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Aggregate Tour-Based Model Framework of Urban Transportation

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Abstract: With the comparison of the practical limitations of the two model frameworks of the activity chain and the trip chain, this paper proposes a new model method based on the Aggregate Tour-based Model and analyzes the core algorithm. Then the Chinese megacity Wuhan is taken as an example to verify the feasibility of this method. The results show that the model framework fully considers the time and spatial constraints and internal consistency of the outbound and return journeys of each tour in terms of time, travel mode, main destination choice and stop selection, as well as the iteration and convergence between demand and supply. The method can adapt to all kinds of tours in a unified framework for modeling. Using the basic tour as the analysis unit, the model can both effectively reduce the complexity of resident activity modeling and ensure the consistent characteristics of residents' activity. In the case of ten million population, 3467 TAZS, and complex traffic environment, the model performs a great convergence process. Gap<0.2% and Gap<0.1% require 28.1 hours and 49.6 hours respectively, while the convergence process of 1678 TAZS only requires 9.5 hours and 17.8 hours, the model calibration and the reality and sensitivity test also fully verified the performance of the model. Finally, this paper discusses the relationship between the Four Steps Model, the Tour-Based Model, and the Activity-Based Model so as to avoid blindly falling into the trap of model refinement and complexity. **DOI:** 10.13813/j.cn11-5141/u.2021.0053-en

Keywords: activity-based model; aggregate tour-based model; basic tour; tour time model; destination mode choice model; empirical research; Wuhan

0 Introduction

Transportation Models provide foundation tools for quantitative analysis and scientific decision-making for transport forecasting and are of great importance in accurately grasping the mechanisms of transport development and scientific prediction[1–2]. Over the last 70 years, along with technology development along with rapid urbanization, and migration, transport researchers in developed countries have been trying to explore advanced scientific solutions than the traditional Four Step Model (FSM), in order to adapt to the ever-increasing requirements of model accuracy and tackle the complexities of transport demand management (TDM) and political decision-making. The Activity-Based Model (ABM) method has been a hot research area among a new generation of model development. However, most of the research was still focused on the theoretical level until 1996, Bowman and Ben-Akiva proposed a modeling framework called the Daily Activity Plan in the US, only when ABM models started to make breakthroughs from theories into practice [3]. Over the last 20 years, more than 30 Metropolitan Planning Organizations (MPOs) in the US have completed or been in the stage of developing ABM models[4–6]. China's engineering practice in this area has largely lagged behind[9], with the exception of Beijing efforts [7–8], which have made some initial explorations.

On one hand, the existing ABM approach is excessively complicated by pursuing disaggregation whilst addressing aggregate bias therefore is facing many unsolved obstacles[10–14] in practice and may not be suitable for cities remaining in the process of rapid urbanization. On the other hand, the traditional FSM is facing great challenges in terms of theoretical foundation, big data environment, and practical

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application, thus in urgent need of transformation and upgrading[4–6,9–12,15]. Therefore, seeking a pragmatic yet solid engineering solution between the FSM and the ABM for Chinese cities is of paramount importance to the urgent need for scientific judgments.

This paper proposes a new aggregate tour-based model (ATBM) method based on a comprehensive comparison of the limitations of the ABM practicality and basic tour-based models. The method is based on an aggregate formulation embedding the ABM characteristics of typical travels in cities of China, by taking the basic tour as the core element of analysis. In aggregated population segmentations a bridge between the FSM technical challenges and the ABM application obstacles has been effectively established. The paper presents an empirical study of Wuhan city demonstrating that the ATBM framework is feasible for large-scale complex engineering scenarios with millions of populations arranged over 3,400 traffic analysis zone (TAZ).

1 Awareness and reflection of traffic model

1.1 Realistic simulation reproduction

Both the FSM and the ABM are fundamentally purposed for simulating and reproducing people's real-life activities. The FSM is based on mathematical and statistical theories, focused on the results of people's travels in reversed causality-the spatial distribution of traffic flows (path choice, traffic assignment, etc.), as well as trip generation, trip distribution, and mode choice, etc., while ignoring why people make the trips and the details of trip making (e.g., trip time of day, etc.). The ABM is rooted in sociology and behavior science, and considers human demands for activities as the root cause of traveling; it investigates from the source why people make trips (the root cause of activity and its inherent mechanism) and how they make trips (time and space, residence, transportation modes, behavior patterns, etc.), thus providing a stronger base for theoretical analysis [10,12].

The concepts of activities and tours have frequently been confused in some previous studies; therefore, it is necessary to clarify and define them first. Fig. 1 illustrates the 24-hour activities of an individual. An Activity Chain is, as the name implies, sequentially-linked individual's daily activities. Fig. 1 can be noted as "HTHCWSWHQHO". The ABM is a modeling approach that uses the chained activities as the basic element to attempt to recreate and reproduce people's activities as realistic as possible.

Broadly speaking, tours are linked in the sequence of daily trips of individuals in sequence, so a tour may be viewed as equivalent to an activity chain with similarities. However, on a closer look, an activity chain is composed of a number of round-trip segments. In this paper, we refer to a sequence of trips from a certain starting point and return to the same (pivot) point as tours, among a series of independent round-trip segments linked with a day. An activity chain can contain one or mode tours, while a tour has one and only one round-trip segment (outward and return). Therefore, the tour-based model may be viewed as a sub-unit of the ABM—a modeling approach in which a tour is a basic segment.

1.2 Technical decision in trade-offs

The ABM is a disaggregate modeling approach due to the need to construct and restore individual activities and may even simulate the complications of family members activity choices [5,10-15], which is by no means an easy task for a megacity with a population of several million or even tens of millions.

1) Model runtimes and computational efficiency. The initial New York ABM used a large server taking a week to run and still takes three days even after the latest improvement [12]. The York region ABM of Canada (with a total population of around 890,000 in 2006) takes 30–35 hours to run once on a Z440 server (Intel Xeon E5-1603v3 with 128 Gb of memory) [16].

