Integrated Model of Travel Demand and Network Simulation

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1 Objectives, motivation, and statement of innovations

This paper describes a new approach to integrate an Activity-Based travel demand Model (ABM) and Dynamic Traffic Assignment (DTA), taking a maximum advantage of the disaggregate nature of both models. This approach is referred to as “deep integration” as distinguished from a “loose coupling” applied in earlier ABM-DTA integration projects. With this approach, all interaction between ABM and DTA including generating a list of vehicle trips by ABM for DTA and providing Level-of-Service (LOS) variables by DTA for ABM is implemented at the individual level without an aggregation bias. The paper is based on the ongoing projects for the Atlanta Regional Commission (ARC) and Ohio State DOT (ODOT) sponsored by the FHWA C10 grants.

The major innovative features of suggested “deep integration” compared to “loose coupling” can be summarized as follows:

1. **List of trips generated by ABM for DTA.** In the “loose coupling” schema it is generated by ABM with a limited level of detail and crude temporal resolution; this requires post-processing such as randomization of trip departure time with violation of individual tour consistency. In the “deep integration” schema, it is generated by ABM with the necessary level of details, temporal resolution, and tour organization for the DTA simulation.

2. **Level-of-Service (LOS) variables generated by DTA for ABM.** In the “loose coupling” schema they take a form of aggregate LOS skims averaged across departure time bins and Value-of-Time (VOT) bins. In the “deep integration” schema LOS is based on individual trajectories for already simulated trips and individual Time-Dependent Shortest Path (TDSP) estimates for trips not yet implemented.

3. **Individual schedule consistency between travel times and activity durations.** In the “loose coupling” schema it is not controlled and can be substantially violated because of the LOS aggregation biases as well as possible internal inconsistencies in the ABM process. In the “deep integration” schema, it is fully preserved as an inherent feature, and possible inconsistencies of the original ABM schedules are getting corrected by the schedule adjustment procedure.
2 Methodology of integration

2.1 Equilibration levels
In practical terms, ABM and DTA are integrated at two nested equilibration levels:

- **Level 1 – global equilibration of the entire daily activity pattern.** The entire ABM is run to generate a daily activity pattern for each individual and then an entire-day network simulation is implemented for each global iteration of the equilibration process. This approach is essential for long-term planning and overall regional equilibrium where details of individual responses to stress conditions in the network become of secondary importance.

- **Level 2: Daily activity schedule.** Interactions between ABM and DTA at this level mimic short-term responses to experienced activities and trips during the day. The sequence of trips, destinations, and modes is fixed for each individual based on the outcome of the latest Level 1 iteration. Only trip departure time adjustments and route choices are made. Individual trip travel times are fed back to the activity adjustment module after completion of the simulation of trips to allow rescheduling of the trip departure times (and corresponding activity durations). The interaction is entirely organized at the individual level and it takes a full advantage of the most disaggregate LOS from individual simulated trajectories of DTA.

2.2 Equilibration process
The integration schema for Loop 1 and Loop 2 is presented in Figure 1 below. It includes several global Loop 1 iterations, each with several nested inner Loop 2 iterations. The established equilibration rules can be summarized as follows:

- **Loop 1:** The sequence of trips, destinations, and modes is regenerated by the ABM for each “stressed” individual. Initially, all individuals (households and persons) are considered “stressed”. Starting from the second iteration, a diminishing in size sample of households is re-modeled using the MSA principle (50%, 33%, 25%, etc) while the other households are “frozen” with respect to all travel choices. The households for the re-modeled sample are chosen probabilistically with the probability of a household to be chosen for re-modeling at the next global iteration is 10 times higher for stressed than for non-stressed ones.

- **Loop 2:** This internal equilibration provides stable LOS estimates through route choice and trip departure equilibration. Loop 2 equilibration ensures individual schedule consistency and evaluates schedule feasibility through important individual “stress” measures that are subsequently used for organization and convergence monitoring at Level 1. The equilibration process in Loop 2 is also integrated with the internal route-choice equilibration of DTA and this can be done in different nesting ways.
2.3 LOS sources

DTA is used to support LOS for ABM choices in the best possible way. LOS from the individual trajectories is used for repeated trips (can be interpreted as experienced LOS) as the best measure. However, for new trips that have not been simulated yet, a surrogate measure of either individual TDSP evaluation or pre-calculated LOS estimate is used (can be interpreted as expected LOS).

