

- Undisturbed roadways such as freeways have capacity constraints given by the maxi-
• Typical arterials have their capacity constraints given by traffic lights.

• In the case of unprotected turning movements (yield, stop, ramps, unprotected left, etc.), the capacity constraints are given as a function of the traffic on the “interfering lanes”. For example, the number of vehicles making an unprotected left turn depends on the oncoming traffic.

Building a simulation which can be adjusted against all these diagrams seems a hopeless task given the enormous amount of degrees of freedom. The TRANSIMS approach for that reason has been to generate the correct behavior from a few much more basic parameters. The correct behavior with respect to the above criteria can essentially be obtained by adjusting two parameters: (i) The value of a certain asymmetric noise parameter in the acceleration determines maximum flow on freeways and through traffic lights; (ii) the value of the gap acceptance determines flow for unprotected movements.

The remainder of this paper will first describe the algorithms TRANSIMS uses for the most important traffic movements, and then describe the resulting flow characteristics.

II. RULES

A. Single lane uni-directional traffic

Our traffic simulation is based on a cellular automata technique, i.e., a road is composed of cells, and each cell can either be empty, or occupied by exactly one vehicle [2,3], see Fig. 1 (a). Since movement has to be from one cell to another cell, velocities have to be integer numbers between 0 and \( v_{\text{max}} \), where the unit of velocity is [cells per time-step]. It turns out that reasonable values are [3,4]:

- length of a box = \( 1/\rho_{\text{jam}} = 7.5 \) m (\( \rho_{\text{jam}} = \) density of vehicles in a jam).
- time step = 1 sec
- maximum velocity = 5 boxes per time step = \( 5 \cdot 7.5 \) m/sec = 135 km/h \( \approx 85 \) mph

For other conditions, such as higher or lower speed limits, this can be adapted.

Note that this approach implies a coarse graining of the spatial and temporal resolution and therefore of the velocities. A vehicle which has a speed of, say, 4 in this model stands for a vehicle which has a speed anywhere between \( 3.5 \cdot 7.5 \) meters/sec \( \approx 95 \) km/h (59 mph) and \( 4.49999 \cdot 7.5 \) meters/sec \( \approx 121 \) km/h (75 mph).

Vehicles move only in one direction. For an arbitrary configuration (velocity and position), one update of the traffic system consists of two steps: a velocity update step consisting of three consecutive rules, and a movement step according to the result of the velocity update. The whole update is performed simultaneously for all vehicles. The complete configuration at time step \( t \) is stored and the configuration at time step \( t + 1 \) is computed from that “old”
information. Computationally we calculate in time step $t$ (with the three rules) the new velocity of each car and write this newly calculated velocity in the same site without moving the car (velocity update). After that we move all cars according to their newly calculated velocity (movement update).

1. (velocity update)
   
   For all particles $i$ simultaneously, do the following:
   
   $\text{IF} \ (v_i \geq gap_i) \ \ \ \ v_i := \begin{cases} 
   gap_i - 1 & \text{with probability } p_{\text{noise}} \text{ if possible} \\
   gap_i & \text{else} 
   \end{cases} \quad \text{(close following/braking)}$
   
   $\text{ELSE IF} \ (v_i < v_{\text{max}}) \ \ \ v_i := \begin{cases} 
   v_i & \text{with probability } p_{\text{noise}} \\
   v_i + 1 & \text{else} 
   \end{cases} \quad \text{(acceleration)}$
   
   $\text{ELSE (i.e. } (v_i = v_{\text{max}} \text{ AND } v_i < gap_i) \ \ \ v_i := \begin{cases} 
   v_{\text{max}} - 1 & \text{with probability } p_{\text{noise}} \\
   v_{\text{max}} & \text{else} 
   \end{cases} \quad \text{(free driving)}$
   
   $\text{ENDIF}$

2. (movement update)
   
   Move all particles $i$ to $x_i(t + 1) = x_i(t) + v_i$.

The index $i$ denotes the position (an integer number) of a vehicle, $v(i)$ its current velocity, $v_{\text{max}}$ its maximum speed, $gap(i)$ the number of empty cells ahead, and $p_{\text{noise}}$ is a randomization parameter.

The first velocity rule represents noisy car following or braking. If the vehicle ahead is too close, the vehicle itself attempts to adjust its velocity such that it would, in the next time-step, reach a position just behind where the vehicle ahead is at the moment. Yet, with probability $p_{\text{noise}}$, the vehicle is a bit slower than this.

The second velocity rule represents noisy acceleration. Essentially, the acceleration is linear (i.e. independent from current speed), but with probability $p_{\text{noise}}$, no acceleration happens in the current time step (maybe as a result of switching gears etc.). Instead of an acceleration sequence of $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow \ldots$, a possible acceleration sequence can now be $0 \rightarrow 0 \rightarrow 1 \rightarrow 2 \rightarrow 2 \rightarrow 2 \rightarrow 3 \rightarrow \ldots$.