2) Model convergence problem. The change of transport network supply will lead to the redistribution/inducing of travel demands, which will further impact the supply level, thus transport models need feedback iterations between supply and demand to achieve convergence and stability. Lack of operational efficiencies, current ABM models in practice terminate runs often with a fixed number of iterations (usually no more than five in setting), which cannot achieve the convergence level required.

3) Uncertainty of the results. Based on Monte Carlo simulations, ABM results are naturally different as output for each run if without fixed seeding. This is an important reason why its application in government investment projects is limited, as most cost-benefit analyses cannot be based on the uncertainty of model results.

4) Application barriers. The ABM requires fine-grained microdata, which is difficult to obtain for cities that are still in the process of rapid urbanization Thus, there are barriers to replacing the FSMs for medium and long-term forecasting analysis. In some US cities, both FSM and ABM models are sometimes co-maintained in order to accommodate different applications for scenario testing. In addition, the high investment in research and development and high-performance computing, the hiding cost of model upgrading, and technical uncertainties are among the other barriers to the real world application of ABM models [14–18].

In contrast, the tour-based model is sufficiently flexible: on the one hand, it links related activities as a tour and maximizes the consistency of meeting the constraints of round trips within a tour in terms of time, destination and mode, in order to overcome the technical shortcomings of the FSM; on the other hand, it moderates the ABM complexities, with the advantage of being applicable to both aggregate and disaggregate modeling approaches. However, constructing a tour-based model is by no means an easy task. Taking Wuhan city as an example, an activity-based household interview survey (HIS) undertaken in December 2020 (15,000 household samples, 0.5% sampling rate) yielded a total of 559 types of raw activity chains. After cleaning and pivot point screening the samples among those who had departed and returned to their home, have still a total of 344 activity chain types resulting in as many as 153 tour types after merging[19]. Therefore the disaggregate path also faces similar complexity obstacles as the activity chains.

Some of the more representative developments in the tour-based models to date include DIADEM[20], developed with the support of the UK Department for Transport; the GBMF[21–22], developed by the ATKINS UK in 2006-2008 for the West of England Partnership; the Visum approach implemented by PTV applied in the Middle East countries (Bahrain, Qatar, the United Arab Emirates), Turkey, and Beijing in China [23]. Realistic limitations among the approaches include 1) the lack of structural resolution and full description of a tour, which fails to be fully independent of the FSM; 2) the model output does not guarantee the integrity of a tour formulation, once the tour structure is interrupted from input, making it impossible to reconstruct and analyze the behavioral characteristics of the overall travel chain; 3) the lack of clear mathematical definitions of key computational processes such as the joint Destination-Mode Choice models and the mode switch behaviors along a tour, etc. The whole demand modeling process is largely black-boxed, making it difficult for users to understand the tour mechanism; 4) the concept of activity duration is not explicitly defined, and there is a lack of response to TDM policies such as parking charging by duration hours, etc.

Nevertheless, the tour-based model still shows broad development prospects [24]. From the perspective of realistic development for Chinese megacities, it is advisable to generate tour-based transport models first for knowledge accumulation and updating, and then gradually move to explore the feasibilities of ABM implementation, when future development needs emerge.

2 A new aggregated tour-based model structure

2.1 Overall model structure

Based on the above analysis, this paper proposes a new aggregate tour-based mode (ATBM) modeling approach. This method takes the basic tour as the unit of analysis and constructs the model in an aggregated manner by person group, taking into account the spatial and temporal constraints and addressing the internal consistency of each tour in terms of time, mode of transport, choice of main destination and choice of the intermediate stop location.

The definition of the so-called Base Tour is derived from the analysis of people's activity-trip paring deducting tours from an activity chain and then, according to the round trip logic, sets the endpoint of the outward trip of a tour as the main destination, with other secondary activity stops during the trip called intermediate stops. A basic tour is a special type of trip chain that retains only the main destination ignoring intermediate stops. For example, "HCWH" in Fig. 1, the main destination is work (W) and the intermediate stop is the place (school) where children are escorted to school (C) on their parents' way to work, thus, "HWH" represents the basic tour. Given a time window (i.e., 24hr), if a trip chain cannot form a completed roundtrip structure (either outward or return but not both), it is called a Half Tour. Fig. 1 activity

