Modeling User Equilibrium in Microscopic Transportation Simulation

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User equilibrium refers to the network-wide state where individual travelers cannot gain improvement by unilaterally changing their behaviors. The Wardropian Equilibrium has been the focus of a transportation equilibrium study. This paper modifies the dynamic traffic assignment method through utilizing the TRANSIMS system to reach the dynamic user equilibrium state in a microscopic model. The focus of research is developing three heuristics in a Routing-Microsimulation-Equilibrating order for reaching system-wide equilibrium while simultaneously minimizing the computing burden and execution. The heuristics are implemented to a TRANSIMS model to simulate a subarea of Houston, TX.

INTRODUCTION

In transportation models, road users reach a Wardropian equilibrium when a user cannot benefit by making a unilateral move (Haurie and Marcotte 1985; Jeihani, Sherali, and Hobeika 2006). In reality, road users frequently change routes and alter driving speeds in response to network conditions to optimize travel plans. Currently, transportation control entities have utilized communication technologies, e.g., message signs, internet mapping, and GPS, to help the general public assess instant traffic states. This information sharing enhances road users' decision making based on nearly real-time knowledge related to on-road conditions. When all road users are making attempts to improve travel experience but fail to obtain substantial gains, the system reaches a point closely resembling the theoretical equilibrium state.

Matching supply and demand is a key challenge in the economic system (Haurie and Marcotte 1985). In a complex system, equilibrium between supply and demand requires effective use of supply resources against market requirements. The effectiveness of the transportation network is conditioned by features of the supply and demand sides. An equilibrium state of a transportation system indicates the balance of supply and demand (Maillé and Stier-Moses 2009).

Reaching equilibrium in transportation analysis is a key objective for the modelers to assess policies' impacts (Bernstein and Smith 1994). Assessments and policies based on the equilibrium state can more accurately represent the real transportation network (Patriksson 2004). Analyses based on non-equilibrium states, where road users can still achieve substantial travel improvement, may underestimate the efficacy of control arrangements, or overestimate unusual congestion, gridlocks, and uneven traffic patterns. The model is thus less likely to diagnose the actual problems embedded in the network. Accordingly, analyses based on non-equilibrium models will not result in the optimal policies (Flyvbjerg, Skamris Holm, and Buhl 2006).

Consider the segment of U.S. 59 crossing Houston, TX. Policy makers intend to evaluate the benefit of widening the segment of U.S. 59 due to congestion problems. Without reaching the equilibrium criteria, planners may overestimate traffic volume assigned on the widened highway 59. Some of those estimated traffic volumes may be traveling on its frontage roads, and the widening of highway 59 would not necessarily reduce the congestion. This error occurs because the model does not reach assignment equilibrium criteria, thus preventing the policy maker from identifying the real factors that cause the congestion. As a consequence, policymakers will make judgments and evaluate projects based on the unreliable data source.

Transportation equilibrium has been extensively studied by macroscopic models. Recently, microscopic models begin to be employed to assess equilibrium. The advantage of the microscopic model is the level of detail and maneuverability of the study method (Lawson 2006). However, the complexity of the modeled vehicular interaction in a transportation network causes challenges for the model to stabilize. As such, a stream of research has begun to develop heuristics to help microscopic models converge (Jeihani, Sherali, and Hobeika 2006).

This paper develops and applies heuristics to approximate the exact Wardropian equilibrium. A heuristic is a modeling strategy that produces a quick and satisfactory solution as the perfect equilibrium entails exhaustive and lengthy computation efforts (Sherali, Hobeika, and Kangwalklai 2003). The heuristics and the simulation model are based on the Transportation Analysis and SIMulation System (TRANSIMS). The TRANSIMS-enabled model combines static traffic assignment (STA) and dynamic traffic assignment (DTA) techniques to simulate individual travelers' movements on studied networks (Stone et al. 2000). This composite method improves simulation control, enhances convergence, and shortens computation time as compared with approaches such as the gap-based methods (Kim and Rilett 2003).

The present research illustrates to researchers and planners how the dynamic simulation model leads to network-wide convergence and approach the Wardropian equilibrium under scenarios. This paper intends to contribute to the microscopic transportation simulation literature with the following aspects: 1) An in-depth review of the TRANSIMS literature to identify its similarities and distinctions versus prevalent microscopic approaches; 2) A composite, STA-DTA system of heuristics to approach a dynamic Wardropian equilibrium state at the microscopic level; 3) Applications of the heuristics to a TRANSIMS-enabled simulation framework; 4) Implementing the microscopic simulation to a subarea in Houston, TX; 5) Incorporating transportation modelers' best practices to validate the simulation model.

The remainder of this paper is arranged as follows: This paper first reviews literature on equilibrating process for transportation models. Next, a set of heuristics is presented under the framework of the TRANSIMS system. The heuristics will be executed on a TRANSIMS simulation using a real transportation network. Actual traffic data are used to validate the model, and sensitivity analyses are performed to examine the impacts of traffic control measures on the simulation model. The paper concludes with a summary and directions for future research.

LITERATURE REVIEW

Methods for Modeling Wardropian Transportation Equilibrium

A perfect Wardropian equilibrium exists where no road users can make any improvement by unilateral actions. Early equilibrium research focused on static equilibria that did not account for temporal variations of a traffic system (Haurie and Marcotte 1985). The analytical model primarily identifies the shortest travel plans for road users. A body of recent research has examined Wardropian equilibria over different durations of a day and captured on-road travelers' interaction (Maillé and Stier-Moses 2009; Ordóñez and Stier-Moses 2010).

A stream of mathematical research uses equation systems to represent actual traffic conditions to model the Wardropian equilibrium (Bernstein and Smith 1994; Patriksson 2004). Modelers amend parameters to reflect different scenarios. Complex road features, namely, speed limits, number of lanes, and signal phasing are examined simultaneously. For a dynamic equilibrium, time-related variables are inserted to account for changes over a predetermined time period.

