LLM Agents in Tradable Credit Schemes: Market-Network Dynamics under Threshold-Based Eligibility

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Short summary

This study develops a large language model (LLM) based behavioural simulation framework to examine how tradable credit schemes perform when car use depends on a qualification threshold in daily operation. The framework combines traveller agents with LLM based decision policies, repeated intraday credit trading, and MFD based network loading in a repeated daily setting. Using a 5/8 credit regime, we show that the system approaches a stable operating state, but realised car use remains below the theoretical upper bound implied by perfect reallocation. Agent level tracing and follow up interviews indicate that threshold inefficiency is sustained by option value holding and optimistic threshold chasing, while car access is redistributed unevenly across traveller groups. These findings provide a mechanism based understanding of daily scheme performance and offer a basis for policy design and future testing of credit endowments, eligibility thresholds, and market rules.

Keywords: tradable credit schemes, Large Language Model, agent-based modelling, transport equity

1 Introduction

Tradable credit schemes (TCSs) have long been regarded as a promising instrument for urban travel demand management because they regulate scarce road use rights through tradable permits rather than relying only on tolls or administrative restrictions (Grant-Muller & Xu, 2014). Early studies showed that TCSs can influence departure time choice and route choice through the exchange of travel rights in a credit market (Nie & Yin, 2013), and more recent work has extended the framework to dynamic and multimodal urban networks (Balzer et al., 2023). As this line of research moves closer to practical transport applications, a key issue is no longer only whether permits can be allocated efficiently in theory, but how permit allocation performs under repeated daily travel decisions. This issue is particularly important when car use depends on a qualification threshold, because the realised effect of the policy then depends not only on credit reallocation in the market, but also on the travel conditions generated in the network after that reallocation takes place.

However, this interaction between market allocation and network performance remains insufficiently understood in the existing TCS literature. Recent review work points to persistent gaps in behavioural response, allocation frequency, and trading design (Albano et al., 2025). At the same time, theoretical studies have shown that the equilibrium of a tradable credit scheme may not be unique under some congestion settings (Bao et al., 2019), while recent market design studies still focus mainly on institutional settings such as allocation rules, expiration rules, transaction fees, and regulator intervention (Chen et al., 2023). As a result, several mechanisms that matter in daily operation remain weakly represented, including failure to reach the driving threshold despite active participation and temporary retention of credits to preserve the possibility of driving.

Recent progress in large language models creates a new opportunity for behavioural modelling in this setting. The main advantage is that travellers here do not face a single static choice, but a sequence of linked decisions involving daily planning, credit trading, and final mode choice. By introducing a language model as the decision policy of each traveller agent, the framework can incorporate socioeconomic attributes, current credit holdings, past outcomes, and realised travel conditions into one sequential behavioural process.
Accordingly, this study develops an integrated simulation framework for tradable credit schemes under threshold based car use eligibility, combining traveller agents with LLM based decision policies, repeated intraday credit trading, and MFD based network loading in a repeated daily setting. The framework addresses a key limitation of equilibrium based assessment: when car use requires the accumulation of a minimum credit bundle rather than payment of a smooth marginal charge, policy performance depends not only on aggregate credit supply, but also on whether credits are reallocated in time and recombined into usable driving eligibility. By linking daily planning, trading, mode choice, and congestion feedback, and by combining agent level outcome tracing with follow up interviews, the study identifies the behavioural mechanisms that strand credits below the driving threshold, explains option value holding, and reveals how these processes redistribute car access across traveller groups. The paper therefore provides a mechanism based account of how tradable credit schemes operate under repeated daily interaction and offers policy relevant insight into how threshold structure, trading behaviour, and market rules shape efficiency and the redistribution of car access.

2 Methodology

Integrated framework

We develop an integrated simulation framework for analysing tradable credit schemes under threshold based car use eligibility. The framework links three components: LLM based behavioural agents, a repeated intraday credit market, and a MFD-based network model. On each day, agents first form a daily plan, then participate in credit trading, and finally make a mode choice after trading. The resulting travel demand is loaded onto the network, and the realised market and travel outcomes are written back into agent memory to shape subsequent decisions. The framework therefore represents a repeated feedback process in which market allocation, traveller behaviour, and network performance evolve jointly over time.

