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Dynamic Road Pricing in Kyiv

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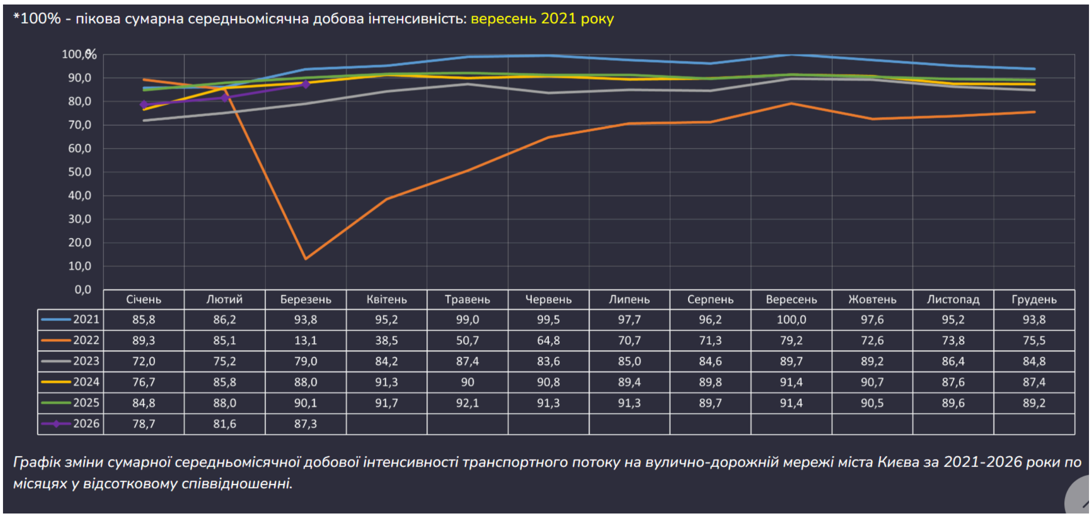
Abstract

Urban road congestion imposes deadweight losses by driving a wedge between private and social travel costs. This thesis evaluates the net welfare effects of Dynamic Road Pricing (DRP) in Kyiv under second-best conditions — imperfect transit substitutes, inelastic bus supply, and strict land-use and building regulation — using a quantitative spatial model calibrated to Kyiv's urban structure. A 24-scenario full-factorial experiment across DRP, bus fleet architecture, zoning regime, and transit quality reveals that DRP is welfare-improving in all configurations, but its magnitude depends critically on complementary reforms. Against the Kyiv status-quo baseline, isolated DRP yields +5.6 pp; the full-reform package reaches 207.1% of baseline (+35.2 pp from DRP alone). Land-use liberalisation is the dominant intervention, outperforming isolated DRP eightfold. DRP and zoning deregulation are super-additively complementary, while bus quality investment under a fixed fleet cap perversely reduces welfare through an overcrowding paradox.These findings imply that the standard partial-equilibrium appraisals that abstract from these complementarities thus systematically misrepresent the true welfare frontier available to urban transport reform.

Keywords: Dynamic Road Pricing, congestion pricing, quantitative spatial model, second-best theory, land-use regulation, Kyiv
Word count: 19421

Introduction

Over the last two decades, Kyiv has experienced a rapid increase in motorization rates. While in the early 2000s, owning a private car was considered a status symbol, by 2022, the number of registered motor vehicles in the capital exceeded 1.3 million units. According to TomTom Traffic Index analytical reports, Kyiv has consistently ranked among the world's leading cities in terms of travel delays; in 2021, Kyiv took 3rd place globally in the congestion rankings with an average delay level of 56%, and during peak periods (weekdays between 8:00–10:00 and 17:00–19:00), when most commuting to work or from work occurs, the delay ranged between 75–110%. This results in massive socio-economic costs. The full-scale invasion and internal migration have altered mobility patterns, yet the fundamental problem of road space scarcity remains acute. Even though traffic flow intensity has decreased compared to the "bronze" year of 2021, by 2025, the average monthly difference compared to 2021 was a mere 5.025%.