Heuristics research is designed to approximate the perfect Wardropian state (Lo and Wong 2002). Equilibrium in an actual system is the result of interplays of the supply and demand forces. At the microscopic level, the set of heuristics needs to address road users' cost-minimizing intents that identify most efficient routes in a network and capture the resulting vehicular actions (Ordóñez

and Stier-Moses 2010). This logic resembles the progression in which road users comprehend the operational features of the road system through repeated learning cycles.

Practically, modelers cannot reach a perfect equilibrium in which all users gain no improvement after each change. As such, managing the computation time becomes a key challenge. Jeihani, Sherali, and Hobeika (2006) develop a system of heuristics that repeatedly simulate portions of travelers until models converge. They also specify the rationale to terminate the iterative process at the near-equilibrium state within a manageable time frame (Jeihani et al. 2006).

Simulation applies mathematical and heuristic approaches to study road systems. Simulations capture the complexities of a system and intend to minimize the discrepancies from reality. As an example, road users' interactions and responses to various control strategies, a primary cause of on-road delays, are difficult to be examined through mathematical equations. A simulation model may develop realistic stopping criteria for a state when the system lacks incentives for further travel benefits and travelers will not make changes – a stage of the Wardropian equilibrium.

Macroscopic Traffic Assignment for Equilibrium Modeling

Macroscopic models set equilibrium as the goal for traffic assignment (Lawson 2006). Equilibrium represents the expected system performance. Modelers assume road users have full knowledge of the system. Therefore, macroscopic approaches gain insights into the system's supply aspects and are more effective in examining policies of control and capacity strategies, such as numbers of lanes and speed limits (Rilett, Kim, and Raney 2000).

Macroscopic models move vehicles by applying aggregate equations and provide gross approximations of the study system (Ben-Akiva et al. 2007). Researchers have utilized the four-step urban transportation planning (UTP) method to model and forecast transportation systems (Ben-Akiva et al. 2007; Buliung and Kanaroglou 2007). Details in the study system are missing due to high level of aggregation (Jeihani, Sherali, and Hobeika 2006). The modeling process does not consider on-road vehicular moves and cannot demonstrate travelers' behaviors (Rickert and Nagel 2001). The UTP method, for example, statistically assigns the volumes on all the links without considering time aspects of travel by the study population (Koohbanani 2004).

Dynamic Traffic Assignment for Equilibrium Modeling at More Detailed Levels

The Dynamic Traffic Assignment (DTA) models address the macroscopic models' limitations on modeling details and complement static traffic assignment (STA) approaches by including time-related variables (Ben-Akiva et al. 2007). DTA research incorporates conditions associated with time variations in traffic flows. Time variations result from changing levels of travel demand, finite speed of vehicular movement, and changes in network capacity (Jeihani, Sherali, and Hobeika 2006). Traffic flows of DTA models are hence time-dependent (Nagel et al. 2008).

Simulations are feasible tools to incorporate DTA methods (Hobeika and Paradkar 2004; Lawson 2006). These tools simulate traffic demand's stochastic responses against supply across a controlled time frame (Rilett, Kim, and Raney 2000). A microscopic simulation provides the most detailed information: individual travelers' travel plans and activities, interactive on-road behaviors, and traveler responses to various road conditions. Each synthetic traveler conducts a series of activities in different locations on a second-by-second basis (Nagel et al. 2008).

While microscopic simulation is able to capture on-road vehicular behaviors and interactions, it does not attempt to accomplish equilibrium (Hobeika and Paradkar 2004). Rather, it usually arrives at a state where supply-demand interactions manifest fluctuation. Microscopic models need to assess how a simulated population identifies solutions under given system constraints, and how these constraints are reinforced by travel needs and the traffic environment.

Finally, mesoscopic simulation models were also developed to implement DTA. They incorporate the features of macroscopic and microscopic models. Mesoscopic models simulate individual travelers' on-road behaviors, similar to microscopic models. However, macroscopic mathematical equations and average speeds on street links are utilized in mesoscopic models (Jeihani, Sherali, and Hobeika 2006). The mesoscopic model with DTA performs the time-varying traffic assignment and simulates travelers' planning processes and their interactions.

Gap-Based Modeling Methods

Gap-based methods are widely used in STA models and can be applied to macroscopic, mesoscopic, and microscopic studies. A gap-based simulation compares experienced travel times to shortest-path travel times (Paschai, Yu, and Mirzaei 2010). A modeler keeps modifying travelers' paths before models converge. An advantage of the gap-based measures is the direct application of the equilibrium principle (Boyce, Ralevic-Dekic, and Bar-Gera 2004).

Gap-based methods may cause long computation times in DTA models (Paschai, Yu, and Mirzaei 2009). This disadvantage is more significant for large metropolitan areas. Accordingly, for large metropolitan planning organizations (MPOs), the gap-based methods may not be the best trade-off solution as MPOs consider the necessary model convergence and computation time.

TRANSIMS Model Used to Develop Research Framework

TRANSIMS is developed by the Federal Highway Administration of the US Department of Transportation. TRANSIMS consists of microscopic mathematical models and incorporates specific rules to help control vehicular movements and network characteristics. The modeling system of TRANSIMS applies the cellular automata method, a matrix-based mathematical calculation to model traveler moves (Rilett 2001; Simon and Nagel 2008).

The cellular automata mechanisms generate sequential matrices that reflect second-by-second vehicular movements in the entire network. Geographical Information Systems (GISs) are used to facilitate the creation of traffic matrices and coordinates of vehicles and travelers. While this approach cannot perfectly reflect the continuity of on-road behaviors in the real world, the small time frames allow researchers to model the system to the most possible details. TRANSIMS can perform DTA study to simulate dynamic equilibria (Rickert and Nagel 2001).

Heuristics are presented in the TRANSIMS literature to achieve simulation convergence (Jeihani, Sherali, and Hobeika 2006; Koohbanani 2004). However, research probing the heuristics for a network-wide Wardropian equilibrium is limited. Accordingly, three heuristics are developed below. The set of heuristics in the modeling procedures includes three consecutive loops: 1) the Routing Heuristic; 2) the Microsimulation Heuristic; and 3) the Equilibrating Heuristic.