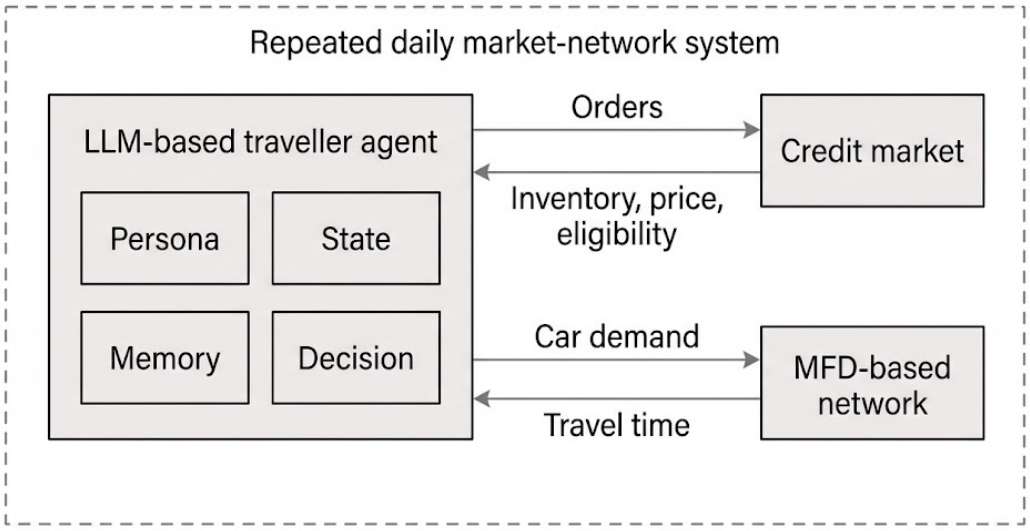


Figure 1: Integrated framework of the proposed model.

LLM based behavioural agent architecture

A large language model is used here as the behavioural decision policy of each agent. This is appropriate because the agent faces a sequence of constrained decisions rather than a single static choice, including daily planning, credit trading, and post-trading mode choice. The agent architecture therefore contains four modules: persona, state, memory, and decision.

Persona module. The persona module stores relatively stable socioeconomic and travel related attributes. Each simulated agent represents a weighted traveller cohort, and its persona is constructed by pairing a local trip template with socioeconomic attribute records sampled from the 2017 U.S. National Household Travel Survey (NHTS). The retained attributes are intentionally minimal and interpretable. Each agent is also associated with a feasible car alternative and a feasible public transport alternative on the local network.

Table 1: Persona attributes used for agent initialization.

Attribute	**Behavioural role**
Age	Basic socioeconomic heterogeneity
Sex	Basic socioeconomic heterogeneity
Employment status	Schedule rigidity and travel need
Household income	Credit affordability and willingness to pay
Household vehicle ownership	Car availability and option value
Observed primary travel mode	Behavioural prior for mode preference
Departure time category	Daily timing context

State module. The state module records the agent's current daily conditions. At decision stage s on day t, the state of agent i is written as

$$\mathbf{x}_{i,t}^{(s)} = \left(h_{i,t}^{(s)}, z_{i,t}^{(s)}, g_{i,t}^{(s)}\right), \tag{1}$$

where $h_{i,t}^{(s)}$ is the current credit inventory, $z_{i,t}^{(s)}$ is the qualification status, and $g_{i,t}^{(s)}$ is the current behavioural target. This module provides the current decision context for planning,

trading, and post trading mode choice.