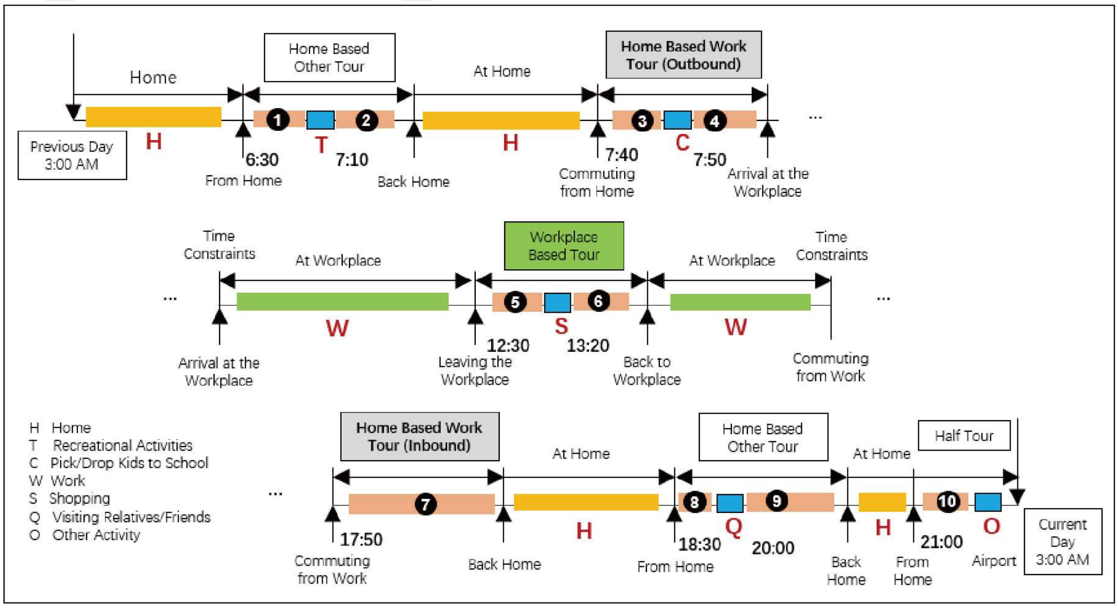

Fig. 1 A typical resident daily activity and tours

chain can be divided into home-based work/escorting tour (HCWH), home-based other tours (HTH, HQH), workplace-based tour (FSF), and half-tour (HO). “HCWH” is first modeled based on “HWH”, and then the intermediate stop “C” is added. The whole analysis and logic context follow “activity chain—tour—basic tour—intermediate stop”, realizing the process of “complex/disaggregate—simplified/ disaggregate—group/aggregate—reduction”. The overall structure of the ATBM is shown in Fig. 2.

The top layer of the model structure is the model input layer, which takes as input planning data and parameters common to that of the conventional FSM, including local population, jobs, schools, socio-economics, car ownership rates, etc., as well as supply model parameters, transport networks, and operational management policies. The model input layer is essentially similar to that of the FSM, thus effectively reducing the difficulty of upgrading which ensures that the model has similar supportabilities in terms of planning year forecasts. The differences are that the ATBM requires finer data dimensions, including population classification, time period specification, parameter settings, etc.

Below the input layer, the activity-trip analysis layer lies. The purpose of this layer is to ensure that the local characteristics of the study area can be accurately represented by the activity-trip analysis, finding the basic tour types before starting the tour demand calculation. In this framework, there are five major tour types: home-based work tour, home-based school tour, home-based other tours, work-based tour, and other tours (mainly for city interchange hubs for the internal study area to external movements), corresponding to the five main activity purposes (commuting, schooling, maintenance, work and employer’s business) respectively and spatial planning units (see Fig. 3). The half tour is also included in the above categorization, thus ensuring a unified modeling framework allowing for the modeling of all types of travel from simple to complex, for both residents and mobile population groups.

The tour-based demand modeling layer consists of three components: a tour generation model, a spatial-temporal consistent Destination-Mode choice model, and an iterative loop between the demand and supply model. Finally, the model output layer outputs assignment OD matrices by converting tour demands when the supply-demand models as a whole reach convergence, for the final traffic assignment and output of the results. The model structure is capable of outputting time-dependent OD matrices thus supporting dynamic traffic assignment, due to the specification of time periods and time period modeling.