The use of stopping criteria is a key technique used in TRANSIMS simulations to reach convergence (Paschai, Yu, and Mirzaei 2009). The convergence may take place under two conditions: the actual Wardropian equilibrium has been reached, or the algorithm cannot make any more effective progress even though the Wardrop conditions are not satisfied. The stopping criteria is to trade off the model's practicality against the optimal state (Boyce, Ralevic-Dekic, and Bar-Gera 2004; Jeihani, Sherali, and Hobeika 2006).

HEURISTICS FOR DTA AND NETWORK-WIDE USER EQUILIBRIUM

A set of heuristics is developed below to approach a dynamic Wordropian equilibrium. First, the Routing Heuristic produces routes for all travelers. The outcome is a static state where all travelers develop shortest paths. Next, the Microsimulation Heuristic models traveler actions and reroutes travel paths. This heuristic takes into account all road-users' on-road behaviors and seeks a stabilized

condition between traffic supply and demand. Finally, the Equilibrating Heuristic determines a network-wide, dynamic equilibrium for all travelers in the network over time. The heuristics developed below combine STA and DTA methods accordingly.
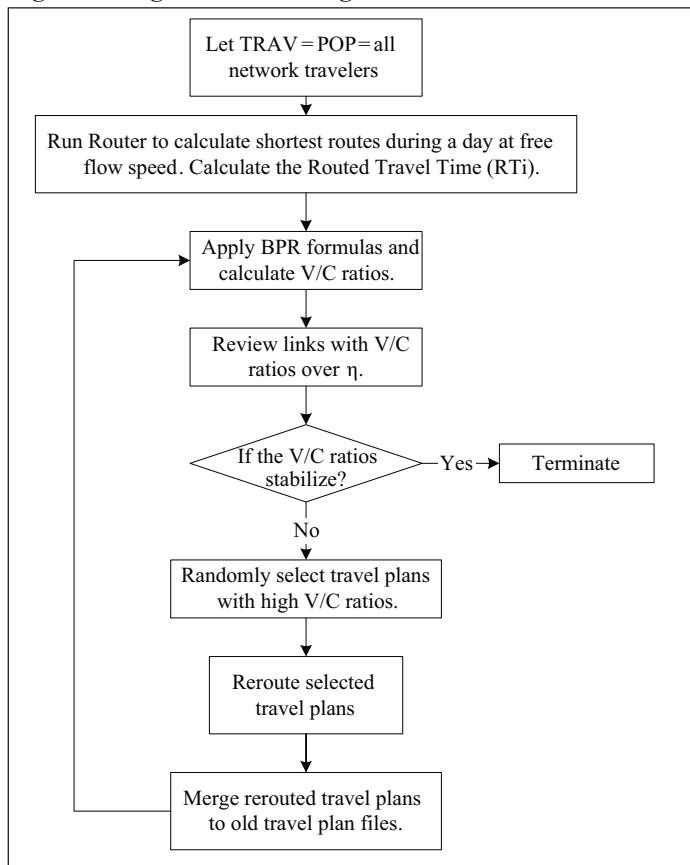
An underlying assumption of the heuristics is that road users intend to minimize the costs associated with their travels. The action of shifting travelers on high-cost paths to lower ones in the heuristics is at the core of equilibrium literature (Ordóñez and Stier-Moses 2010). However, the cost-minimizing behaviors are conditioned by the road-users' on-road interaction.

Routing and Microsimulation Heuristics intend to minimize the simulation running time. Contrastingly, the Equilibrating Heuristic models the equilibrium of traffic supply and demand for the entire study area. The combination of the foregoing heuristics aims to efficiently simulate the network so the model can converge to a state that reflects the Wardropian Equilibrium.

Routing Heuristic

The Routing Heuristic determines each road user's shortest travel length. It loads their origin-destination trips to the transportation network. The travel speeds are at free flow, and the resulting routes do not consider on-road interactions. This heuristic modifies the Incremental Individual Loader (IIL) in Jeihani, Sherali, and Hobeika (2006) and Koohbanani (2004), which computes road users' paths one at a time and in turn updates volumes and travel times of related road links. The iterative loop below identifies shortest travel plans for travelers. Figure 1 illustrates the logic of the heuristic. Details are discussed below.

Figure 1: Logic of the Routing Heuristic

1. Let $TRAV_{Router}$ = POP be the set of all network travelers.
2. Run Router to calculate shortest-paths travel plans during a day at free flow speed. Calculate the Routed Travel Time (RT_i), the shortest-path travel time for traveler i.
3. Apply Bureau of Public Roads (BPR) equations and calculate V/C ratios. (See endnotes).
4. Review links with V/C ratios over a predetermined value, η.
5. Randomly select travel plans by p_{Router}% containing links with high V/C ratios. The subset of selected travelers is $TRAV'_{Router.}$ $TRAV'_{Router}$ is expected to be smaller than $TRAV_{Router}$, since not all travel plans in $TRAV_{Router}$ contains links with high V/C ratios.
6. Reroute selected travel plans in $TRAV'_{Router}$.
7. Merge rerouted travel plans to old travel plan files. Let $TRAV_{Router}$ = the new set of all network travelers. The new $TRAV_{Router}$ is expected to include updated travel plans with better travel performance, i.e., lower V/C ratios.
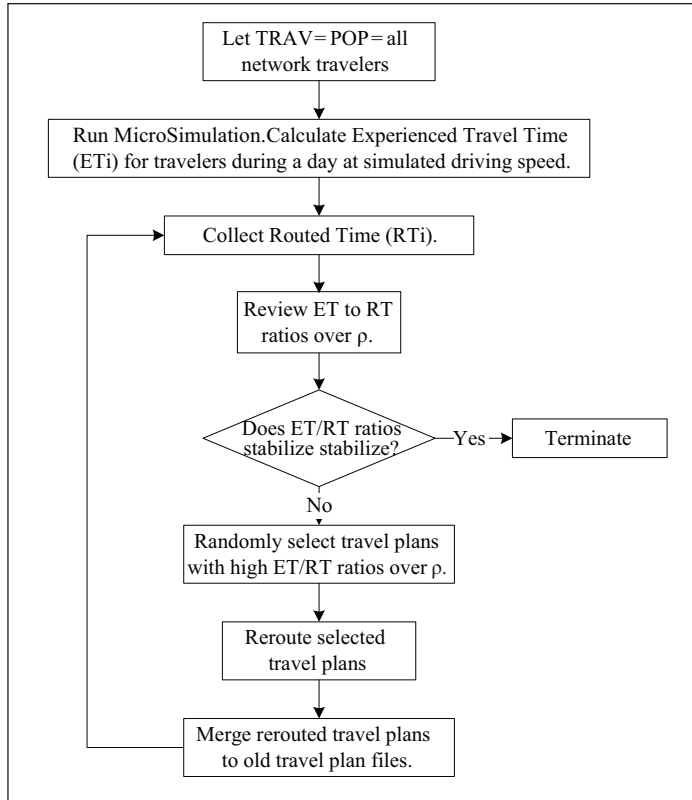8. Repeat 3 through 7.