Memory module. The memory module stores summarised past market and travel experience and provides the behavioural link across repeated days. Rather than storing full histories, the model maintains a compact memory state,

$$\mathbf{m}_{i,t} = \left(p^e_{i,t}, \sigma^e_{i,t}, \tau^{car,e}_{i,t}, \tau^{pt,e}_{i,t}, \phi^e_{i,t}, c^{top,e}_{i,t}, w^e_{i,t}, q^e_{i,t}\right), \tag{2}$$

where the variables are listed in Table 2.
For standard expectation variables, memory is updated after day t by

$$m^{(k)}_{i,t+1} = m^{(k)}_{i,t} + \alpha_t \left(\hat{m}^{(k)}_{i,t} - m^{(k)}_{i,t}\right), \qquad \alpha_t = \frac{1}{t}, \tag{3}$$

where $m^{(k)}_{i,t}$ is agent i's expectation for variable k on day t, and $\hat{m}^{(k)}_{i,t}$ is the realised day t observation. This rule is applied to p^e, σ^e, $\tau^{car,e}$, $\tau^{pt,e}$, ϕ^e, and $c^{top,e}$. For behaviourally persistent variables, we use

$$m^{(k)}_{i,t+1} = m^{(k)}_{i,t} + \beta_t \left(\hat{m}^{(k)}_{i,t} - m^{(k)}_{i,t}\right), \qquad \beta_t = \begin{cases} 1, & t \leq 1, \\ 0.35, & t > 1, \end{cases} \tag{4}$$

which is applied to w^e and q^e. The updated memory state is passed to the next day's planning, trading, and mode choice stages.

Table 2: Behavioural memory variables.

Symbol	Variable	Interpretation
p^e	Expected credit price	Reference for buy and sell valuation
σ^e	Price uncertainty	Dispersion of recent market outcomes
$\tau^{car,e}$	Expected car travel time	Anticipated car travel condition
$\tau^{pt,e}$	Expected PT travel time	Anticipated public transport travel condition
ϕ^e	Expected fill rate	Probability of successful order execution
$c^{top,e}$	Expected top up cost	Expected cost of acquiring missing credits
w^e	Expected wasted credits	Memory of unused credits after qualification
q^e	Expected shortage rate	Memory of failing to reach the threshold

Decision module. The decision module maps persona, state, and memory into stage specific actions. At decision stage $s \in \{\text{plan}, \text{trade}, \text{mode}\}$ on day t, agent i selects an action according to

$$a^{(s)}_{i,t} = \pi_\theta\left(\mathbf{p}_i, \mathbf{x}^{(s)}_{i,t}, \mathbf{m}^{(s)}_{i,t}, \mathcal{A}^{(s)}_{i,t}, \mathcal{R}^{(s)}\right), \tag{5}$$

where $\mathbf{p}_i$ is the persona vector, $\mathbf{x}^{(s)}_{i,t}$ is the current state, $\mathbf{m}^{(s)}_{i,t}$ is the memory state, $\mathcal{A}^{(s)}_{i,t}$ is the feasible action set, and $\mathcal{R}^{(s)}$ denotes the rules and eligibility constraints of stage s. In the planning stage, the module generates the daily target, target inventory, maximum willingness to pay, and reservation price for selling. In the trading stage, it selects an action together with the associated quantity and price. In the mode choice stage, it selects between car and public transport conditional on the post trading inventory and the applicable eligibility rule.

Credit market design

The credit market operates on a repeated daily basis. In the baseline setting, each agent receives 5 credits per day, while 8 credits are required for car use eligibility. Each day

contains ten market rounds, including three discovery rounds, five live trading rounds, and two closing rounds. Agents submit buy or sell orders according to their current inventory, expected benefit from driving, and memory state. This staged structure allows price discovery and behavioural adjustment within the day, rather than imposing one shot market clearing.

The behavioural market model is coupled to an MFD-based network model calibrated from the MATSim Sioux Falls scenario. Aggregate car demand determines network accumulation, and the calibrated macroscopic fundamental diagram (MFD) maps the network state to mean speed. Let n_t denote network accumulation in period t, and let $v_t = \mathcal{V}(n_t)$ denote the corresponding mean speed. For an agent with car trip distance d_i, realised car travel time is computed as

$$\tau_{i,t}^{car} = \frac{d_i}{v_t}. \tag{6}$$

The no-credit case is used as the behavioural–network reference for subsequent policy experiments.