The last velocity rule represents free driving. Instead of remaining always at the same speed, such vehicles fluctuate between $v_{\text{max}}$ (with probability $1 - p_{\text{noise}}$) and $v_{\text{max}} - 1$ (with probability $p_{\text{noise}}$). Note that a vehicle which is set to $v_{\text{max}} - 1$ will go through the acceleration step next time, thus in the next time step either staying at $v_{\text{max}} - 1$ with probability $p_{\text{noise}}$ or getting back to $v_{\text{max}}$. Note that the resulting average speed of a freely driving vehicle is thus $v_{\text{max}} - p_{\text{noise}}$.

This microsimulation is also fairly well understood from a theoretical perspective; see [5,6] for more information.
B. Lane changing for passing

For multi-lane traffic, the model consists of parallel single lane models with additional rules for lane changing. Here we describe the two lane model which can be modified to any kind of multi lane model. Lane changing is modeled by an additional update step, which is added before the velocity update. The new sequence of steps is presented below. Steps two and three are the same in the single lane model and they are executed separately for each lane.

1. Lane changing decision
2. Velocity update
3. Vehicle movement

According to this lane changing rule set the vehicles are only moving sideways during the lane changing step; forwards movement is done in the vehicle movement step. One should, though, look at the combined effect of the lane changing and the movement, and then vehicles will usually have moved sideways and forwards. The decision to change lane is implemented as strictly parallel update, i.e. each vehicle is making its decision based upon the configuration at the beginning of the update.

- Lane changing decision for passing
  - IF neighboring position $x_o(i)$ in other lane is vacant
    * THEN Calculate:
      - $gap(i)$ Gap Forward in Current Lane,
      - $gap_o(i)$ Gap Forward in Other Lane,
      - $gap_b(i)$ Gap Backward in Other Lane,
      - IF ($gap(i) < v(i)$ AND $gap_o(i) > gap(i)$ )
        - THEN $weight_1 = 1$
        - ELSE $weight_1 = 0$
      - $weight_2 = v(i) - gap_f(i)$
      - $weight_3 = v_{max}(i) - gap_b(i)$.
    * IF ($weight_1 > weight_2$ ) AND ($weight_1 > weight_3$ )$^2$
      - THEN mark vehicle for lane change$^3$

$^2$Weights are used because of extensibility towards “lane changing for plan following”. See below.

$^3$In the current version, the lane change is actually still rejected with a probability of 0.01 even when all the rules are fulfilled. This is in order to break the following artifact or variations of it: Assume one lane is completely occupied and one is completely empty. The above rule set will result in these vehicles just changing back and forth between the lanes—the vehicles will never get smeared out across the lanes. See Ref. [7] for more details.
The rules are working in the following way (see Fig. 1 (b)): First we look at the neighboring position in the target lane. If this cell is vacant, we calculate the gap forward in the current lane \((gap)\), the gap forward in the target lane \((gap_o)\), and the gap backward in the target lane \((gap_b)\). With these results we calculate the \(weight1\) to \(weight3\) described above. Finally if the weight comparisons render true the car will change to the new lane. After executing the lane changing decision we calculate the new velocity for all cars and move them according to this velocity.

For three or more lanes, a simultaneous implementation of the lane changing decision can lead to collisions. For example, in a three-lane road two vehicles on the left and right lane could decide to go to the same spot in the middle lane. From an algorithmic point of view, this is possible because the lane changing decision is based on the configuration on time \(t\); but it is also an entirely realistic situation.\(^4\) To avoid collision we only allow lane changes in a certain direction in each time step:

- **IF** the time step is even
  
  **THEN** start procedure \(lane\ changing\ decision\) to the left for cars on the middle and then on the right lane

- **IF** the time step is odd
  
  **THEN** start procedure \(lane\ changing\ decision\) to the right side for cars on the middle and then on the left lane

Thus, left lane changes occur only on even time steps, right lane changes occur only on odd time steps. This behavior is collision free.

### C. Lane changing for plan following

Vehicles in TRANSIMS follow route plans, i.e. they know ahead of time the sequence of links they intend to follow. This means that, when they approach an intersection, they need to get into the correct lanes in order to make the intended turn. For example, a vehicle which intends, according to its route plan, to make a left turn at the next intersection needs to get into one of the lanes which actually allow a left turn.

This is achieved in TRANSIMS by supplementing the basic lane changing rules with a bias towards the intended lanes. This bias increases with increasing urgency, i.e. with decreasing distance to the intersection. Technically, this is achieved by adding another weight to the acceptance conditions for lane changing:

- **IF** \((weight1 + weight4 > weight2)\) AND \((weight1 + weight4 > weight3)\)
  
  **THEN** change lane

\(^4\)In a deeper sense, the problem is caused by the fact that the underlying decision making dynamics has a time scale which is smaller than the time resolution of the simulation. The simulation thus must resolve the conflict by other means.
weight4 is calculated according to

\[ weight4 = \max \left[ \frac{d^* - d}{v_{max}}, 0 \right] \]

for lane changes in the desired direction as long as the vehicle is not in one of the correct lanes, cf. Fig. 1 (c). \( d \) is the remaining distance to the intersection, \( d^* \) is a parameter; both are given in the unit of “cells”. \( d^* \) is currently set to 70 cells, i.e. approx. 500 m or 1/3 of a mile, throughout the simulation. In consequence, \( weight4 \) increases from zero to \( \frac{d^*}{v_{max}} = 14 \) during the approach to the intersection. If \( weight4 = 0 \), then it does not influence lane changing decision. \( weight4 = 1 \) has the same effect as a slower vehicle ahead on the same lane. Further increases of \( weight4 \) more and more override the security criterions that the forward and the backward gap on the destination lane need to be large enough. \( weight4 > v_{max} \) lets the vehicle make the lane change even if only the neighboring cell on the destination lane is free.