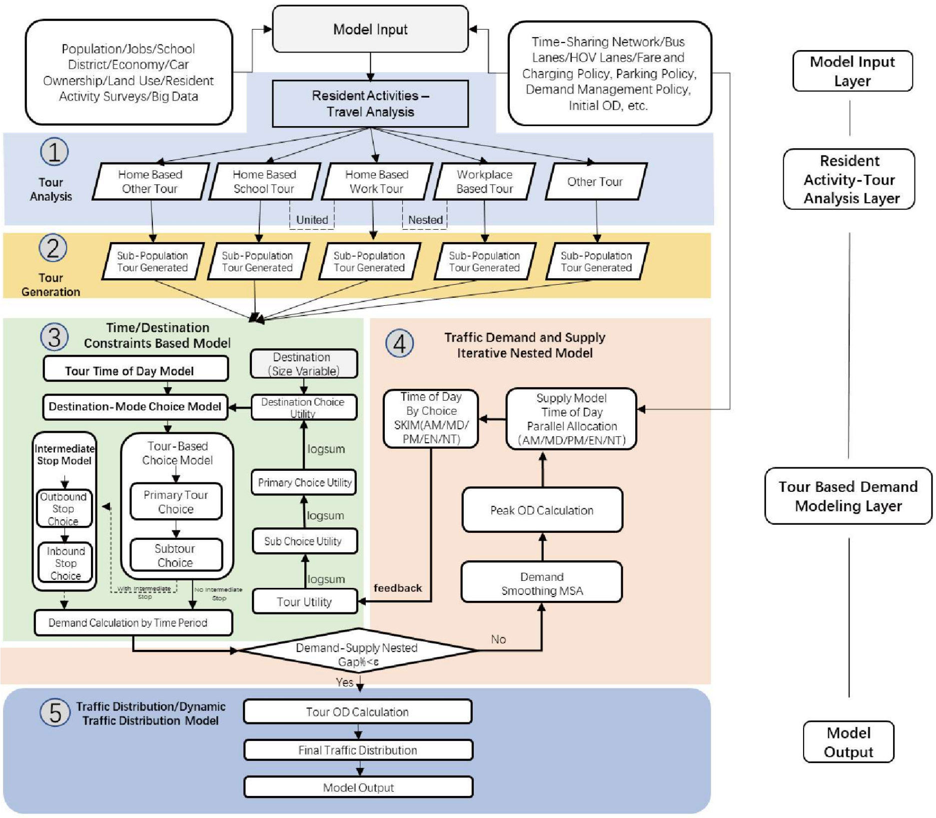

Fig. 2 Framework of aggregate tour-based model

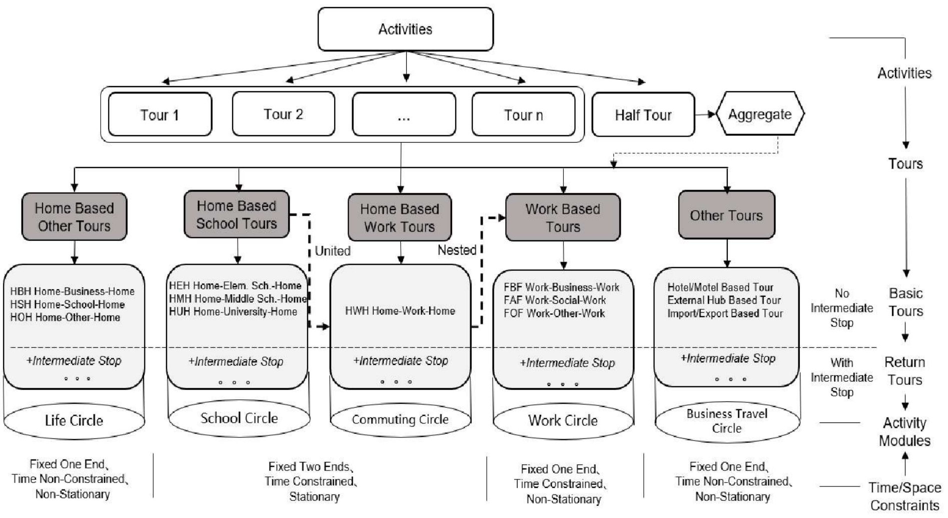

Fig. 3 Category of basic tour based on activity

2.2 Core module functions

Tour-based demand modeling is the core of the technology. The tour generation module is specified by the common cross-classification of population groups and tour types, as the basis for the ATBM calculation.

In the tour-based Destination-Mode choice model, three sub-models are integrated: the tour time of day choice model, the main destination and mode choice model, and the intermediate stop model. As shown in step three in Fig. 2, the rightmost branch is used for the logsum accessibility calculations bottom-up, the middle branch for demand calculations top-down, and the leftmost branch for modeling intermediate stops during a round-trip journey. While seeking behavioral realism and model sensitivity, the tour time of day choice model explicitly considers the departure time of each trip within the tour as well as the duration of the activity in order to realistically reflect, for example, the parking costs of time-sharing and the time characteristics of different groups. The tour mode choice model considers the modes for outward and returns trips separately, allowing for mode switching between them while maintaining consistency. The intermediate stop model is used as an optional sub-module to accommodate different tour specifications with or without intermediate stops. In this structure, it is not until the last step for the calculation of OD demands by time period, that the tours are split into trips, reflecting the integrity and consistency of the tour modeling throughout the demand calculation process.

The modeling framework introduces an iterative feedback mechanism between transport supply and demand models to ensure the model system reach an acceptable level of convergence, for the stability of the model results. As mentioned earlier, this mechanism effectively mitigates the inadequacies of the ABM in this aspect. The convergence criterion is based on a gap function, which is calculated as:

$$\mathrm{Gap}=\frac{\sum_{ijpcmT} C\left(X_{ijpcmT}\right)\left|D\left(C\left(X_{ijpcmT}\right)\right)-X_{ijpcmT}\right|}{\sum_{ijpcmT} C\left(X_{ijpcmT}\right)X_{ijpcmT}}\times 100\% ,$$

where X and C are the current demand matrices and generalized impedance matrices respectively; D is the new demand just calculated for the next round of iteration; i and j refer to the TAZ origin and destination, respectively; p is the activity purpose; c is the person type; m is the mode of transport; T is the trip time period. According to the TAG (Transport Analysis Guidance) published by the UK Department for Transport [25], the demand-supply model convergence Gap being less than 0.2% is considered acceptable, and with an even higher level of convergence below 0.1% for special scenarios. To speed up the convergence process, the MSA smoothing calculation is introduced to leverage the current demand calculation and the previous demands for the next iteration of demand matrices.

2.3 Features and advantages

1) Comprehensive tour-based demand modeling based on activities.

In contrast to existing tour-based models, this ATBM structure ensures the full consistency of tour modeling from generation, time choice, main destination choice, mode choice, and then intermediate stops. The tour specification as input is consistent with the tour demands as output. Under this mechanism, it is theoretically extensible to more complicated ABM formulation based on either person types or individuals.

2) Using the basic tour as the analysis unit effectively reducing the level of complexities of tour modeling, whilst maintaining the consistency of people's activity characteristics.

In Wuhan, for example, although there are 344 activity chains and153 tour types, 86.9% of sampled tours belong to the basic tours, with only 13.1% of them having intermediate stops, of which 92.3% of tours have only one intermediate stop [13]. Modeling the basic tours first and then inserting the intermediate stops second significantly reduces the number of intermediate stop calculations thus improving the model's practice reliability and operational efficiency.

3) Using multi-constrained destination choice to meet the supply-demand balance, while using the accessibility variable (logsum of the lower-level utilities) and the size terms of the combined land use as inputs for the destination choice process to enhance the model's analytics.

The home-based work tour and home-based school tours are stable tours, closely relating to population and jobs/school places with time-window constrained at both ends of production and attraction, thus the model calibration is particularly adaptable for the big data environment; the work-based tour is pivoted at one end with the workplace related to the home-based work tour less-time constrained; the home-based other and non-home-based other tour types are pivoted similarly at the starting point of tours, flexible with constraints relaxed on time budget (see Fig. 3). Different from home-based work, home-based school tours are subdivided into different categories of primary school, middle school, and colleges corresponding to cascaded education groups. Compared to the traditional FSM with gravity-based distribution constrained by population and employment, the destination choice model can reflect inherent relation, on job and residence, school district division, points of interest, etc.

4) Model structure is clear and transparent, easy to upgrade and maintain.

Compared to the FSM, the ATBM architecture is embedded with tour time-of-day choice modeling (time periods specified for the outward and return journeys respectively), takes into account the consistency and variability of destination-mode choice modeling for tours, replacing the traditional distribution model with a destination choice model facilitating the insertion of one or more (up to three) intermediate stops for half-tours, much more realistic on scenarios in decision-making. In terms of data requirements, the traditional HIS and SP surveys [26] are largely the same but with targeted adaptions. In population-group-based modeling, the ATBM structure may require even lower sample rates than that of traditional models in cases when the population samples are sufficiently broad in coverage.