The iterative design of this heuristic accounts for the time-consuming rerouting process. The heuristic selects p_{Router}% of travel plans with high V/C ratios for the next routing assignment. While there is no strict rules to determine the value of p_{Router}%, the modeler can determine the baseline value through two approaches: 1) Using values documented in the TRANSIMS literature; or 2) Consulting MPOs that provide data and conduct similar simulations.

To have a finite number of Routing Heuristic iterations, one stopping criterion is added: if the number of links with high V/C ratios does not strictly decrease, the heuristic loop is stopped. At this point, the synthesized network creates static, optimal travel plans for each traveler. It shall be noted that at this stage, the on-road interactions of travelers are unknown, and the network performance is yet to be fully analyzed. The DTA method will be incorporated into the following Microsimulation Heuristic.

Microsimulation Heuristic

The Microsimulation Heuristic reflects the DTA process and captures the actions between travelers and the features of traveling behaviors in the study area. In doing so, this heuristic addresses the relatively unrealistic states of no on-road interactions developed by the Routing Heuristic (Hobeika and Paradkar 2004; Jeihani, Sherali, and Hobeika 2006; Nagel et al. 2008). The Microsimulation Heuristic's logic is illustrated in Figure 2. The details are as follows:

1. Let $TRAV_{Microsimulation}$ = POP be the set of all network travelers.

2. Run MicroSimulator for $TRAV_{Microsimulation}$. Calculate Experienced Travel Time (ET_i), the resulting travel time including on-road delays for traveler i at driving speed,

3. Collect data on Routed Travel Time (RT_i) for traveler i in $TRAV_{Microsimulation}$ calculated from the Routing Heuristic.

4. Review travel plans with ET_i to RT_i ratios. Examine when the ET/RT ratio is higher than a predetermined ρ for traveler i in $TRAV_{Microsimulation}$.

5. Randomly select $p_{Microsimulation}$% of travel plans with high ET/RT ratios more than ρ. The set of selected travelers is $TRAV'_{Microsimulation}$. $TRAV'_{Microsimulation}$ is expected to be smaller than $TRAV_{Microsimulation}$, since not all travel plans in $TRAV_{Microsimulation}$ contains links with high ET/RT ratios.

6. Reroute selected travel plans in $TRAV'_{Microsimulation}$.

Figure 2: Logic of the Microsimulation Heuristic

7. Merge and sort rerouted travel plans with old travel plan files. Let $TRAV_{Microsimulation}$ = the new set of all network travelers. The new $TRAV_{Microsimulation}$ is expected to include updated travel plans with better travel performance, i.e., lower ET/RT ratios.

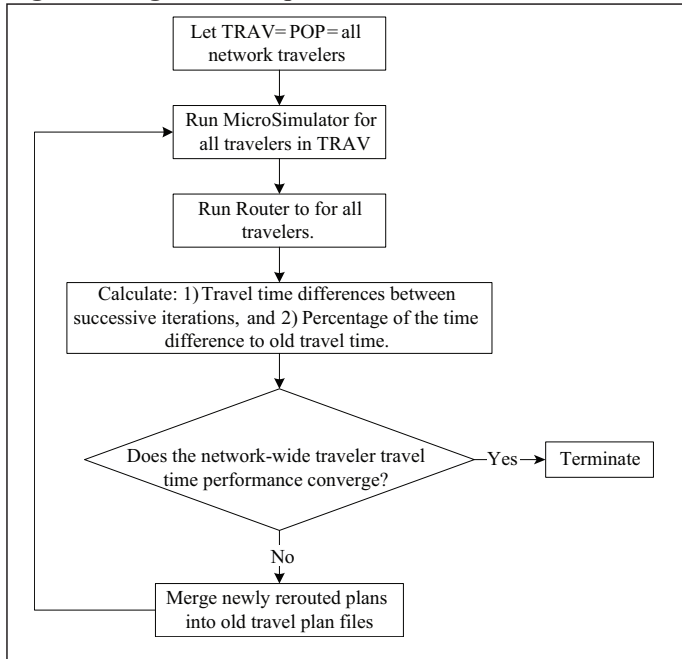8. Run MicroSimulator for $TRAV_{Microsimulation}$.

9. Repeat 3 through 8.

This heuristic attempts to improve the rerouting efficiencies. It intends to help the routing process converge faster by selecting $p_{Microsimulation}$% of travel plans with high ET/RT ratios. The modeler can determine $p_{Microsimulation}$% by using values documented in TRANSIMS literature or consulting MPOs conducting similar simulations. To have a finite number of Microsimulation iterations, one stopping criterion is created: If the number of plans with high ET/RT ratios does not strictly decrease or arrive at a predetermined level, the heuristic loop is stopped.

By far, the two foregoing heuristics modify and complete the DTA process comparable to Jeihani, Sherali, and Hobeika (2006). The objective of the two heuristics is a stable state of the entire model under controlled efficiencies. In the following section, an additional and final heuristic is developed to simulate the user equilibrium state for the entire studied network.