Individual trajectories cannot and need not be pre-calculated and stored for all combinations of trip and user characteristics such as trip origin, trip destination, departure time, car occupancy, and VOT. The LOS for ABM is supplied on the fly given the individual characteristics and the relevant subsets of origins and/or destinations in the following order of preferences:
• First, the same trip is searched for the given individual among his trajectories and sub-trajectories,
• Secondly, all trajectories/sub-trajectories are mined for the needed combination of origin, destination, departure time, car occupancy, and VOT for similar users,
• If not found, TDSP router is called to calculate the LOS on the fly.

At each subsequent global iteration of Loop 1, there is more reliance on the individual trajectories due to the diminishing share of “stressed” households and accumulated databank of trajectories.

2.4 Individual schedule consistency
Schedule consistency is absolutely essential for time-sensitive policies like congestion pricing. It can be shown, that under certain circumstances, an attempt to alleviate congestion in the AM period by pricing may result in worsening congestion in the PM period because of the compression of individual daily schedules that are forced to start later.

An individual’s schedule is initially based on anticipated travel times. The Individual Schedule Adjustment Module (ISAM) transforms the DTA output (individual trajectories), with departure and arrival times represented at a high level of temporal resolution, into adjustments to the individual schedules generated by the ABM. The adjustment of individual daily schedules was formulated as an optimization problem and is solved by an efficient Linear Programming (LP) approach. The program simultaneously considers all travelling members of the household with the possibility of linked trips for joint travel parties. The program builds new schedules for all household members that satisfy the constraints of full consistency with the simulated travel times through the entire day. The objective function minimizes penalties associated with behavioral implications of changing the schedule:

- Shifting trip departure time earlier or later,
- Shifting trip arrival time earlier or later,
- Shortening or lengthening activity duration.

2.5 Sampling of destinations and individual memory
The outer Loop 1 is based on the fact that trip origins, destinations, and departure times can be pre-sampled during the ABM solution and LOS would only be necessary for a subset of origins, destinations, and departure times; the probability for the same trip to be repeated by the same individual would be tremendously enhanced. Loop 1 includes a full regeneration of daily activity patterns and schedules but with a sub-sample of locations for which trajectories are available. This feature in implementation implies an “individual memory” component borrowed from the Agent-Based Modeling (AgBM) framework. Rather than re-sample destinations for each trip randomly, where the only linkage between two global iterations is the change in the aggregate LOS variables, the AgBM implementation retains knowledge about the preferred set of destinations and it is updated systematically rather than randomly at each global iteration for each individual.
3 Measures of Convergences
The integrated model generates many useful measures of convergence that can be broken into the following three groups:

• Standard measures of convergence of travel demand generated by the CT-RAMP ABM,
• Standard measures of convergence of DTA in terms of a gap between the actual generalized cost and minimal generalized cost at the route level,
• Unique new measures of convergence applied for Level 1 and Level 2 equilibration that integrates ABM and DTA outcomes at the individual level.

The new measures of convergence are generated by the Level 2 loop with a subsequent linkage to Level 1 equilibration:

• Number of persons with inconsistent schedules after simulation that contain a negative activity duration; this measure relates to the requirements for a full schedule consistency between travel times and activity durations.
• Number of stressed persons and households; this measure relates to assessment of the realism of the individual activity-travel pattern in terms of the given list of activities, tours, and trips. The tress thresholds are defined in terms of the total daily travel time and travel time ratio to total out-of-home activity duration by person type.
• Number of persons with substantial schedule adjustments between two successive inner iterations of Loop 2 (5 min for at least one trip departure time); this measure relates to the stability of simulation and convergence of trip departure times to a certain stationary point.

4 Summary of results
Observed empirical level of convergence was very good with 4-5 global iterations of Loop 1 and 8-10 inner iterations of Loop 2. With this equilibration setting, the number of stressed households gradually decreases with each global iteration while schedule consistency and schedule adjustment metrics tend to zero with each global iteration and within each global iteration, i.e. with each inner Loop 2 iteration. Some results that relate to Loop 2 and new introduced measures of convergence are presented below as an example. The full paper and presentation include multiple tests with both Loop 1 and 2.

Multiple tests were implemented with different variations of stress measures. First, it was important to explore convergence properties of Loop 2 in terms of the number of iterations needed to achieve a stationary solution as well as to ensure that this solution is consistent in terms of individual travel times and activity durations. Secondly, it was important to explore how the identification of “stressed” household for the outer Loop 1 would work under different conditions. The series of tests included doubling and halving the absolute and relative stress measures.