3 Empirical case study and analysis of key technologies

3.1 Overview of the empirical case study model

This paper uses the Wuhan as a case study to verify the feasibility and practical performance of the entire ATBM structure. Wuhan is a megacity with a resident population of over 12 million located in central China. Covering the whole city area of 8,569 km^2, a comprehensive FSM has been built as early as 1999 and continuously maintained and upgraded, thus establishing a solid assessment foundation. In this paper, two levels of zoning systems are utilized with 3,476 TAZs and 1,678 TAZs respectively, with calibrated parameters, network supplies, and underlying data the same. The input data incorporate the 7th Census data, the 4th economic survey data, current land use, building information, points of interest, education establishments (including student numbers in various types of schools), employment jobs, school places, and school catchment areas, etc. The data used for model calibration and verification include MND (mobile network data), smart transit card data, checkpoint data, and other big data such as GPS for taxis and buses, together with traditional screenline count data. The city's 15,000 HIS samples collected in December 2020 with 1,500 SP samples[19,26] provide the basis for the overall model development.

The ATBM is implemented with a cross combination of tour types based on 12 person types and 9 basic tours, with the main city area divided into two parts (inner and outer), with five time periods and considering five main modes. The supply model consists of 108,000 road links, 43,000 nodes, and 1,457 directional transit routes (including rail, public bus, BRT, etc.), with 11,000 intersections with turns verified. In order to match the time-of-day demand modeling for a true reflection of time-varying services and network operations, the supply modeling consists of five road network models distinct by time period, corresponding to different network details.

Tab. 1 Example of tour time series combination coefficient matrix %

Tour t=1,2,…,14,15		Return time period (t)				
		AM (t =1)	MD (t =2)	PM (t =3)	EN (t =4)	NT (t =5)
Outward Time Period (t°)	AM (t =1)	0.29	2.70	72.58	14.47	0.87
	MD (t =2)		0.38	1.96	5.13	1.18
	PM (t =3)			0.00	0.01	0.11
	EN (t =4)				0.00	0.00
	NT (°=5)					0.32

3.2 Tour time-of-day specification model

As time is a continuous variable, there are infinitely many combinations of outward and return times for tours, time periods are commonly used to represent an average weekday. With t^o and t^r representing the outward and return time periods of a tour respectively, we have $t^o < t^r$, as shown in Table 1. With T_O representing the set of time periods available for the departure of the outward trip, and T_r representing the set of time periods available for the departure of the return trip, we have $t^o \in T_O$, and $t^r \in T_r$. Let t be a complete tour composed of t^o and t^r, denoted as $t = (t^o, t^r)$. Divide an average weekday into n time periods denoting as $T_1, T_2, \square, T_n$, considering only a 24hr cycle (within one day), there are a total of $(n+1) \times n/2$

time period combinations of the outward and return trips per tour. For example, if there are five time periods, such as AM (06:00–09:00), MD (09:00–16:00), PM (16:00–19:00), EN (19:00–22:00), NT (22:00–06:00), for each tour segment by "person type + purpose" used in the tour generation model, there will be 15 combinations of time periods for the outward and return trips (see Tab. 1).

3.3 Joint tour destination-mode choice model

To ensure the consistency of "activity-trip" in the ATBM structure, the joint tour destination-mode choice model presented in this paper implements a three-layered logit mechanism. According to the round-trip logic the modes of return trips are influenced by their outward trips, so when constructing the Nested-Logit model (NL model), the return mode choice is at a sub-mode choice level to the outward mode choice placed at a lower level down. The mode choice for the outward trip (the main mode) is carried out first, and then the mode choice for the return trip (the sub-mode) is carried out in the ATBM (Fig. 4).

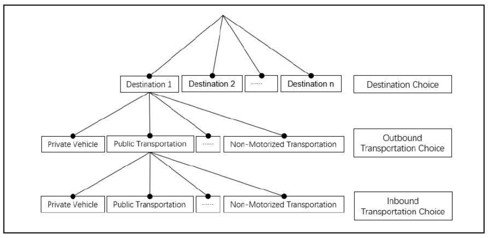

Fig. 4 Tour destination-mode choice model

(1) Mode choice modeling

The empirical Wuhan model considers a total of five main modes of transportation, M={car as driver, car as passenger, public transport, taxi/ride hailing, non-motorized walk/cycling}. Based on behavior realism, the car-as-driver is defined as the only non-exchangeable mode, i.e., if the outward trip is by this mode and so is the return trip in definition; the other four modes are changeable in-between for tour trips. Therefore, there are 17 mode combinations for outward and return trips in total for the ATBM mode choice modeling (see Tab. 2).

Tab. 2 Combination of Outward-return modes in one tour

Category		Inbound Tour Transportation (m^r)				
		Private Vehicle (Driver)	Private Vehicle (Passenger)	Public Transportation	Taxi /Ride Hailing	Non-Motorized Transportation
Outbound Tour Transportation (m)	Private Vehicle (Driver)	√				
	Private Vehicle (Passenger)		√	√	√	√
	Public Transportation		√	√	√	√
	Taxi /Ride Hailing		√	√	√	√
	Non-Motorized Transportation		√	√	√	√

For the only non-exchangeable mode (car as driver), the outward and return modes are the same (m^r=m) and the tour utility is calculated using a weighted average of the trip utilities, i.e.,

$$U_{ijpcm}=\sum_t W_{pct}U_{ijpcmt}=\sum_t W_{pct}\left(U_{ijpcmt^o}+U_{jipcmt^r}\right)\times 0.5\ ,$$

where i is the origin; j is the main destination; p is the tour purpose; c is the person type; m *is* tour mode. U_{ijpcm} is the weighted daily average utility for tours from origin i to destination j then back to i, for person type c, trip purpose p and mode m,$U_{ijpcmt}o$, and $U_{jipcmt}r$ are the utilities for outward and return trips respectively, W_{pct} is the proportion of demands for tour t over the daily total demands by activity purpose p and person type c satisfying the condition $\sum_t W_{pct}=1$(Table 1).