Equilibrating Heuristic

The Equilibrating Heuristic seeks a dynamic equilibrium for the entire study transportation system. The heuristic and the entire simulation logic are terminated when network travelers cannot make significant travel time improvements by a pre-determined percentage. Figure 3 illustrates the logic of the Equilibrating Heuristic. The details are discussed below:

Figure 3: Logic of the Equilibrium Heuristic

1. Let $TRAV_E$ = POP be the set of all network travelers.

2. Run Microsimulation for all travel plans in $TRAV_E$.

3. Utilize ET (the Experienced Travel Time) as inputs for Router and then route all travel plans in $TRAV_E$.

4. Compare the new travel plans in Step 3 against old travel plans in $TRAV_E$ from the last iteration. Calculate $p_{iE}\%$, the ratio of Travler$_i$'s travel time difference in new and old files to old plan's travel time.

5. Let ε be a predetermined percentage of POP. In addition, let π be a predetermined percentage that represents travel time improvement. If modeling outcomes have more than ε of travelers of POP whose travel time improvement ($p_{iE}\%$) is larger than π, it represents a non-equilibrium state. Namely, travelers still have room to make travel time improvement. Continue with Step 6 below. However, if modeling outcomes have fewer than ε of travelers of POP whose travel time improvement ($p_{iE}\%$) is larger than π, terminate the equilibrating loop.

6. Merge newly rerouted plans obtained from Step 3 into old travel plan files and obtain $TRAV'_E$. Number of travelers in $TRAV'_E$ and $TRAV_E$ will be identical.

7.   Let $\text{TRAV}_E = \text{TRAV'}_E$.

8.   Rerun 2 through 7.

In this heuristic, the supply and demand of the entire transportation network are modeled through multiple iterations. All travel plans are rerouted, and all vehicle motions and interactions are simulated at the most detailed, road user level. This iterative mechanism mimics network-wide travelers' learning behaviors, and the modelers will seek that the vast majority of the travelers can approach near-optimal travel times through iterative runs (Nagel et al. 2008). Each iteration seeks improvements of all road users from the last iterative runs, and the modelers will compare traveling performances of successive iterations. A stopping criterion is developed to have a finite number of the Equilibrating iterations: If the values of $p_E\%$ in successive iterations do not strictly decrease, the loop is stopped.

TRANSIMS' Relations to Gap-Based Microscopic Simulation Methods

Table 1 summarizes the relations between TRANSIMS and microscopic gap-based approaches. Both methods can apply STA and DTA approaches. Further, similar to the gap-based methods, TRANSIMS allows modelers to compare experienced travel time against shortest-path time.

Table 1: TRANSIMS vs. Microscopic Gap-Based Methods Comparison

	STA	Decision Rules for Sequential Iteration Improvement	DTA Convergence	Simulation Duration
Gap-Based Methods	Yes	Comparing experienced travel times to shortest-path travel times for all routes.	Requiring more iterations to stabilize modeling outcomes	Long computation time for large metropolitan areas
TRANSIMS	Yes		Allowing adjustments for control parameters to reach convergence criteria faster	Short computation time with predetermined convergence accuracies

A distinction differentiates TRANSIMS from the gap-based methods. The TRANSIMS system allows the modeler to control parameters to quickly reach convergence criteria. An example is to identify a predetermined percentage of problematic paths that displays abnormally high experienced travel times. With the inclusion of stopping criteria, TRANSIMS may be quicker to reach model convergence. For DTA tasks in the large metropolitan areas, TRANSIMS hence has appeal for planners seeking feasible solutions under modeling time constraints.

SIMULATION METHOD

Preparation for Simulation

A subarea in Houston, the Texas Medical Center (TMC), is the study area to perform the heuristics developed previously. TMC has the world's largest complex for patient care, medical research, and educational institutes for illness and injury treatment and prevention. It consists of approximately 142 buildings, including hospitals, colleges, and research centers. There are 72,000 employees, 32,000 students, and thousands of patients traveling to TMC every day. A significant of number of households and other people travel to work through the TMC area.

GIS data on network shapefiles and trip tables are collected from the Houston TRANSTAR and Houston-Galveston Area Council (H-GAC). The modelers synthesize the transportation network into TRANSIMS format. ArcGIS and TRANSIMS are utilized to process data to establish the skeletal network files. Skeletal network files only display the center lines of all streets; hence, more specific data below are required to specify the supply side of the simulation.

TRANSIMS requires numbers of lanes and speed limits for road links to specify the characteristics regarding the network capacities. Further, data on traffic signal phasing at intersections, one-way/two-way regulation, and U-turns, are necessary for the study area. In the absence of data items (e.g., control signal and stop sign data), TRANSIMS built-in functions are used to generate synthetic control systems.

The next task is trip table conversion. Traffic Analysis Zone (TAZ)-based, O-D trip tables represent the TMC transportation demand. O-D zone trips are hence demand inputs to the simulation. TRANSIMS trip table conversion functions are used to calculate trip counts.

Key characteristics of the TMC transportation network and traffic demand are as follows:
- Number of Input Node Records = 1,223
- Number of Input Link Records = 1,553
- Number of Input Zone Records = 37
- The total number of daily trips = 358,210

Simulation Procedures and TRANSIMS Programs Utilized in Executing Heuristics
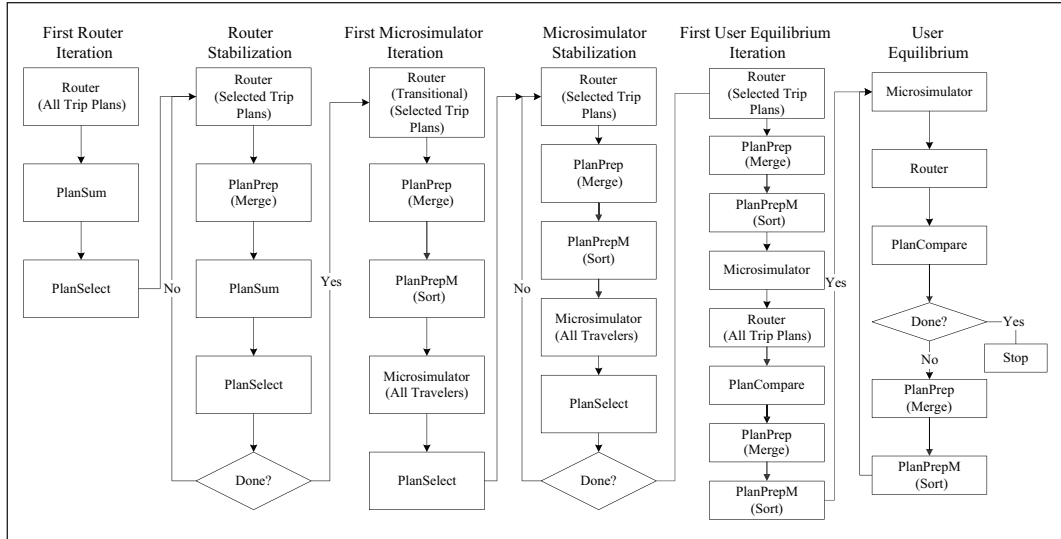
The simulation model specifies a 24-hour clock for a complete run. Each iteration starts at 0:00 and completes at 24:00. The computing environment is a high performing computer with Core 2 Duo, 2.66 GHZ CPUs. Table 2 lists the TRANSIMS programs and their associations with respective heuristics. The table briefly explains their main functions in the simulation iterations.