	Січень	Лютий	Березень	Квітень	Травень	Червень	Липень	Серпень	Вересень	Жовтень	Листопад	Грудень
2021	85,8	86,2	93,8	95,2	99,0	99,5	97,7	96,2	100,0	97,6	95,2	93,8
2022	89,3	85,1	13,1	38,5	50,7	64,8	70,7	71,3	79,2	72,6	73,8	75,5
2023	72,0	75,2	79,0	84,2	87,4	83,6	85,0	84,6	89,7	89,2	86,4	84,8
2024	76,7	85,8	88,0	91,3	90	90,8	89,4	89,8	91,4	90,7	87,6	87,4
2025	84,8	88,0	90,1	91,7	92,1	91,3	91,3	89,7	91,4	90,5	89,6	89,2
2026	78,7	81,6	87,3									

Fig. 1. Changes in the total monthly average daily traffic intensity on the road network of Kyiv (2021–2026) in percentage terms.
Source: Kyiv Traffic Management Center (2026)

As cars become more accessible to Kyiv residents—either through rising incomes or a decrease in vehicle acquisition costs—vehicle ownership will increase under current conditions, which will translate into even greater overall vehicle usage and heightened congestion. This constitutes a significant risk to Kyiv's mobility.

An additional critical factor is the dynamics of the European second-hand vehicle market. The tightening of emission standards in the EU is leading to the rapid depreciation of older vehicles in Europe. Consequently, a massive influx of low-cost transport into Ukraine is expected. For large cities like Kyiv, this poses a threat of transport collapse. At the same time, direct administrative prohibitions on vehicle imports are a socially unjust and economically inefficient instrument. In rural areas or remote districts where public transport is poorly developed and congestion is non-existent, an affordable car is a critically important means of mobility. Thus, instead of nationwide restrictions, cities require flexible localized management instruments that allow for the regulation of vehicle numbers precisely where they generate problems.

Limitations of the Traditional Approach The Kyiv municipal authorities rely predominantly on supply-side policies: operational flow management via Intelligent Transport Systems (ITS), public transport subsidies, expansion of the road network, and the construction of new interchanges and bridges. However, such measures have proven ineffective in combating congestion due to the laws of transport economics.

Regarding road network expansion and operational flow management via ITS, numerous studies have demonstrated the impossibility of overcoming congestion solely through methods that increase the supply of space for cars, due to the "induced demand" phenomenon (Duranton & Turner, 2011; Small & Verhoef, 2007) . American researcher Anthony Downs (2004) explains this process in detail through the principle of "triple convergence." The essence of this principle is that as soon as an intelligently regulated or expanded road becomes less congested during peak hours, traffic begins to shift onto it due to three factors:

1. Spatial convergence — drivers who previously used parallel bypass routes return to the main road;
2. Time convergence — drivers who previously departed earlier or later to avoid peak loads begin to travel at their most preferred time;
3. Modal convergence — passengers who previously used public transport switch to private automobiles because the trip has become faster. As a result, the new capacity is very quickly exhausted, congestion returns to previous levels, and the society's colossal capital investments (e.g., in new bridges or interchanges) yield only a temporary effect in the struggle against congestion.

Another key direction of the traditional approach is the subsidization of public transport. Financing the operating losses of municipal carriers to maintain service levels and low tariffs is a hybrid instrument. On one hand, it ensures the supply of services (supply-side), but from the perspective of congestion management, it acts as a demand management policy. The city attempts to divert a portion of demand from the roadways by creating a price and time advantage for public transport through subsidies. However, this approach is fiscally burdensome and significantly less efficient than the direct pricing of a scarce resource (the road).

A further instrument actively employed by Kyiv today is the physical reallocation of road space—the implementation of dedicated lanes for transit vehicles and the development of a trunk cycle network (e.g., the "Vynohradar-Centre" and "Teremky-Centre" routes budgeted (Київська міська державна адміністрація. 2026)). This measure also possesses a distinct hybrid nature: on one hand, it alters the spatial structure of supply (supply-side) by administratively withdrawing scarce traffic lanes from motorists, and on the other, it acts as an indirect demand-side instrument, stimulating a modal shift in favor of sustainable transport modes. Despite the undeniable benefits for alternative mobility, from the standpoint of transport economics, such an administrative approach remains a "second-best" policy and is not the optimal way to overcome congestion. As urban economics researchers note, the rigid administrative allocation of area to a specific transport mode creates inflexibility and inefficiency in conditions where real-time demand fluctuates constantly throughout the day(Small & Verhoef, 2007) . Furthermore, narrowing the carriageway for private cars without the simultaneous introduction of pricing mechanisms leads to an even higher concentration of vehicles in the remaining lanes, thereby locally degrading speed and environmental indicators. Moreover, any freeing of general road space thanks to those who switched to bicycles or rapid transit is inevitably negated by the aforementioned triple convergence effect: new motorists from other routes or times of day immediately occupy the vacated space. Thus, administrative measures without price regulation are incapable of independently preventing the system from returning to a state of hyper-congestion.