For exchangeable modes, the tour mode choice requires a main mode (m) choice for (outward trip) followed by a sub mode choice for the return trip in mode m^r. For tour t =(t^0,t^r), the tour mode utility is calculated by the combinations of modes (m,m^r), as a weighted average of the outward utility and the return trip utility in mixed-modes:

$$U_{ijpcm}=\sum_t W_{pct}\left[U_{ijpcmt^o}+\left(\alpha_1 U_{jipcmt^r}+\alpha_2 U_{jipcm^*t^r}\right)\right]\times 0.5\ ,$$

where α_1 and α_2 are the mode shares of the outward and return trip respectively: when the modes are different for a basic tour the two coefficients are set as α_1=0.9, α_2=0.1 respectively (evidenced by the HIS); when the modes are the same for car drivers, then α_1=1， α_2=0. $U_{jipcm^*t}r$ refers to the mixed-mode utility (m∈mix, m^r≠m) for return trip, which is calculated by the formula below for the sub-mode choice after the main destination choice is calculated:

$$U_{jipcm^*t^r}=\ln\sum_{\substack{m^r\in \text{mix}\\ m^r\neq m}} e^{\lambda_{pc}^m U_{jipcm^r t^r}}\ ,$$

where mix is the set for exchangeable modes, m^* refers to the mix-mode for the return trip different from the outward trip when its mode is exchangeable, and $\lambda^m{}_{pc}$ is the scaling factor for the mode choice modeling.

(2) Destination choice

The tour main destination choice is placed at the upper level above the main mode choice. The destination choice utility contains two parts: the first is the mode choice logsum from the lower level mode choice with scaling parameter $\beta^d{}_{pc}$; the second is the log of the combined Size Variables at destination j by activity p with coefficients σ_{jp}:

$$U_{ijpc}=\beta_{pc}^d\ln\left(\sum_m e^{U_{ijpcm}}\right)+\ln\left(\sum_k \sigma_{jpk}\times Size\ Variable_{jpk}\right).$$

Destination choice probability calculation is done for both singly and doubly constrained distribution. For home-based work, the main destination choice is balanced by a two-dimensional IPF algorithm (rectangular IPF) with doubly constrained; for home-based education tours, the IPF algorithm is also two-dimensionally balanced (square IPF) with double constraints; the rest of the tour types are modeled by a singly constrained mechanism. Based on the above utility functions, the probabilities of the tour main destination choice and main mode choice, and the return-trip sub-mode choice can be calculated accordingly. The probability of tour main destination choice is

$$P_{ijpc}=\frac{B_{jp}e^{\theta^d_{pc}U_{ijpc}}}{\sum_j B_{jp}e^{\theta^d_{pc}U_{ijpc}}},$$

the probability of tour main mode choice is calculated as

$$P_{ijpcm}=\frac{e^{\lambda^m_{pc}U_{ijpcm}}}{\sum_k e^{\lambda^m_{pc}U_{ijpck}}},$$

and the probability of the sub-mode choice for mixed-mode return trips is

$$P_{jipcm^r t^r}=\frac{e^{\lambda^m_{pc}U_{jipcm^r t^r}}}{\sum_{m^k} e^{\lambda^m_{pc}U_{jipcm^k t^r}}},$$

where B_{jp} is the balance coefficient of the travel purpose of J-Community P (work/school), which indicates the adjustment result of IPF calculation.

3.4 Intermediate stop location model

Taking the "HWEH" tour as an example for employees going for dinner after work on their way home, this type of tour is modeled by the implementation of the so-called "rubber band" algorithm, considering the spatial tradeoff of intermediate stops between workplaces and homes on return trips. In the intermediate stop location choice model, the impedance in the ATBM is calculated from the set Q of feasible intermediate stops q ($q \in Q$) on the way back from the destination to the origin.

$$IMP_{jicm^r q}=\left[IMP_{jqcm^r}+IMP_{qicm^r}\right]-IMP_{jicm^r},$$

where $IMP_{jqcm}r$ is the impedance from the tour destination to intermediate stop q; $IMP_{qicm}r$ is the impedance from q back to origin home; $IMP_{jicm}r$ is the impedance from the tour destination back to the tour origin without any intermediate stop.

The model assumes that each traveler has the objective of minimizing the total cost of travel when determining an intermediate stop. The attractiveness of where the intermediate stop is located is handled similarly to that of the main destination choice. The utility of these return trips with an intermediate stop q is estimated as:

$$U_{jicm^r q}=\beta^d_{pc}IMP_{jicm^r q}+\ln\left(SizeVariable_{pcq}\right),$$

where β^d_{pc} is the scaling parameter and $SizeVariable_{pcq}$ is the intermediate stop location size variable.

After the utility calculation, the standard singly-constraint destination choice is used to determine the TAZ location corresponding to stop point q.

4 Model validation and performance testing

The calibration and validation of model parameters is a large systematic task, for the ATBM, the tour generation model parameters are fitted using multinomial logistic regression and multinorm function in R language; the time of day model is fitted based on polr() and lm() function in R; while the utility function parameters are calibrated based on the SP survey results using Biogeme package. The intermediate stops were calibrated from the fitted Hurdle model. The empirical model was validated comprehensively, on the demand modeling side covering the tour generation, time of day choice, trip length distribution, and mode choice, and on the supply modeling side including screenline flows, peak-hour imbalanced tidal flows, and transit passenger flows, etc. The validation checks are carried out by comparing the modeled output to mobile phone data, expanded HIS data to population, and automatic count data, etc. Example validation results are shown below, which exhibit a good match between the modeled results and observed volumes (Fig. 5–Fig. 7).