Table 2: TRANSIMS Programs Utilized in the TMC Simulation Study

TRANSIMS Program	Functions	Heuristic
Router	To develop the travel plans for all travelers	Router, Microsimulation, and Equilibrium
PlanSum	To generate Router performance summary	Router
PlanSelect	To select travel plans for rerouting	Router & Microsimulation
PlanPrep	To merge new travel plans from new Router into travel plan files for all travelers	Router, Microsimulation, and Equilibrium
PlanPrepM	To sort all trips according to the time of day	Microsimulation and Equilibrium
Microsimulator	To model all traveler actions in the network	Microsimulation and Equilibrium
PlanCompare	To examine whether the network traffic pattern arrived at an equilibrium state according to outputs from prior process.	Equilibrium

Figure 4 shows the simulation processes for the study. The first heuristic, Routing Heuristic, is executed after the completion of the trip table conversion process. This step loads and distributes the travelers to the network according to a trip table and diurnal distribution, which describes the recurring 24-hour traffic patterns in Houston, TX. The Routing Heuristic loop is repeatedly executed until the traffic volume and network capacities converge (Roden 2007).

Figure 4: Routing Heuristic, Microsimulation Heuristic, and Equilibrating Heuristic Logics

The next step is the Microsimulation Heuristic process. The MicroSimulator program of TRANSIMS is utilized to model individual travelers' activities and on-road vehicle interactions (Stone et al. 2000; Roden 2007). Each Microsimulation process identifies travel plans with performance worse than predetermined values and reroutes them.

The model proceeds with the Equilibrating process. In the various iterations, all travelers' travel plans are routed and all vehicles' interactions are simulated with multiple repetitions (Roden 2007). Similar to prior two loops, the modelers repeat the Equilibrating loop until the model displays convergence on link performance parameters and all travelers arrive at the optimal travel state. The entire TRANSIMS simulation process is complete when no travel time could significantly improve in consecutive runs.

Execution of the Routing Heuristic Loop

The Router program produces shortest paths at free flow speed. A system of built-in BPR equations (see endnotes) computes and updates the link travel times (or delays) and calculates link V/C ratios in the transportation network (AECOM Consult 2007). Practically, selecting the most problematic travel plans for rerouting is a more efficient way to reach convergence (Stone et al. 2000). A set of TRANSIMS programs allows modelers to identify non-optimal network links. The travel plans are selected for rerouting according to the following criteria:

1. Links of travel plans which have high V/C ratios
2. Discrete modeling time periods during morning peak hours of the day (6:00-9:00 AM)

The selected travel plans are then loaded to the next Router iteration for rerouting. For the 25 iterations performed, V/C ratios of the selected links oscillate in early iterations but appear to stabilize after iteration 15 until the end. The number of links with V/C ratios $\geq$ two (η) decreases from 795 to 600 from iteration 1 to iteration 24. Thus, the heuristics lead to a more stable status.

However, a closer observation identifies a number of links with unexpected high V/C ratios. For instance, V/C ratio is 3.03 for Link 1493 between 7:00 AM and 7:15 AM of the 24th iteration. These links are likely to generate long delays. One of the reasons for the high V/C is the feature of traveling at free-flow speed assumed by Router (AECOM Consult 2007). Router runs do not consider on-road behaviors and the resulting actual travel speeds. This causes more trips to be loaded on the same links and result in high V/C values.

Execution of the Microsimulation Heuristic Loop

The Microsimulation Heuristic generates road users' travel routes, which account for on-road interactions, and finds realistic travel plans, as opposed to routes produced previously with free flows (Jeihani, Sherali, and Hobeika 2006). Microsimulation runs include on-road interaction to be a key additional dimension for rerouting travel plans. Modelers utilize the outcomes by the MicroSimulator program to identify links with low performance and develop new travel plans in subsequent iterations. Travel plans are selected for rerouting according to the following criteria:
1. Experienced Travel Time to Routed Travel Time (ET/RT) ratios
2. Percentage of travel time difference between two consecutive runs

The iterative loop chooses a small number of problematic travel plans for rerouting (Roden 2007). Afterwards, MicroSimulator will simulate all vehicles after the modified travel plan files are merged into old travel plans.

The TMC Project executes 11 runs for the Microsimulation Heuristic process. Table 3 presents the progress over Microsimulation Heuristic iterations. The table reports the numbers and percentages of travelers whose ET/RT ratios are larger than a predetermined ρ (1.2) in each iteration. Numbers of links with high V/C ratios ($\geq$ two) remain at one throughout the iterative processes. In addition, percentages of traveler with high travel time ratios show a convergence across iterative runs. While the numbers of travelers with high ET/RT ratios does not decrease strictly, the numbers display a decreasing trend, as attempted by the Microsimulation Heuristic.