Under the credit policy, market outcomes and network outcomes are linked through a daily feedback loop. On each day, agents first form a plan, then trade credits, and finally make a mode choice conditional on their post-trading inventory. Agents below the threshold are not eligible to drive and are assigned to public transport, whereas agents meeting the threshold may choose between car and public transport. Aggregate car demand generated by these choices is then loaded onto the calibrated MFD network to obtain realised car travel times. Realised travel and market outcomes are subsequently written back into agent memory and become inputs to the next day's planning and trading decisions.

The main experiments use 1,000 LLM agents, each representing a weighted traveller cohort with a weight of 80, over repeated daily interactions. In the baseline credit specification, each agent receives 5 credits per day and must hold 8 credits to be eligible for car use. This implies a theoretical upper bound of $5/8 = 0.625$ on car use under perfect reallocation. The main outcome measures are car share, public transport share, credit prices, traded volume, threshold failures, wasted credits, and realised travel times.

3 Results and discussion

Aggregate market and mobility dynamics

Figure 2 shows the aggregate dynamics of the 5/8 credit regime over 10 days. Panel (a) shows that car share stabilises below both the theoretical upper bound of $5/8 = 0.625$ and the no-credit baseline, but converges to a narrow steady range rather than continuing to drift across days. Panel (b) shows that the credit market also converges: both the closing price and the average executed price settle into a stable band, while traded volume remains substantial throughout the convergence process. Taken together, these results indicate that the system reaches a persistent operating state in which both market allocation and aggregate car use stabilise over repeated daily interaction.

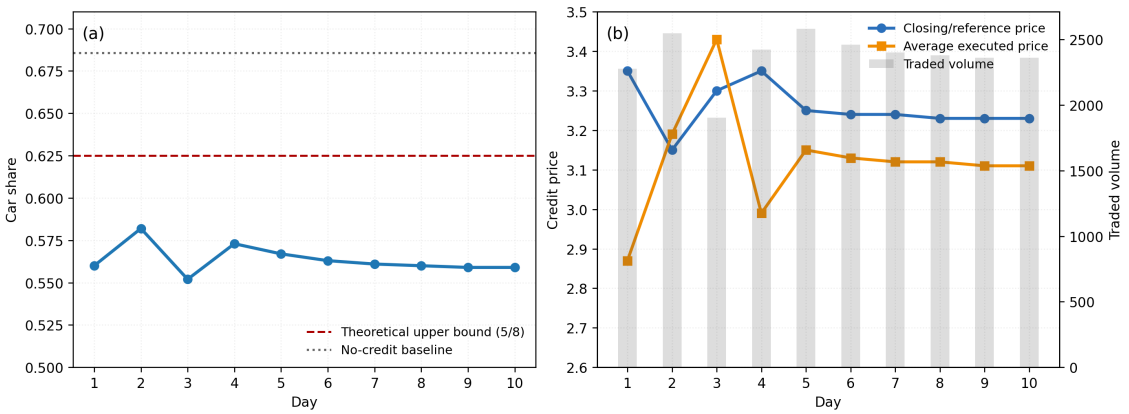


Figure 2: Aggregate results over 10 days under the 5/8 tradable-credit regime: (a) car-share trajectory and (b) credit-price trajectory.

Redistribution relative to the no-credit baseline

Figure 3 shows that the credit regime reallocates car access rather than simply reducing it. Among baseline car users, 521 remain in car and 351 shift to public transport, so only 59.7% retain car access. Among baseline public transport users, 46 gain car access and 82 remain in public transport, implying a gain rate of 35.9%.

The redistribution is unequal. Among baseline car users, retention rises from 53.0% in the below-50k group to 71.2% in the above-100k group, and from 46.4% for trips below 2 km to 84.6% for trips above 10 km. Among baseline public transport users, gains in car access are much less common for zero-vehicle households than for households with vehicle access. The policy therefore disadvantages lower-income and shorter-distance baseline drivers, while favouring travellers with stronger mobility resources.