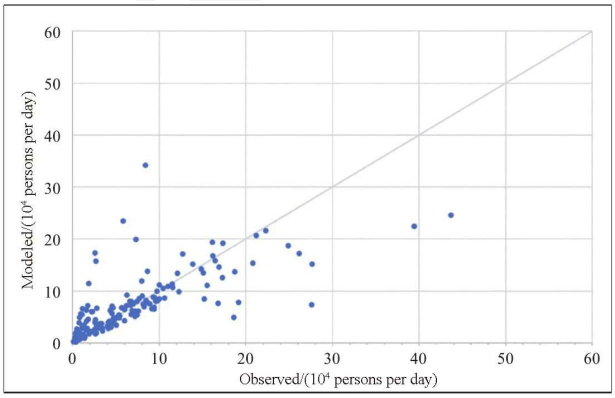

Fig. 5 Typical travel chain generation calibration

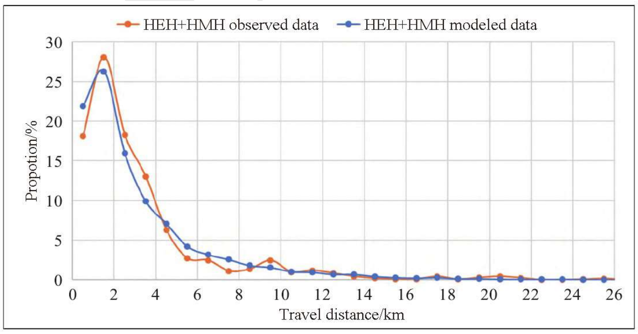

Fig. 6 Travel distance calibration of typical basic tour destination selection

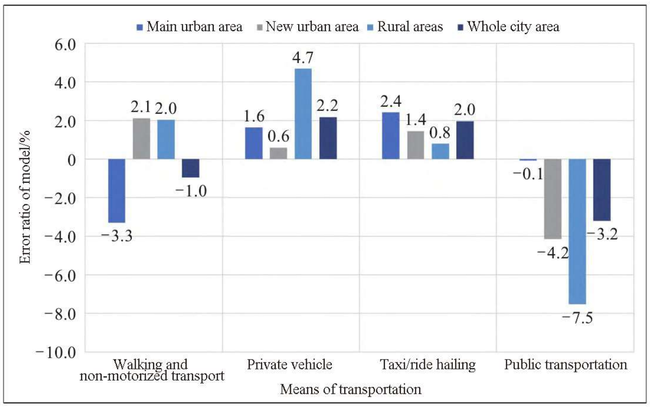

Fig. 7 Travel mode choice calibration in different districts

In terms of model convergence and computational efficiency, test runs show that the model reaches a good convergence level (Gap<0.2%) with 24 iterations in 28.1 hours for a cold start, under the hardware environment of Precision7730 mobile workstation (Intel(R) Xeon(R) E-2186MCPU@2.90 GHz; 128 Gb RAM); further running can reach an even finer convergence level of Gap<0.1% in about 49.6 hour and 43 iterations (see Fig. 8). The model achieves the above levels of convergence with 30 and 58 iterations in 9.5 and 17.8 hours respectively, after reducing the number of TAZs from 3,400 to 1,678 in testing. The Wuhan cast study verifies the realistic feasibility and operational stability of the ATBM structure, which is superior when compared to the ABM model.

Realism test is aimed at examining model's responsiveness to supply changes through the valuation of elasticities. The term elasticity is defined as the % change in trip demands due to a 1% change in cost or other supply characteristics (e.g., operating speed or level of service), calculated by $\eta=\dfrac{\Delta\log Q}{\Delta\log P}=\dfrac{\log Q_2-\log Q_1}{\log P_2-\log P_1}$, where P_1 and P_2 represent the costs for the base case and changed case, and Q_1 and Q_2 represent the demand trips corresponding to P1 and P2, respectively. The paper focuses on three common types of realism tests for TDM policy studies: fuel cost, transit fare and parking costs. The results show that (see Table 3): a 10% increase in fuel costs results in an overall city-wide elasticity of −0.17 (i.e., a 1% increase in fuel costs would lead to a demand decrease of 0. 17%); a 10% increase in public transport fee results in an overall fare elasticity of −0.63; a 10% increase in parking rates results in an elasticity of −0.68 overall for car trips and −0.9 for the main urban areas respectively, indicating that the center areas are more sensitive to cost changes in parking fees. The model is also sensitive to capturing differential impacts in parking charges for car users between passengers and drivers (assuming that car drivers and passengers share the cost of parking equally, see Table 4, with elasticities of −0.77 and −2.67 respectively, indicating that car passengers are more elastic than drivers and more sensitive to changes). As there are no relevant standards in China, the model elasticities have been compared to the elasticity values in the literature [29], showing that the empirical elasticities are mostly within the recommended range of values.

Tab. 3 Comparison of model elasticity test based on multiple schemes

Basic Tour	Fuel Cost Elasticity	Public Transportation Fee Elasticity	Activity Based Parking Fee Elasticity
HWH	-0.28	-0.52	-0.74
HBH	-0.06	-0.48	-0.21
HSH	-0.07	-0.56	-0.89
HOH	-0.08	-0.85	-0.24
HCH	-0.16	-2.48	-1.51
FAF	-0.04	-0.37	-0.71
FBF	-0.05	-0.36	-0.78
FOF	-0.05	-0.34	-0.81
Elasticity Value Reference System			
Reference Value	-0.55—-0.05	-1.0—-0.4	-0.541

Tab. 4 Calculation of elastic value of parking fee in main urban areas

Category	Mode Structure/%	Elasticity
Private Car Driver	19.77	-0.77
Private Car Passenger	1.34	-2.67
Private Car Driver+Passenger	21.11	-0.90

5 Research exploration and insights

Migrating China's transport models from the traditional FSM to the ABM with realistic and feasible engineering solutions, is a necessary path for China's urbanization process, moving from the speed-focused developments to the high-quality standard developments based on science. This paper presents our explorations and insights into the new