D. Unprotected turning movements

A necessary element of traffic simulations are unprotected turning movements. By this we mean that that for the movement the driver intends to make, some other lanes have priority. Examples are stop signs, yield signs, on-ramps, unprotected left turns.

The general modeling principle for this in TRANSIMS is based on a gap acceptance in the interfering lanes, see Fig. 1 (d). Interfering lanes are the lanes which have priority; for example, for a stop-controlled left turn onto a major road this would be all lanes coming from the left plus the leftmost lane coming from the right. In order to accept the turn, there has to be a sufficient gap on each of these lanes.

Note that “gap divided by the velocity of the oncoming vehicle” is the oncoming vehicle’s time headway, which is the typical measure used in the Highway Capacity Manual [8]. If one wants a time headway on an interfering lane of at least 3 seconds, then a vehicle with a velocity of 4 cells/second would have to be at least 12 cells away from the intersection.

The current TRANSIMS microsimulation uses a gap acceptance (gap between intersection and nearest car to the intersection which is approaching) of 3 times the oncoming vehicle’s velocity, i.e. when the gap on each interfering lane is larger than or equal to the first vehicle on that lane, the move is accepted. For example, if the oncoming vehicle has a speed of 3, at least 9 empty cells have to be between the oncoming vehicle and the intersection. A special case is if the oncoming vehicle has the velocity zero, in which case no gap is necessary.\(^5\)

\(^5\)The condition for the “case study” microsimulation of TRANSIMS [9,10] was that a movement was accepted if, for all interfering lanes, the gap was larger than \( v_{max} \). That means that for fast oncoming traffic the acceptance was higher than in the newer version, but for low speed oncoming traffic the acceptance rate was lower—with the extreme case that no turns were possible against oncoming traffic of speed zero.
E. Signalized intersections

In TRANSIMS, we distinguish between signalized intersections and unsignalized intersections because they are modeled differently in TRANSIMS. In signalized intersections, the priorities are changing in time and regulated by signals. In unsignalized intersections, the priorities are fixed.

When a simulated vehicle approaches a signalized intersection, the algorithm first decides if, according to its current speed, it potentially wants to leave the link, i.e. its current speed (in cells per update) is larger than or equal to the remaining number of cells on the link. If a vehicle wants to leave the link, the algorithm checks the “traffic control”, which determines if the vehicle can leave the link. If it encounters a red light, it can not leave the link and no further action is taken. If it encounters a protected (green arrow) or caution (yellow) signal, the vehicle is allowed to enter the intersection. If it encounters a permitted signal (green, for example permitted left turn against oncoming traffic), the vehicle checks all interfering lanes for the gap that is larger or equal to 3 times the oncoming vehicle’s velocity (see Subsec. II D above).

If the movement into the intersection is accepted, the vehicle is moved into an “intersection queue”; there is one queue for each incoming lane. This queue models vehicle behavior inside an intersection. The vehicle gets a “time stamp”, before which it is not allowed to leave the intersection; this time stamp is representative for the duration of the movement through the intersection. The intersection queues have finite capacity; once they are full, no more vehicles are accepted and the vehicles start to queue up on the link. This models the finite vehicle storing capacity of an intersection.

Once a vehicle is ready to leave the intersection, it moves to the first cell on the destination link if available. The speed of the vehicle is not changed when it is in the intersection queue so it exits on the destination link in the first cell with the same velocity that it had when it entered the queue.

Note that vehicles turning against interfering traffic make their decision to accept the turn when they enter the intersection queue, not when they leave it. This can have the effect that a vehicle enters the intersection queue when there is no oncoming traffic, but, because of other vehicles ahead of it in the same queue, cannot make its turn immediately. Yet, since the turn was already accepted, it will be executed as soon as all vehicles ahead in the same queue have cleared the queue and a cell on the destination link is available. The turn can occur during oncoming traffic. So in some sense vehicles will go “through” each other. Yet, note that on average the result is still correct. The approach described above will not let more vehicles through the intersection than a gap acceptance calculated when leaving the intersection queue. The above logic was chosen for simplification purposes since unsignalized intersections (see below) do not have queues and thus need to make their acceptance decisions when entering the intersection.

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6Vehicles may accelerate or slow down before they actually reach the intersection. See below.

7Algorithmically, it only “reserves” a cell. See below.
F. Unsignalized intersections

Unsignalized intersections in TRANSIMS have no internal queues, i.e. vehicles go right through them. Also, vehicles leaving an unsignalized intersection go down the destination link as far as prescribed by their velocity, not just into the first cell as in the signalized intersections. Apart from these two differences, unsignalized intersections are similar to signalized ones.