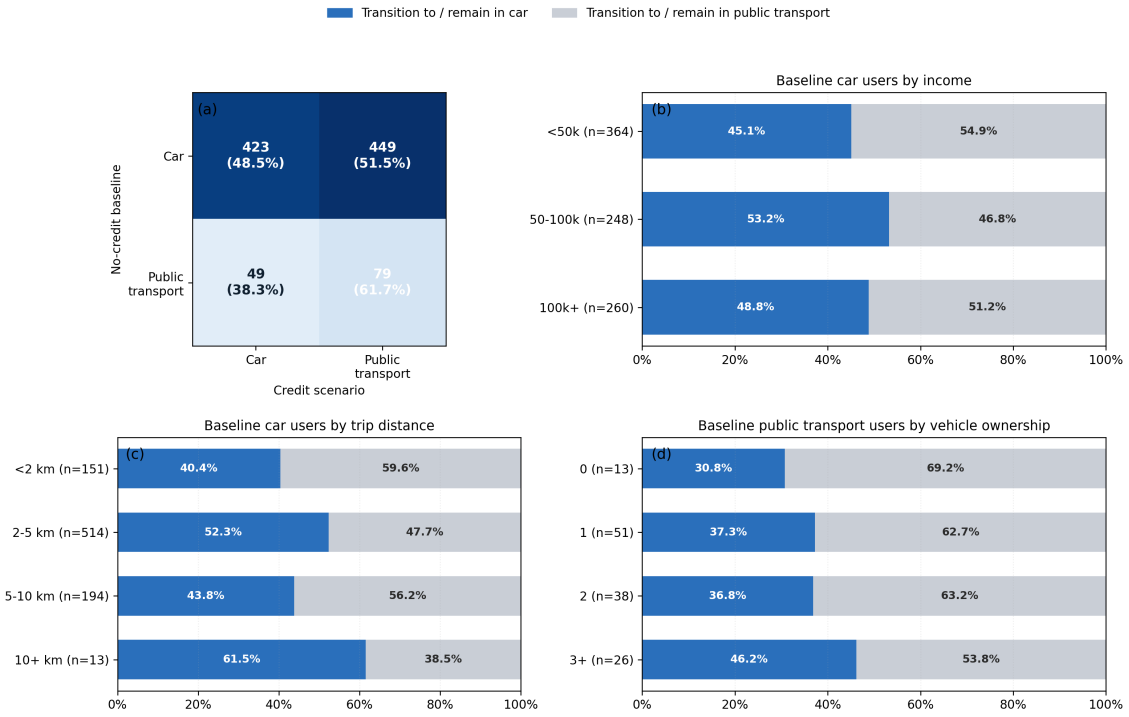


Figure 3: Redistribution relative to the no-credit baseline, shown as transition counts and conditional transition rates for selected traveller groups.

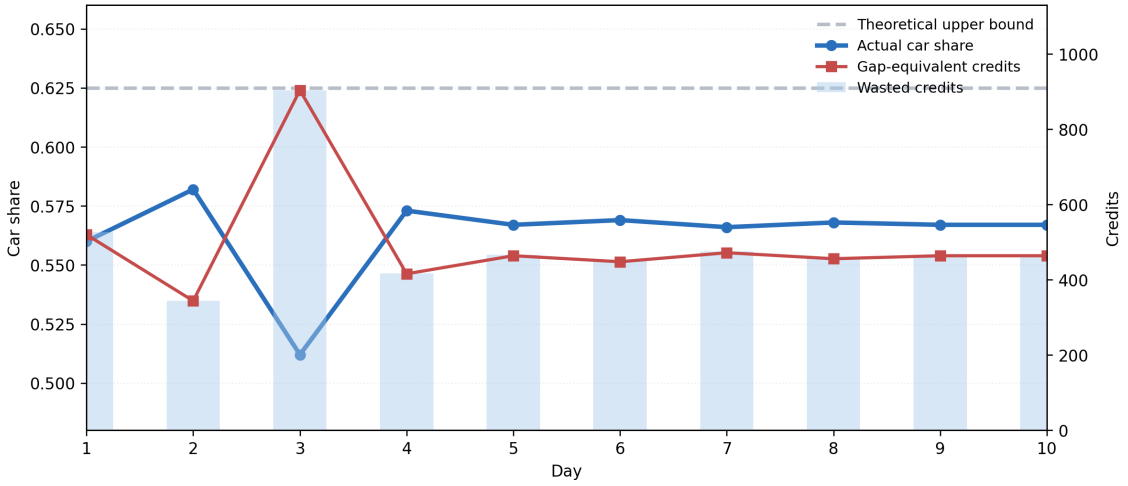


Figure 4: Ten-day dynamics of threshold inefficiency under the 5/8 tradable-credit regime.