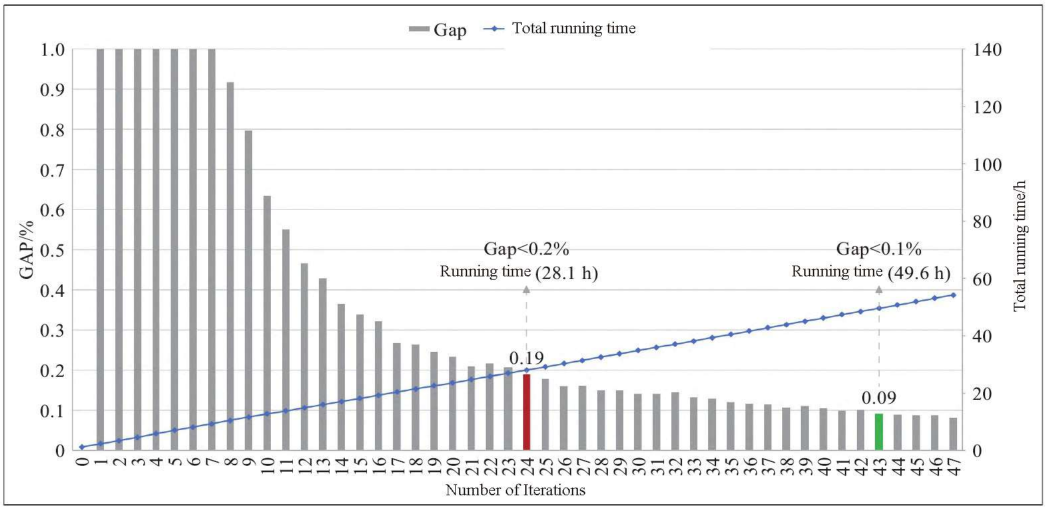

Fig. 8 Convergence index (GAP) and running time of the model

development, taking the case study of Wuhan city as empirical evidence for the overall construction of the ATBM system.

1) Objective knowledge in understanding the relationship among the four-stage model, the tour-based model and the activity-based model.

Despite theoretical limitations, the FSM is still the most economically feasible and scientifically viable forecasting method for Chinese cities that have been urbanizing at high speeds over the past 30 years, mainly oriented toward medium and long-term development decisions. In the process of transformation and upgrading the shift from the aggregate modeling to the disaggregate ABM developments cannot be achieved overnight. The tour-based model proposed in this paper has the advantages of both FSM and ABM models and the empirical evidence shows its feasibility, thus warranting further research efforts as a pragmatic choice.

2) Avoid the trap of blind seeking model complexities and fine resolutions

Even the tour-based modeling exhausts abundant resources. Its core constraints are multi-dimensional, including the number of person types, tour types, time periods and transport modes, as well as the requirement for fine-grained TAZ system. In the big data era, the division of TAZs can be done at the building-block level, the division of time periods can be at an hourly or even finer level, and the number of the person types and basic tour types can be much more, but any increase of such dimension will lead to a geometric increase of computing resources. Taking the number of time periods as an example, when it is increased from 5 to 15, model runtimes and the number of parameters are about 7 times higher. The case study of this paper may be served as empirical guidance, in about 2,000 TAZs, model runs until an acceptable level of convergence can be broadly managed within a 12-hour benchmark (the so-called overnight rule in no more than one night of runtimes: a modeler is able to see converged results the next morning when starting work, by setting a model run just before off-work to home in the previous evening). And, the requirement of computing resources need CPU power and memory: the RAM consumption in 3,476 TAZs is close to the upper limit of 128 GB for current single machines.

3) Emphasis and strengthening model's validation check.

As a large systematic study, this paper focuses on the engineering feasibility of the model structure and the analyses of the convergence performance, computational efficiency, realism and sensitivity, all of which are among crucial criteria for the practical engineering application of the activity model. The traditional FSM development, often using a small-sampled cross-sectional HIS to derive population trip ODs and even using them for parameters, calibration and verification, is increasingly being questioned by big data researchers. Urban traffic models should be based more on the analysis of traveler's characteristics and their intrinsic behavioral patterns, subject to the validation check in a realistic simulation environment, which is precisely the direction advocated by the activity modeling. Model's accuracy and verification depend on, not only the model mechanism itself but also a fine requirement on input data such as population and jobs, etc.; it depends on the quality of the survey data, statistical processing and data fusion technology in timing matching; all of these need to be viewed rationally and is not discussed in detail in this paper.`

4) Case study and more extensive empirical testing.

Encapsulating all aspects of the FSM in terms of functionalities in advancement, the empirical implementation of the ATBM structure completely replaces the FSM; with a similar level of data requirement to the FSM, the ATBM is straightforward in applications for transport forecasting in future, in contrary to the ABM approach which is not really applicable. Broadly speaking, it is theoretically achievable to consider all types of tours (trip chains) under a unified modeling framework for all population groups such as local residents, seasonal workers, short-term visitors, and also half-tours via transport interchange hubs from/to the study area to external areas. For most types of urban TDM policy decisions, for example differential parking pricing, transit ticketing with interchange concessions, road congestion charging, etc., the empirical model can find appropriate ways of resolving them showing wide application prospects. Due to the page limitation of the paper, more empirical evidence and exploration of other cities are needed but not presented. The validation of the tour-based model and the four-stage model in comparison, for example the destination choice model compared to the conventional gravity model, warrants further research.

5) Developing tour-based modeling standards and guidelines, establishing mechanism for activity-based household interview surveys in continuation.

Finally, it is undeniable that although China has accumulated a wealth of practical experience in the R&D of FSM applications, there is not yet a complete set of modeling guidelines lack of systematic standards on parameter calibration and model validation, which undoubtedly makes it more difficult to promote the research of new technologies. In particular, on the data requirements for modeling, the industry has fully acknowledged that big data are not yet capable to replace small-sampled surveys. Guaranteeing the quality of man-powered surveys requires both financial and policy supports, and the institutional development on regular surveys, similar to population censuses and economic censuses, need to be managed from the top down. The tour-based modeling as a brand new topic asks for a higher level of quality surveys, and the establishment of innovative ATBM structure opens a window of new opportunities. This research may have started a new modeling era, with much-needed domestic and oversea collaborations, technical communications and joint development efforts.

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