Transition to Demand Management Despite the imperfections of the current system, paid parking has become Kyiv’s first step toward pure demand-side policies in the transport sector. However, no Ukrainian city has yet experimented with pricing mechanisms for congestion management or with transport pricing linked to demand. Yet, the introduction of such pricing mechanisms is the "first-best" way to rid cities of congestion and all its associated negative consequences.

For this reason, the objective of this work is a comprehensive analysis of the potential consequences of implementing a Dynamic Road Pricing system in Kyiv. Forecasting the response of the urban system to such a regulatory shock will allow not only for an assessment of the feasibility of the reform and its impacts but also for the definition of strategic guidelines for the capital’s transition to a model of sustainable and efficient management of the scarce road infrastructure resource.

Against this backdrop, the thesis is structured around one overarching research question and three subsidiary questions. The central research question asks: what is the net welfare effect of introducing Dynamic Road Pricing in Kyiv, given the city's particular configuration of second-best distortions across transport, housing, and labour markets? Three subsidiary questions specify the analytical scope. First, does Dynamic Road Pricing generate positive welfare effects across all configurations of institutional constraints examined, or do sufficiently severe distortions in complementary markets reverse its welfare sign — and if consistently positive, how sensitive is the magnitude of the gain to the institutional environment in which the policy operates? Second, which institutional constraint — inelastic land supply or bounded transit capacity — constitutes the primary bottleneck on DRP's welfare potential in Kyiv, and through what general-equilibrium mechanism does it suppress the spatial reallocation that road pricing would otherwise induce? Third, do DRP and land-use and building liberalisation exhibit super-additive complementarity such that their joint welfare effect exceeds the sum of their individual contributions, and does improvement in transit service quality follow standard welfare logic in a supply-constrained public transport system?

Chapter 1. Congestion Management: From Pigouvian Theory to Modern Demand Management Systems

1.1. Physical and Economic Mechanics of Urban Congestion: From Flow Dynamics to Market Failure

Physical and Spatial Mechanics of Road Congestion

The laws of transport economics and engineering analyze road traffic through the lens of driver behavior and the geometric constraints of infrastructure. A fundamental condition for safe movement is maintaining a distance between vehicles, which is necessary to compensate for human reaction time and braking distance in the event of a sudden stop by the vehicle ahead. In transport planning, this requirement is typically standardized as the safety time headway rule, which averages approximately two seconds.

Since this interval is measured in time, the physical area of the roadway (or lane length) required for the safe movement of a single vehicle is not a constant value. It is a function that increases sharply depending on the vehicle's speed. Alain Bertaud formalizes this relationship of the space consumed by each vehicle in moving traffic using the following equation:

$$A = \left(\frac{S \cdot R}{3.6} + L\right) W$$

where A is the road area consumed by one vehicle (m^2), S is the vehicle speed (km/h), R is the driver's reaction time (seconds), L is the vehicle length (meters), and W is the lane width (meters).

As evidenced by the formula, under low-speed conditions (S), the required spatial buffer zone is minimal and approaches the physical dimensions of the vehicle itself. Conversely, to achieve arterial speeds, the spatial buffer that a driver is forced to maintain ahead manifoldly exceeds the size of their car. Accordingly, at high speeds, a single moving vehicle "consumes" significantly more of the scarce road space. Empirically, however, deviations from the 2-second interval are common; drivers are particularly inclined to reduce this interval at higher speeds. In Kyiv, a case was recorded where the actual capacity on a specific section for the most heavily loaded lane reached 2,230 passenger car units (PCU) per hour during peak periods; the headway value was 1.61 s, the average distance between vehicles in the flow was 15.8 m, at a speed of approximately 35 km/h and a traffic density of 48 veh/km.