When a simulated vehicle approaches an unsignalized intersection, the algorithm first decides if, according to its current speed, it potentially wants to leave the link, i.e. its current speed (in cells per update) is larger than or equal to the remaining number of sites on the link. If a vehicle wants to leave the link, the algorithm checks the “traffic control”, which determines if the vehicle can leave the link. Currently occurring traffic controls are: no control, yield, and stop.

If a “no control” is encountered, the vehicle is moved to its destination cell without any further checks. For example, if a vehicle has a velocity of 5 cells per update and 2 more cells to go on its link, then it attempts to go 3 cells into the destination link. If that cell is already reserved (either by another “reservation” or by a real vehicle), then the next closer cell is attempted, etc., until the algorithm either finds an empty cell or returns that the destination lane is full. “No control” is usually used for the major directions, i.e. for the lanes which have priority.

If a “yield” is encountered, the vehicle checks the gap on all interfering lanes. According to the same rules as above, on all interfering lanes the gap needs to be larger or equal three times the first vehicle’s speed on that lane. If the movement is accepted, the destination cell is selected according to the same rules as with the “no control” case.

If it encounters a “stop”, the vehicle is brought to a stop. Only when the vehicle has a velocity of zero for at least one time step on the last cell of the link, is it allowed to continue. If the result of the regular velocity update indeed accelerates the vehicle, then it attempts to go through the intersection. On all interfering lanes the gap, according to the same rules as above, needs to be larger or equal to three times the first vehicle’s speed on that lane. If the movement is accepted, a vehicle coming from a stop sign will always go to the first cell on the destination link (if empty) and will have a velocity of one.

G. Parking locations

In the current TRANSIMS microsimulation, vehicular trips start and end at parking locations. Each link in the microsimulation, except for freeway ramps, freeway links, and some

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8 Again, technically the vehicles only reserve cells on the destination links. The actual move through the intersection happens later and can also be postponed if after the velocity update the vehicle actually does not make it to the intersection.

9 I.e. there is a probability of $1 - p_{\text{noise}}$ that the vehicle will not accelerate in the given time step.
“virtual” links such as centroid connectors, has at least one parking location. Parking locations thus represent the aggregated parking options on that link. Parking locations have rules about how vehicles enter and exit the simulation:

- Each vehicle in TRANSIMS has a complete route plan, together with a starting time. At the starting time, the vehicle is added to a queue of vehicles that want to leave the same parking location. When the vehicle is the first one in the queue, it attempts to enter the link. The acceptance logic is in spirit similar to the logic of the unsignalized intersections, i.e. vehicles check the available gap and make their decision based on that. Parking accessory logic is not the focus of the current paper, and since that logic may change in TRANSIMS in the near future and we also expect no influence on the results presented here, we omit further technical details.

- A vehicle that has reached its destination parking location according to its plan will leave the microsimulation. It is simply removed from the traffic.

II. Parallel logic

TRANSIMS is designed to run on parallel computers, such as coupled workstations, desktop multi-processors, or supercomputers. The parallelization approach used for the microsimulation is a geographical distribution, i.e. different geographical parts of the simulated area are computed on different CPUs.

The current TRANSIMS microsimulation has these boundaries always in the middle of links. This is done in order to keep the complexity of the parallel computing logic as far away as possible from the complexity of the intersection logic.

Information needs to be exchanged at the boundaries several times per update in order to keep the dynamics consistent. For example, if a vehicle changes lanes and end up close in front of another one, that other one is probably forced to brake. Now, if the lane changing vehicle is on one CPU and the following one on another, one needs to communicate the lane change. This will be called “Update boundaries” in the following section.

I. Complete scheduling

For a complete transportation microsimulation, we need to specify when movements are accepted, and also how conflicts are resolved. For example, vehicles simultaneously attempting to change lanes into the middle lane represent such a conflict. Another conflict is two vehicles from two different links competing for the same site on the destination link.

The complete update of the current TRANSIMS microsimulation is as follows. Assume that the state at time $t$ is the result of the last update. Let $t_1, t_2$, etc. be intermediate partial time steps.

1. Vehicles which are ready to leave intersection queues from signalized intersections reserve cells on outgoing lanes. They only attempt to reserve the first cell on the link;
their velocity is the same as it was when they entered the intersection. When the cell is occupied (either by another “reservation” or by a vehicle), then the vehicle cannot leave the intersection. Note that there can be a conflict between different queues for the same destination cell. The current solution in TRANSIMS is that queues are served on a first come first served basis in some arbitrarily defined way, i.e. a queue which happens to be treated earlier in the microsimulation has a slightly higher chance of unloading its vehicles. — Result: $t_1$ information.

2. Vehicles change Lanes. Use information from time $t_1$ to calculate situation at time $t_2$.

3. Exit from Parking. Results in $t_3$ information.

4. Exchange boundary information for parallel computing.

5. Non-signalized intersections reserve sites on target lanes. Note that there can be a conflict of two incoming links competing for the same destination cell. The current solution in TRANSIMS is that links are served on a first come first served basis, i.e. a link which happens to be treated earlier in the microsimulation has a slightly higher chance of unloading its vehicles. Note that this conflict only happens between minor links. Major links never compete for the same outgoing link except when there is a network coding error; and for the competition between major and minor links, the major link always wins because of the interfering lanes conditions.\footnote{Note that the situation slightly different when the speed of the vehicle on the major link is zero—see below.} Result: $t_4$ information.