Table 3: Progress in Travel Time Performance in Microsimulation Runs

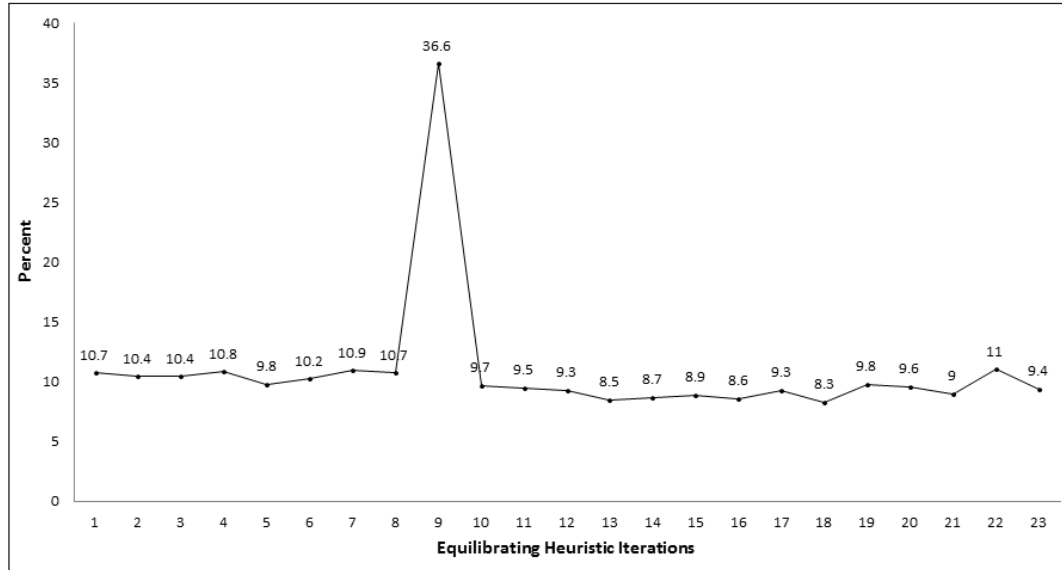| Iteration	No. of Travelers with Travel Time Rate > 1.2	Percentage of Travelers with Travel Time Rate > 1.2
1	55449	15.50%
2	36528	10.20%
3	26701	7.50%
4	22487	6.30%
5	13774	3.80%
6	9804	2.70%
7	16795	4.70%
8	14024	3.90%
9	5813	1.60%
10	4402	1.20%
11	3391	0.90%

At iteration 11, travelers with ET/RT ratios higher than ρ become lower than 1%. The percentages of travelers with high ET/RT ratios decrease from 15.5% to 0.9%. Because of the low percentage, the Microsimulation runs are terminated and the simulation proceeds to the next loop.

Execution of the Equilibrating Heuristic Loop

This loop is aimed at identifying a dynamic equilibrium state to complete the simulation. The simulation process will stop when no travel times can improve by a predetermined percentage. Travel plans are selected when the displayed Travel Time changes are larger than 2% (p_{iE}%) in consecutive Equilibrium iterations. The simulation is stopped when fewer than 10% (ε) travelers have time changes, or no travelers have larger than 2% travel time changes.

In executing the loop, V/C ratios remain constantly low. The number of links with V/C ratios larger than two reduces from one to zero gradually. In terms of travel times, Equilibrating iterations have most of the links improved. In Figure 5, percentages of trips with changes larger or less than 2% in absolute values remain below 10% after the 9th iteration, except iteration 22.

Figure 5: Percentages of Trips Experiencing High Travel Time Change

According to the stopping criterion, the progress suggests a state similar to the Wardropian Equilibrium (Nagel et al. 2008). The iterative runs are stopped since the loop displayed convergence in terms of travel time improvement through consecutive iterations. Completion of the Equilibrating runs concludes the simulation run for the study network.

In summary, 25 Routing iterations are completed in 26 minutes, 11 Microsimulation iterations in one hour and two minutes, and 22 Equilibrating iterations in approximately four hours and two minutes. Compared with the CPU time (30 hours) consumed by Jeihani, Sherali, and Hobeika (2006), the combination of the computing platform and simulation framework of the present research demonstrates considerable improvement regarding modeling efficiency.

Validating Baseline Simulation Results for TMC Transportation Networks

This task examines the validity of the baseline simulation outcomes. Convergence in simulation iterations indicates a proper setup of the modeling procedures, whereas the validity test determines to what degree the simulation approaches or deviates from realistic traffic conditions.
Two primary parameters are utilized to validate the TMC simulation model:
1. Total daily volumes of major roads of all directions
2. Total peak hour volumes of major roads of all directions

Data on actual traffic volume are collected to be the basis of validation. The researchers calculate H-GAC's (Houston-Galveston Area Council's) daily volumes for major roads in the TMC. Traffic counts for "links" (or road segments in the model) of major roads are then retrieved from the simulation outputs. The data values of links are combined to be the simulated major road's total traffic volume. Lastly, H-GAC traffic volumes are compared against simulation outcomes.

According to the H-GAC's decision rule for traffic simulation runs, an interval of plus and minus 15% difference between a major road's actual traffic volumes and simulated outcomes are

deemed as an acceptable range. An 8% interval is considered excellent for modeling performance. The difference intervals may be widened to be as much as plus and minus 30% for less traveled streets. Differences between actual and simulated outcomes beyond these ranges suggest potential errors in original data or simulation procedures.

The simulated TMC traffic volumes of major roads are compared with H-GAC's daily traffic volume. The differences are within the plus/minus 15% interval, suggesting that the simulation performance is comparable to the local MPO's traffic model standard.

Sensitivity Analysis

A sensitivity test is performed to evaluate the variations of simulation under different scenarios (Patriksson 2004). The extant model consists of time-actuated signals at major and local road intersections. Time-actuated signals are similar to fix-time (also known as pre-timed) signals in that they are constrained by time limits. However, unlike fix-time signals, actuated signals can change phases before they reach their time limits if the demand is low. They can even skip a phase if there is no demand for that phase (e.g., left turns). For this reason, actuated signals are especially useful in low-demand settings, such as in rural areas or at night.

As a comparison, the scenario of fixed-time signalization is created. The new model replaces the time-actuated signals with fixed-time signals. After the changes, the modelers execute identical TRANSIMS procedures and examine changes in the simulation outputs.