The following logical response of the integrated model can be mentioned:
• In all tests, a good level of convergence was observed after 10 iterations or even less. Number of households with inconsistent schedules tends to zero very quickly that indicates that by the end of equilibration process we obtain a realistic set of simulated travel times and individual schedules that match each other. Number of households adjusted from iteration to iteration also strongly tends to zero but does not reach zero within 10 iterations.

• The overall direction of the model response was always logical. Lower absolute thresholds or overhead ratios cause more stressed households and adjusted households from iteration to iteration. Conversely, higher absolute thresholds or overhead ratios cause fewer stressed households and adjusted households from iteration to iteration.

• As expected, the number of stressed persons and households was quite stable during the equilibration process but does not tend to zero. It should be remembered that it is theoretically impossible to reduce the number of stressed households substantially within Loop 2 alone. This requires a global equilibration (Loop 1) where individual daily patterns are allowed to change. The purpose of Loop 2 is to identify these households.

• When making the stress measure more rigid, lowering the allowed absolute threshold on total travel time per person had somewhat a stronger effect than lowering the allowed travel time overhead. The strongest effect was observed when both measures where made more rigid in parallel.

• When relaxing the stress measures, raising the absolute threshold for total travel time per person had a stronger effect than raising the allowed travel time overhead. The latter by itself had a very minor effect. The strongest effect was observed when both measures were enforced in parallel.

5 Implications for theory and practice of travel modeling

5.1 Future research directions
The current projects generated many new ideas and avenues that are worth further exploration:

• Behavioral foundation of a complete microsimulation model system for travel demand and network simulations. Traditionally, ABMs and DTAs have been evolving by following different behavioral paradigms that are not so easy to bring together. Bringing activity participation based on random utility maximization and generalized travel cost based on network optimization to a common denominator in a single measure of activity-travel pattern is an important strategic direction.

• Further development of Techniques of ABM-DTA integration and handling individual LOS. Individual trajectories contain multiple sub-trajectories and eventually after multiple iterations provide a good coverage of the LOS across the needed dimensions for the model. However, mining a databank of individual trajectories is quite time-taking at the moment and algorithms of quick search with relaxations for space and time should be further improved.
• **Further movement towards Agent-Based Modeling (AgBM) paradigm.** The current project, was bound to take a maximum advantage of the existing software such as CT-RAMP and Dynus-T, built largely following conventional microsimulation templates rather than AgBM. Further principal steps with ABM-DTA integration should follow a more holistic approach where demand and network parts do not have to be separated. A fundamental change in the model system structure could be considered where the ABM and DTA could be replaced with planning and real-time implementation modules. This system would completely integrate activity-travel decisions but separate planning (say day-to-day) horizon and real-time implementation (within-day) horizon.

### 5.2 Perspectives for use in practice

Below is a summary of our recommendations from the practical perspective:

• **Importance of individual VOT for highway pricing studies.** Both ABM and DTA were introduced because of the inherent limitations of conventional tools in handling highway pricing. Projects like managed lanes, congestion pricing, dynamic pricing, or global mileage-based pricing made it necessary to model a multitude of traveler responses such as mode choice, route choice, and time-of-day choice, where VOT plays a crucial role. The disaggregate nature of the “deep integration” schema represents a solution to this central problem.

• **Equilibration rules for evaluation of practical projects and policies.** One of the major practical concerns with microsimulation systems has always been stability of the results and (not always) well-defined equilibration rules. Planning needs in practice are most frequently expressed in comparison of different alternatives where the common denominator and logical relative responses to different inputs are more important than the absolute numbers. The current project demonstrated operational ways to ensure a reasonable level of system convergence.

• **Types of projects and policies where the ABM-DTA integrated model is useful.** First of all, the Integrated ABM-DTA system can replace a conventional 4-step model or ABM integrated with static assignment for practically any core planning work at an MPO including conformity analysis, conventional highway and pricing highway projects, transit projects, as well as potentially parking policies, bike-promoting policies, pedestrian environment improvements, and various land-use and population growth scenarios. Through the entire course of the project we have not identified any inherent drawback of the integrated ABM-DTA model that would represent a principal problem in practice.

• **What remains to be done to make an integrated ABM-DTA model viable for a large region.** The only practical issue that should yet be resolved is a relatively long runtime. Several future efforts have to be made to bring the integrated model system down to an acceptable runtime range (like an overnight run of not more than 12 hours). One of the possible solutions is to employ more hardware for a parallel processing that is essentially unlimited. ABM can be distributed across hundreds of nodes with a projected runtime reduction inversely proportional to the number of nodes. It is more problematic on the DTA side where only the routing stage
can be equally distributed. The vehicle movement simulation component does not lend itself for distributing due to a sequential conditional structure of calculations.