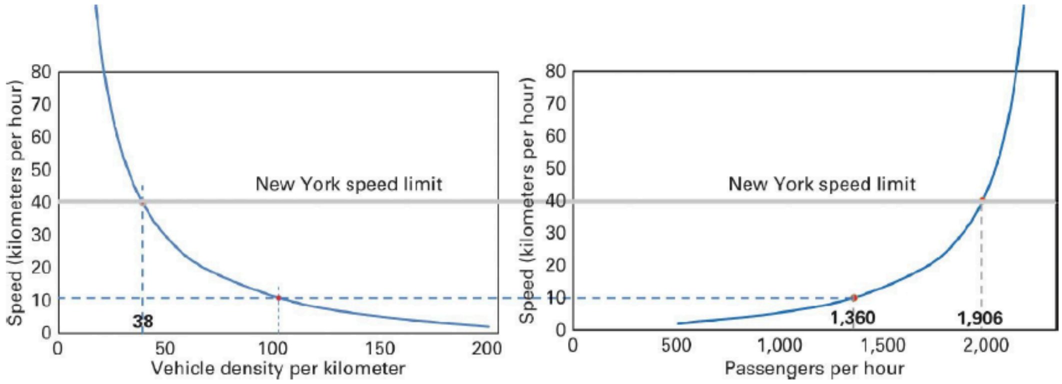
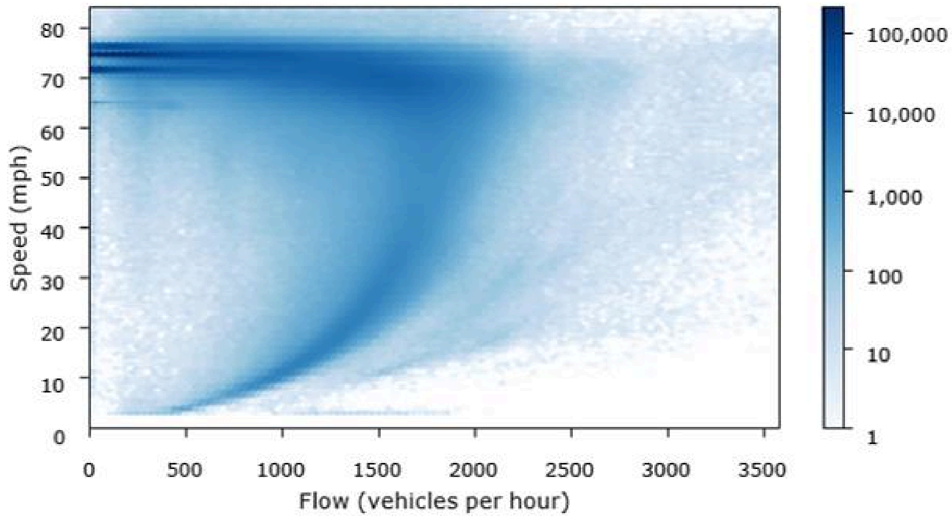


Fig. 2. Relationship between traffic speed, vehicle density, and passenger throughput under speed limit conditions.

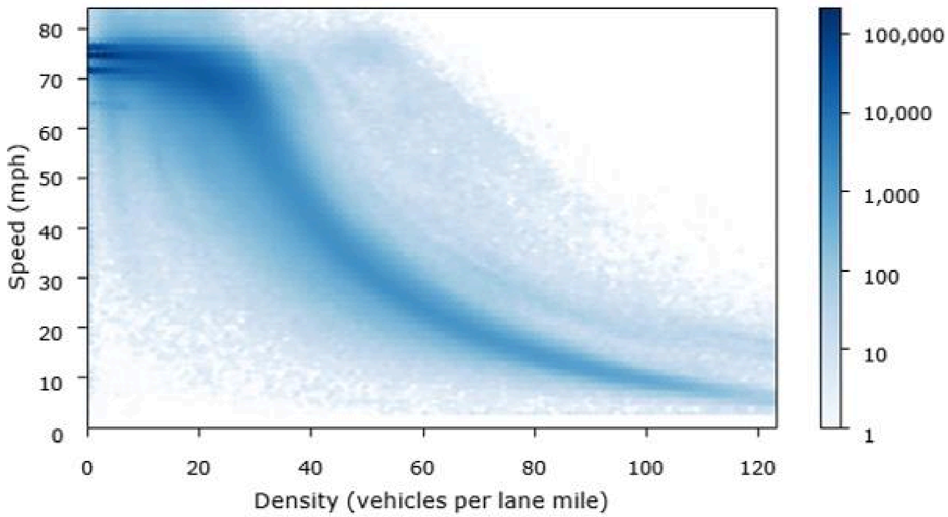
Source: Bertaud (2018, p.)

According to modern empirical research in transport economics, the relationship between density and speed is non-linear and characterized by a distinct structural break. In the initial stages of increasing the number of vehicles on the road, speed remains absolutely constant, staying in a free-flow state. Although the physical distance between cars decreases, the system is still capable of absorbing new traffic because the available space exceeds the minimum required for safe braking.