6. Calculate speeds and do movements. If a vehicle scheduled for an intersection does not go through the intersection as a result of the velocity update, the reservation is cancelled. Vehicles which go through unsignalized intersections have $p$ set to zero, i.e. if it turns out that the result of the velocity update indeed brings them into the intersection, they need to go to the site on the destination lane which was reserved earlier. Result: $t_5 = t + 1$ information.


III. STANDARDIZED FLOW TEST SUITE FOR SIMULATION MODELS

In order to control the effect of driving rules, TRANSIMS provides controlled tests for traffic flow behavior. These tests are simplified situations where elements of the microsimulation can be tested in isolation. This test suite uses the standard microsimulation code in the same way it is used for full-scale regional simulations, and it also uses the same input and output facilities: The test network is currently defined via a table in an oracle database, in the same format as the Dallas/Fort Worth network is kept. Input of vehicles is, following individual vehicle’s plans, via parking locations, the same way vehicles enter regional simulations.
Output is collected on certain parts of the network on a second-by-second basis, the same way it can be collected for regional microsimulations. The collected output is then post-processed to obtain the aggregated results presented in this paper.

The test cases we look at in this paper are the following (see also Fig. 1 (e)):

- One-lane traffic, in order to see if car following behavior generates reasonable fundamental diagrams.
- Three-lane traffic, in order to see if the addition of passing lane changing behavior still generates reasonable fundamental diagrams, and in order to look at lane usage.
- Stop sign, yield sign, and left turns against oncoming traffic, in order to see if the logic for non-signalized intersections generates acceptable flow rates.
- A signalized intersection, in order to see if we obtain reasonable flow rates, and in order to check lane changing behavior for plan following purposes.

A. Measured quantities

We look at three minute averages of the following quantities:

- **Local Flow.** Flow $q$ is defined as usual by:

  $$ q = \frac{N}{T} \quad \text{[vehicles/hour]} $$

  $N$ is the number of cars which pass a certain site at a time period $T$.

- **Local Density.** Density is in principle easily defined, $\rho = N/L$, where $N$ is the number of vehicles on a piece of roadway of length $L$. Yet, given current sensoring technology, this is not easy to achieve since one would need a sensor which counts, say once a second, cars on a predefined stretch of length $L$ of the roadway. For that reason, empirical papers sometimes resort to occupancy, which is the fraction of time a given sensor has been occupied by a vehicle. Current TRANSIMS measures density according to its original definition, i.e., once a time step, we count the number of vehicles on a stretch of roadway of $L = 5$ sites $= 5 \times 7.5 \text{ m} = 37.5 \text{ m}$.\(^{11}\) We add these counts for $k = 180$ measurement events and then divide the resulting number by $L$ and by $k$:

  $$ \rho = \frac{N}{k \times L} $$

\(^{11}\)The “magical” number of $L = 5$ sites is equal to the maximum velocity of $v_{\text{max}} = 5$ sites/update. This ensures that each vehicle is counted at least once.
The result can be scaled to convenient units, for example “vehicles per km”.

Note that this way of computing density averages the counts over a length of 37.5 m, which is longer than the usual sensor extensions. The effect of this should be systematically studied.

• **Local velocity.** It is well known that one can measure velocity either analogous to our flow definition (local velocity) or analogous to our density definition (space-averaged velocity). Under non-stationary conditions, the measurements give different results, since, for example, the first definition never counts vehicles with velocity zero. Local velocity is easier to measure in practice; the space-averaged velocity is easier to interpret since it is equal to the travel velocity and it is also the velocity which needs to be used in the fundamental relationship between flow, density, and velocity, \( q = \rho \cdot v \). Since in a simulation model, both are similarly easy to measure, we measure the more useful travel velocity. Once a time step, we sum up the individual velocities of all vehicles on a stretch of roadway of \( L = 5 \) sites = \( 5 \times 7.5 \) m = 37.5 m. We add these sums for \( k = 180 \) measurement events and then divide the resulting number by \( N \) and by \( k \), where \( N \) is the same number as obtained during the density measurement above:

\[ v = \frac{\sum v}{k \ast N} \]

• **Lane usage.** Lane usage of a particular lane is the number of cars on this lane divided by the number of cars on all lanes. It can be computed as:

\[ f_i = \frac{\rho_i}{\sum_{j=1}^{n} \rho_j \cdot n} \]

where \( i \) is the lane we look at and \( n \) is the number of lanes.

### B. Test networks

Essentially two test networks are used: a circle of 1000 sites = 0.75 km in various configurations, and a simple signalized intersection. Most of the test are run on the circle networks. The circle can have one or two or three lanes. In all tests, the circle is slowly loaded with traffic via a parking location at \( x = 1 \) sites. Velocity, flow, and density are measured on \( 486 \leq x \leq 490 \), thus generating the fundamental diagrams for one-lane, two-lane, and three-lane traffic. Since the circle gets slowly loaded, the complete fundamental diagram is generated during one run.