Figure 4 shows that realised car use remains persistently below the theoretical upper bound of $5/8 = 0.625$, and that this shortfall closely tracks wasted credits over time. This suggests that the main inefficiency does not stem from insufficient aggregate credit supply. Instead, available credits are not fully recombined into usable driving eligibility, and the remaining gap is largely driven by credits stranded below the qualification threshold.

To explain this pattern, travellers are classified by allocation outcome and trading pattern rather than by end-of-day inventory alone. Table 3 shows that most travellers fall into efficient groups, namely qualified drivers and clean sellers. The remaining inefficiency is concentrated in a smaller group of unresolved traders, especially buy-sell oscillators, who both buy and sell within the day but still end below the threshold and use public transport. Follow-up interviews suggest that this pattern is mainly driven by three behavioural responses. First, some agents retain credits for option value, delaying sale because preserving the possibility of driving is itself valuable even when actual driving becomes unlikely. Second, some agents continue to chase the threshold by attempting to acquire the remaining credits late in the day despite a low probability of successful completion. Third, some agents remain inactive near the threshold, waiting for more favourable market conditions rather than resolving their position early. In each case, credits are not released in time to be recombined into usable driving eligibility for other travellers. The residual gap is therefore not simply a matter of price, but a behavioural failure of timely inventory resolution near the threshold.

The policy implication is straightforward. Improving scheme performance is not only a matter of adjusting total credit supply or the qualification threshold. It also requires market rules and information signals that encourage earlier selling, reduce prolonged near-threshold waiting, and make likely non-attainment more visible within the day.

Table 3: Traveller groups, population share, and dominant behavioural mechanisms.

Group	**Travellers**	**Share**	**Dominant behavioural mechanism**
Qualified drivers	472	47.2%	Successful threshold attainment and timely inventory resolution
Clean sellers	280	28.0%	Early release of unused credits and a clear non-driving strategy
Under-bought only	8	0.8%	Optimistic threshold chasing
Incomplete sellers only	34	3.4%	Option-value holding and late-seller inertia
Buy-sell oscillators	206	20.6%	Option-value holding, passive waiting, and optimistic threshold chasing

4 Conclusions

This paper develops an integrated simulation framework for tradable credit schemes under threshold based car use eligibility. The framework combines traveller agents with LLM based decision policies, repeated intraday credit trading, and MFD based network loading in a repeated daily setting. Rather than evaluating permit allocation in isolation, it is designed to capture how daily planning, credit trading, mode choice, and congestion feedback jointly determine realised car use when driving requires the accumulation of a minimum credit bundle.

The analysis yields three main findings. First, the 5/8 credit regime converges to a stable operating state in both market outcomes and aggregate car use, but realised car use remains persistently below the theoretical upper bound implied by perfect reallocation. Second, this gap is not mainly caused by insufficient aggregate credit supply, but by threshold inefficiency: available credits are not fully recombined into usable driving eligibility. Third, by combining agent level outcome tracing with follow up interviews, the study shows that this inefficiency is sustained by identifiable behavioural mechanisms, including option value holding, optimistic threshold chasing, and delayed inventory resolution near the threshold. The results also show that the policy redistributes car access unevenly across traveller groups, with lower income and shorter distance baseline drivers more likely to lose car access than travellers with stronger mobility resources.

The paper contributes a mechanism based framework for analysing tradable credit schemes under repeated daily interaction. It shows how market reallocation, network performance, and traveller adaptation jointly determine realised car use under threshold based eligibility. The framework also provides a basis for future evaluation of policy design alternatives by showing how threshold structure, market rules, and behavioural responses jointly shape efficiency and the redistribution of car access across traveller groups.

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