Interestingly, the fixed-time signal scenario generates fewer volumes comparing to the time-actuated signal system. The fixed-time system also results in less travel time. Stopping criterion is met faster by fixed-time signals than actuated signals: The number of travelers with significant change in travel time decreases to 7.5% in 14 iterations. In sum, the three heuristics are successfully executed in the new scenario and the simulations reach convergence.

DISCUSSION AND FUTURE RESEARCH

Discussion

The equilibrium state needs to serve as the baseline for policy-oriented analyses. For variants of simulation scenarios, a modeler can adopt the method reported in the paper and maneuver simulation parameters to capture tentative occurrences as well as long-term development in the study network. For instance, the changes in signalization designs may affect the system's travel performance. The modelers can also alter performance parameters to fine-tune model designs.

Interviews are conducted to verify the importance of equilibrium modeling. For H-GAC, reaching equilibrium has nontrivial benefits. The system-wide equilibrium can reduce model assignment uncertainty for major roadway projects, such as freeway widening and new major arterial streets. Further, vehicle miles traveled (VMT) and total vehicle times (VHT) are crucial parameters to evaluate regional performances of major roadway projects. Reaching system-wide equilibrium is necessary for keeping the regional VMT and VHT stable in the model.

For instance, H-GAC recently ran a macroscopic travel demand model with forecast data in the year 2035. The system-wide equilibrium nearly reaches convergence criteria in the 40th assignment iteration. The VMT in the 11th iteration is 156,163 miles lower than that in the 10th iteration. However, the VMT in the 40th iteration is only 8,556 miles lower than that in the 39th iteration. Hence, model stability improves when system-wide equilibrium criteria is satisfied after more simulation iterations. This underscores that system-wide equilibrium criteria help provide reliable project evaluation sources to policy makers.

Hence, deficiencies in policies based on unstable models cannot be overstated. They may cause suboptimal development efforts, and public investments will not be adequately allocated. It will eventually lead to a vicious cycle of inaccurately allocated resources and low performance.

Limitations and Future Research

The assumption of the simulation framework is that road users will identify cost-minimizing travel plans by learning from on-road experiences. A solution to validate the assumption is to use real data showing the actual route choice process over time. Future research may simulate day-to-day dynamic equilibrium over a week. This approach requires richer data sets and more sophisticated analyses. Using TRANSIMS, modelers need to collect new data on trip tables diurnal distributions on both weekdays and weekends. Continual simulation over multiple weekdays and weekends is necessary with new data.

In this paper, the convergence measures are based on the improvement of the solution. The equilibrium of the simulation is actually a heuristic. At the termination, the model does not specify how closely the end state satisfies the Wardropian conditions. It is difficult to tell whether the algorithm terminates because the actual Wardropian equilibrium has been reached, or because the algorithm simply cannot make any more effective progress even though the Wardropian conditions are not satisfied.

Actual data on travel patterns will be necessary to assess the gap between the equilibrium outputs and road users' behaviors. According to H-GAC, there are no existing data or survey plans for the route choice in the TMC area. Traffic counts are the only available, real data to validate the algorithm applied in the paper. Future research can consider developing a method to collect data on actual travel paths in a study area on a constant basis. A longitudinal database of the dynamic travel pattern is necessary. For longitudinal traffic data, sample observations are collected from a larger population over a given time period. This database can help validate the DTA outcomes as well as refine the parameters (e.g. $p_{Router}\%$ and $p_{Microsimulation}\%$) for the sensitivity analyses.

The comparison between the TRANSIMS models and other methods is not performed in this study. Planning agencies in the Houston area do not have plans to evaluate the benefits of running different simulation models. Future research can perform cross-evaluation among traffic planning methods and examine the characteristics of respective equilibrium states. Specifically, a methodology comparing various microscopic simulation systems will allow policy makers and planners to analyze the resources entailed to execute different models (e.g., TRANSIMS vs. gap-based methods). Respective benefits, such as convergence speeds, and costs, such as man-hours, can be quantified to assess the impacts of implementing various approaches.

CONCLUSION

This paper makes the following accomplishments: First, the research reviews microscopic simulation literature and positions TRANSIMS methods relative to prevalent methods. Second, this paper develops a set of heuristics and stopping criteria to route travelers and model traveler movements and on-road interactions. The TRANSIMS system is used to implement the heuristics and perform microscopic simulation. Finally, the simulation approximates a system-wide Wardropian equilibrium at the most disaggregate traveler level.

Three heuristics are developed to simulate a transportation system and reach an equilibrium state. The Routing Heuristic produces routes for individual travelers and reroutes travelers to seek optimal routes. In turn, the Microsimulation Heuristic generates traveler behaviors to obtain realistic on-road interactions. Ultimately, the Equilibrating Heuristic finds the network-wide state where individual travelers cannot gain improvement by unilaterally changing travel plans.

The heuristics are executed in TRANSIMS simulation loops. Stopping criteria are developed according to a number of link performance measures. The heuristics, TRANSIMS model, and stopping criteria work jointly to determine the equilibrium for the study network. The sensitivity test also leads to convergence in the presence of distinct transportation characteristics. Lastly, potential directions are discussed to extend microscopic simulation research for assessing transportation improvement plans of action or policy. These plans are designed to achieve transportation goals such as travel time reduction, emission reduction, and safety improvement. The value of the present research to examine the effectiveness of these plans are also discussed.

Endnotes

A set of built-in BPR equations computes and updates the link travel times (or delays) and calculate link performance in the transportation network (AECOM Consult 2007). The BPR function default values for α, β, and γ in the present research are 0.15, 4.0, and 0.75, respectively. The BPR equation for computing the link travel time is as follows:

$$t = t_0 * (1 + (\alpha * (\text{Volume/Capacity})^{\beta})),$$
where
t = Average travel time in seconds
t_0 = Baseline (free flow) travel time in seconds
$\alpha = 0.15$
$\beta = 4.00$

Volume = Traffic volume on the link in a given time period
Capacity = Adjusted Capacity of a link in a given time period

Capacity of the link in a given time period is calculated by the following equation:
Capacity = γ*Hourly Capacity * (Time Increment/3600)
Where
$\gamma = 0.75$
Time Increment = Time Period (in seconds)

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