For testing yield signs and stop signs, an incoming lane is added on the right side of traffic at \( x = 501 \) (i.e. the first cell for the incoming traffic is 501). The characteristics of the incoming traffic is measured on a measurement box on the last 5 sites of the incoming lane. The incoming lane is operated at maximum flow, i.e. with as many vehicles as possible entering at its beginning. The incoming vehicles are removed at \( x = 900 \) via a parking accessory.
The result of this measurement is typically a diagram showing the flow of incoming vehicles on the y-axis versus the flow on the circle on the x-axis.

For testing left turns against oncoming traffic, an opposing lane is added so that it ends at \( x = 500 \). The traffic control here is again a “yield” logic; the difference from before is that vehicles only traverse the interfering traffic, they do not join it.

Last, a three-lane intersection approach is used. The left lane makes a left turn, the middle lane goes straight, the right lane makes a right turn. Incoming vehicles have plans about their intended movement at the intersection and attempt to reach the corresponding lane. The intersection has signals with 1 minute green phase and 1 minute red phase. The typical output from this run is the flow of vehicles which go through the intersection, and the number of vehicles which cannot make their intended turn because they did not reach their lane.

The results are shown in Figs. 2 to 4. Note that the HCM has the same curves for stop sign and for yield sign, whereas we obtain higher flows through yield signs, as should be the case.

**IV. SOME STUDY RESULTS**

Most of the results presented here were generated with an experimental code. The disadvantage of an experimental code is that actual implementation in the production version may still introduce changes in the results due to small discrepancies. The advantage is that turnover (compile times, complexity of code, etc.) is much higher than with a production version. We used that advantage to test many different rules. In the following, we want to present a small subsection of tests.

All results presented in this section refer to the situation of a 1-lane minor street merging into a 1-lane major street, with the intersection control being a yield sign. Fig. 5 (a) repeats the result from above for convenience. Figs. 5 (b)–(c) show the result of different average free speeds (e.g. result of speed limits) in the simulation (same speed limit for both streets). A high average free speed of approx. 130 km/h (\( \approx 80 \text{ mph} \), generated by \( u_{\text{max}} = 5 \)), maybe a freeway merge, generates a flow of approx. 2000 veh/hour/lane in the incoming lane when there is no traffic on the major road. From there, maximum incoming flow decreases continuously. Lower average free speeds of approx. 75 km/h (50 mph) and 50 km/h (30 mph) generate lower maximum incoming flows and are generally closer to the Highway Capacity Manual curve. Yet, it should also be clear from these curves that the flow on the minor road as a function of flow on the major road is also a function of the speed limit and not only of the gap acceptance, which is constant in all three simulations.

Another series of experiments shows the effect of different acceptance logics. Fig. 5 (d) shows, when compared to Fig. 5 (a), the difference between “accept when \( gap \geq 3v_{\text{back}} \)” vs. “accept when \( gap > 3v_{\text{back}} \).” This seems like a negligible difference in the rules; yet, the results are quite different in the congested regime. Whereas in the first, quite many vehicles are able to get into the congested major road, in the second, only few of them make it. The difference is easiest explained by looking at a vehicle of speed zero on the major road just in front of the merge point, with space for a vehicle downstream of the merge point. With the first rule, a vehicle at the yield sign will accept the move and move in front of the vehicle
on the major road, in the second case, it will not. Both scenarios seem to be plausible to us; only systematic measurements can probably resolve which one is better for a simulation model.

A last series of experiments shows the effect of different values for the gap acceptance. Figs. 5 (e) and (f) show “accept when gap > v_{back} and gap > v_{max}. Clearly, more vehicles are accepted, leading to a higher flow of turning vehicles as a function of the flow on the major road. Note that the flow via the yield sign is never higher than 1800 minus the flow on the major road. This reflects the fact that the major road cannot have a higher flow than 1800 veh/h/lane (free speed approx 50 mph); traffic through the yield sign can thus at most fill the major road to capacity. This explains why the much weaker gap acceptances to not produce even more difference in the regime where the major road is uncongested. The situation is clearly different for unprotected turns across instead of into traffic, as can be seen for the left turns in the next section.

V. COMPARISON TO CASE STUDY LOGIC

The gap acceptance logic presented here and used in the current TRANSIMS microsimulation is different from the logic used in the “Dallas/Fort Worth Case Study” [9,10]. The logic during that case study was: “Accept an unprotected movement if in all interfering lanes the gap is larger than v_{max} = 5.” This means that at low flow rates on the major road, more turns were accepted, whereas at high flow rates on the major road, less turns were accepted.

Fig. 6 compares the results for the current gap-acceptance logic and the one used in the case study for the case where the major road is a 3-lane road. Note that the results for the turns into other traffic are not that much different whereas the result for the turns across other traffic yields dramatically higher flows with the case study logic. This is due to the fact that for turns into other traffic, there is a capacity constraint of the form that the joint flows from the major and the incoming road cannot exceed capacity of the major road. Such a constraint obviously does not exist for turns across the major road.