The process of congestion formation is triggered precisely at the moment when flow density exhausts its throughput capacity and crosses the critical threshold (the break point). When the free-flow regime ends, the transport system transitions into a state of congested flow. After passing this threshold, traffic density increases to such an extent that it becomes physically impossible to provide the spatial buffers necessary to maintain free-flow speed. With a further increase in density, the volume of free space per vehicle decreases rapidly and inevitably. Since drivers instinctively strive to maintain the mandatory safety time headway, their only possible way to adapt to such an extreme reduction in physical distance is a synchronous reduction in the speed of the entire traffic flow.



(a) Relationship between speed and flow



(b) Relationship between speed and density

Fig. 3. Empirical fundamental diagrams of traffic flow: (a) speed-flow relationship and (b) speed-density relationship.

Source: Bento, Hall, and Heilmann (2023).

Consequently, the immediate indicator of congestion is any speed lower than the free-flow speed. To quantify this drop in speed and the level of delays, transport economics utilizes the Travel Time Index (TTI). This metric is calculated as the ratio of the actual travel time during peak hours (in a congested state) to the base travel time under ideal free-flow conditions. The higher the TTI value, the greater the time loss due to the forced mechanical adaptation of drivers to the lack of space.

It should be noted that the consequence of such a synchronous reduction in speed is not only an increase in travel time but also a collapse in the efficiency of the infrastructure itself. According to the fundamental diagram of traffic flow, roadway capacity (traffic flow) is the product of speed and density. Until the point of maximum capacity is reached, an increase in density increases the total flow. However, when speed drops below this point, speed falls so sharply that the total number of vehicles able to pass through a section per hour begins to decrease. This phenomenon is known in transport economics as hypercongestion. In a state of hypercongestion, the road functions on the principles of: higher density—lower speed; lower speed—lower throughput capacity, despite the higher density.

In the city of Kyiv, a speed limit of 50 km/h is in effect (actual 70 km/h). The point of maximum capacity varies across different sections of the Kyiv road network; however, based on empirical data from other cities, I will assume that on major routes, it lies within the range of 50–70 km/h. This implies that in most cases in Kyiv, the transition from a free-flow state leads very quickly to a state of hypercongestion. This is significant as it demonstrates that the level of delay in Kyiv, beyond greater time expenditures, directly and almost always results in lower infrastructure capacity and congestion.

Road Space as a Scarce Resource: The "Tragedy of the Commons" and the Economic Value of the Road

The fundamental problem of urban mobility lies in the erroneous perception of road space as a public good, whereas during peak hours, it effectively transforms into a common-pool resource with a high level of rivalry, requiring solutions to avoid overconsumption. A highway or an urban street has a fixed physical capacity, and as soon as traffic intensity reaches the critical limit, every additional vehicle begins to interfere with the movement of all other participants. At this moment, a state of scarcity arises, where the demand for road space exceeds the supply at zero price. In the absence of a market price signal, this scarce resource is allocated through a queueing mechanism, expressed in travel time losses—i.e., congestion. Satisfying this demand to an equilibrium level with supply in established urban conditions is often so costly that following demand with supply becomes unjustifiable. The economic scarcity of road space is exacerbated by the fact that most trips (commuting) are relatively rigidly tied to schedules.

The central concept of transport economics in this context is the divergence between private and social costs. Transport mobility is a derived demand; therefore, when deciding to enter a congested road, an individual driver considers only their Marginal Private Cost (MPC), which includes fuel costs, vehicle depreciation, and the valuation of their own travel time. However, they ignore the fact that their presence in the flow requires an increase in safety distance, forcing all other vehicles behind them to slow down slightly. In aggregate, these micro-slowdowns create massive time losses for the entire flow. These additional costs, imposed on society and not compensated by the user, form the Marginal External Congestion Cost (MECC).

Equilibrium in a market of free roads is reached at the point where the demand curve intersects the average private cost curve, leading to overconsumption of the resource. From a welfare economics perspective, this creates a deadweight loss—the volume of social wealth that simply evaporates because people spend time in traffic instead of engaging in productive activity or leisure.