VI. SUMMARY AND CONCLUSION

In transportation simulation models for larger scale questions such as planning, the flow characteristics of the traffic dynamics are in some sense more important than the microscopic driving dynamics of the vehicles itself. This becomes especially true since a “complete” representation of human driving is impossible anyway, both due to knowledge constraints and due to computational constraints. Yet, calibrating a traffic simulation model against all types of desired behavior (for example against all HCM curves and values mentioned in this paper) seems a hopeless task given the high degrees of freedom.

TRANSIMS thus attempts to generate plausible macroscopic behavior from simplified microscopic rules. This paper described the more important aspects of these rules as currently implemented or under implementation in TRANSIMS. Before we implement rules in the TRANSIMS production version, we usually try to run systematic studies with more exper-
imental versions. The results of the traffic flow behavior from that study were presented. Also, we showed the effects of some changes in the rules for the example of a yield sign. Finally, some comparisons were made between the logic currently under implementation and the logic used for the Dallas/Fort Worth case study.

One problem with microscopic approaches is that, in spite of all possible diligence, subtle differences between design and actual implementation can make a significant difference in the macroscopic outcome. For that reason, this paper should also be seen as an argument for a standardized traffic flow test suite for simulation models. We propose that simulation models, when used for studies, should first run these tests to see how the macroscopic flow dynamics actually is. We think that the combination of results presented in Figs. 2 to 4 are a good test set, although extensions may be necessary in the future (e.g. merge lanes, weaving, etc.). We will attempt to provide future TRANSIMS results also with updated versions of the results of the traffic flow tests.
REFERENCES

FIGURES

Situation I

(b) gap

Situation II

(a) gap

(c) gap = 3 * velocity(oncoming vehicle)

(d) Weight 4 added for lane changing

(e) gap

Vehicle with velocity 1 cell per time-step

Weight 4 added for lane changing

No Weight 4 added for lane changing

Measurement Box

Flow

Parking Location

Parking Accessory

Opposing Lane

x=1

x=486

x=490

x=501

x=900
FIG. 1. (a) Definition of gap and examples for one-lane update rules. Traffic is moving to the right. The leftmost vehicle accelerates to velocity 2 with probability 0.8 and stays at velocity 1 with probability 0.2. The middle vehicle slows down to velocity 1 with probability 0.8 and to velocity 0 with probability 0.2. The right most vehicle accelerates to velocity 3 with probability 0.8 and stays at velocity 2 with probability 0.2. Velocities are in “cells per time step”. All vehicles are moved according to their velocities at a later phase of the update. (b) Illustration of lane changing rules. Traffic is moving to the right; only lane changes to the left are considered. Situation I: The leftmost vehicle on the bottom lane will change to the left because (i) the forward gap on its own lane, 1, is smaller than its velocity, 3; (ii) the forward gap in the other lane, 10, is larger than the gap on its own lane, 1; (iii) the forward gap is large enough compared to its own velocity: \( \text{weight}_2 = v - gap_f = 3 - 10 = -7 < 1 = \text{weight}_1 \); (iv) the backward gap is large enough: \( \text{weight}_3 = v_{max} - gap_b = 5 - 6 = -1 < 1 = \text{weight}_1 \). Situation II: The second vehicle from the right on the right lane will not accept a lane change because the gap backwards on the target lane is not sufficient. (c) Value of \( \text{weight}_4 \) when in wrong lane during the approach to the intersection. (d) Example of a left turn against oncoming traffic. The turn is accepted because on all three oncoming lanes, the gap is larger or equal to three times the first oncoming vehicle’s velocity. (e) Test networks.
FIG. 2.  (a) One-lane traffic: Flow vs. density, travel velocity vs. flow, and travel velocity vs. density.  (b) Number of vehicles going through the intersection and number of vehicles “off plan” per green phase, re-scaled to hourly flow rates per lane.
FIG. 3. Three-lane circle: Flow vs. density, travel velocity vs. flow, travel velocity vs. density, lane usage vs. flow, and lane usage vs. density. The asymmetry in the lane usage at low densities is due to the fact that the parking locations start filling in vehicles on the right lane, and they only move to the left when traffic on the right lane becomes dense.
FIG. 4. Flow through stop sign, yield sign, and unprotected left turn. Left column: one-lane traffic on major road (circle). Right column: two-lane traffic on major road (circle). Solid line: Highway Capacity Manual [8]. Note that for “left turn across two lanes” (bottom right) the interfering volume is the sum of both lanes, i.e. twice the value show on the x-axis.
FIG. 5. Comparison between different rules for the case of a 1-lane minor road controlled by a yield sign merging into a 1-lane major road. (a) Figure as shown earlier, i.e. “accept if \( \text{gap} > 3 \text{v}_{\text{back}} \)” and \( v_{\text{max}} = 3 \). (b) – (c) Effect of different maximum velocities \( v_{\text{max}} = 5 \) and \( v_{\text{max}} = 2 \). (d) Effect of a slightly different acceptance rule “accept if \( \text{gap} \geq 3 \text{v}_{\text{back}} \)” (\( v_{\text{max}} = 3 \)). (e) – (f) Effect of weaker gap acceptances “accept if \( \text{gap} > \text{v}_{\text{back}} \)” and “accept if \( \text{gap} > v_{\text{max}} \)” (\( v_{\text{max}} = 3 \)).
FIG. 6. Comparison between current TRANSIMS microsimulation gap acceptance logic and the one used in the case study where the major road has three lanes. Flow through stop sign, yield sign, and unprotected left turn into/across one-lane traffic on major road. Left column: current TRANSIMS microsimulation. Right column: case study TRANSIMS microsimulation. Note that the results for the turns into other traffic are not that much different whereas the result for the turns across other traffic yields much higher flows with the case study logic.
Flow blue cars unprotected left turn vs flow red cars one_lane
Fundamental Diagram for 3-lane Circle simulation

Circle = 1000
P_Brake = 0.2
V_MAX = 5
Flow – Flow Diagram for 3–lane Circle simulation

Circle = 1000

P_Brake = 0.2

V_MAX = 5

gap_back = 3 * Vel
Flow blue cars unprotected left turn vs flow red cars three lane
Flow – Flow Diagram for 1–lane Circle simulation

Circle = 1000

P_Brake = 0.2

V_MAX = 3

gap_back = 3 * Vel
Flow – Flow Diagram for 3–lane Circle simulation

Circle = 1000
P_Brake = 0.2
V_MAX = 5
gap_back = 3 * Vel
Flow – Flow Diagram for 1-lane Circle simulation

Circle = 1000
P_Brake = 0.2
V_MAX = 3
gap_back = 3 * Vel
Flow - Flow Diagram for 1-lane Circle simulation

Circle = 1000
P_Brake = 0.2
V_MAX = 3
gap_back = 2 * Vel
Flow – Flow Diagram for 1–lane Circle simulation

Circle = 1000
P_Brake = 0.2
V_MAX = 3
gap_back = 3 * Vel
Movement

Before

\[ v=2 \quad v=3 \quad v=4 \]

After

\[ v=2 \quad v=2 \quad v=5 \]

Rules:

- If gap > speed, speed = speed + 1.
- If gap < speed, speed = gap. (No collisions)
- Sometimes slow down for no reason.
Left Lane Change

\[ v = 3 \]

\[
\begin{array}{cccccccc}
\text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} \\
\text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} \\
\text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} \\
\text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} & \text{I} \\
\end{array}
\]

Gap = 3
Gap Forward = 5
Gap Backward = 5
Desired Speed = 4
Current Speed = 3

\[
\begin{align*}
\text{Weight1} &= 4 > 3 \ \text{AND} \ 5 > 3 = 1 \\
\text{Weight2} &= 3 - 5 = -2 \\
\text{Weight3} &= 5 - 5 = 0 \\
\text{Lane Change} &= (1 > -2) \ \text{AND} \ (1 > 0) = 1
\end{align*}
\]
Stop-After Movement

Link 3

- v=3
- v=4
- v=2

Link 2

- v=1
- v=5
- v=5

Link 1
Stop--Before Movement

Link 3

\[ v = 0 \]
\[ v = 3 \]
\[ v = 5 \]

Link 2

\[ v = 0 \]
\[ v = 3 \]
\[ v = 5 \]

Link 1

\[ v = 5 \]

\[ v = 5 \]
Signal - Phase 1

Link 1

Link 2

Link 3
Rules for Traffic Signal

Protected, Caution (green, yellow):
Proceed if intersection buffer not full.

Wait (red):
Move as far as possible on current link,
(gap > 0), then wait.

Permitted:
Proceed if gap on interfering lanes >= maxV,
intersection buffer not full.
Rules for Yield

Proceed if:

Gap on interfering lanes $\geq \text{maxV}$.

Destination cell on destination link vacant.
Rules for Stop

Proceed if:

Stopped for at least 1 time step.

Gap on interfering lanes $\geq \text{maxV}$.

Destination cell on destination link vacant.
Plan Following Rules

Lane Changes to follow plan ignored until vehicle is within the consideration distance (70 cells from intersection).

Is current lane an acceptable lane for plan following?

Yes - bias vehicle to stay in current lane (Weight 4 = -1).

No - bias vehicle to change lanes based on distance from intersection. (Weight 4 = MaxSpeed - (Distance From Intersection - MaxSpeed) / 13)

Execute lane change rules modified to include plan following weight (Weight 4).

Weight 1 = (Gap in current lane < desired speed AND Gap Forward in new lane > Gap in current lane) + Weight4.
Lane Change Rules

Probability of 0.5 - skip lane change.

Cell at Current Position in New Lane Must be vacant.

Calculate Gap in Current Lane, Gap Forward in New Lane, Gap Backward in New Lane.

Weight 1 = Gap in current lane < desired speed AND Gap Forward in new lane > Gap in current lane. [1,0]

Weight 2 = Current speed - Gap Forward in new lane.

Weight 3 = Max Speed - Gap Backward.

Change Lanes if:

(Weight 1 > Weight 2) AND (Weight 1 > Weight 3).
Stop-After Movement

Link 3

- $v=3$

Link 2

- $v=5$

Link 1

- $v=3$

STOP
Stop-Before Movement

Link 3

v=3

Link 2

v=0

v=5

STOP

Link 1

v=4