To mathematically justify and formalize this phenomenon, it is necessary to consider the total cost function of the transport system. The total cost of moving all users along a certain road section is defined as the product of the number of vehicles (Q) and the average trip cost for one user ($C(Q)$), where this average cost includes both monetary expenditures and monetized travel time. The Marginal Social Cost (MSC), the real economic price of adding one (marginal) vehicle to the flow, is calculated as the derivative of the total cost function with respect to traffic volume:

$$MSC = \frac{d(C(Q) \cdot Q)}{dQ} = C(Q) + Q\frac{dC}{dQ}$$

In this fundamental formula, the first term $C(Q)$ represents the Marginal Private Cost (MPC), which is the cost in time and money borne and felt by the additional driver themselves. The second term ($Q\frac{dC}{dQ}$) mathematically describes the magnitude of the Marginal External Congestion Cost (MECC). The component $\frac{dC}{dQ}$ shows the microscopic additional delay (increase in cost) caused by the entry of one new vehicle onto the road. Since this micro-delay is imposed on the entire quantity of vehicles Q already in the flow, the total social cost of this delay reaches macroeconomic proportions. The failure of the driver to account for the $Q\frac{dC}{dQ}$ component (in the absence of price regulation) creates a systemic gap between the private and social price of the trip, generating structural scarcity and congestion.

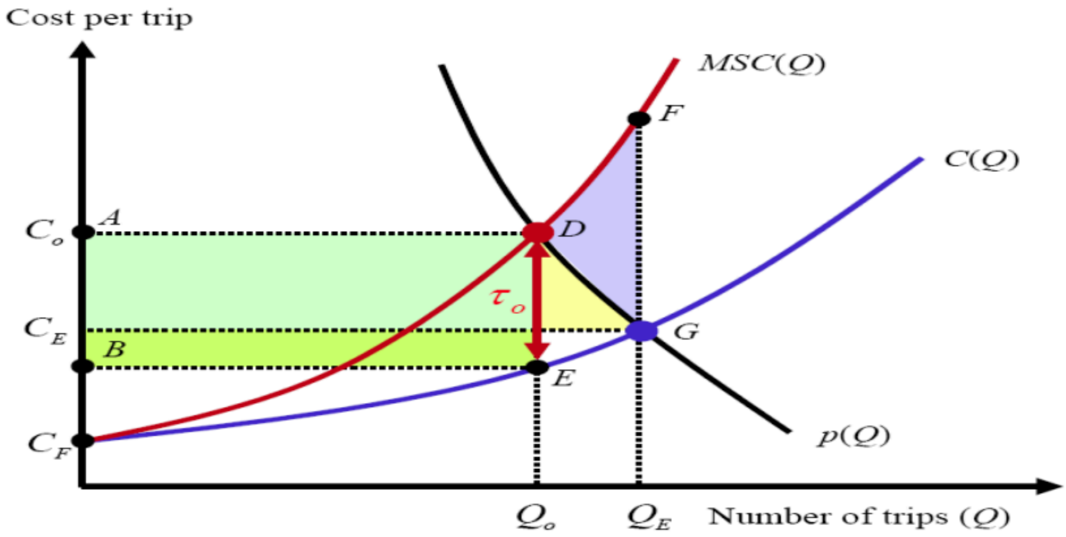


Figure 4. Welfare economic effects of road pricing: Market equilibrium (G) vs. socially optimal traffic volume (D).
Source: Song (2012).

In classical (static) transport network economic theory, the optimal traffic level is achieved by introducing a corrective Pigouvian tax equal to the marginal external congestion costs ($Q\frac{dC}{dQ}$), forcing users to internalize the damage they cause. However, in real urban conditions, applying a single (static) Pigouvian tax proves sub-optimal due to aggregate demand uncertainty and the regulator's inability to *a priori* know the distribution of the Value of Time (VOT) among a finite number of drivers. A static tax in such conditions can lead either to excessive congestion or to the artificial underutilization of infrastructure.

To address the bottleneck problem, a dynamic pricing model based on the works of William Vickrey (1969) is applied. According to this model, the instrument providing the highest traffic efficiency is Dynamic Road Pricing (DRP), which acts as an adaptive market-clearing mechanism (akin to the Vickrey-Clarke-Groves mechanism)(Heller et al., 2019) . Since the magnitude of delay changes actively depending on the network load level, the dynamic tariff overcomes information asymmetry: it adjusts to reality in real-time, forcing drivers to "reveal" their true willingness to pay and eliminating the need to know the VOT distribution in advance.

While in reality, an absolutely "ideal" solution—requiring price differentiation for every single user with millisecond precision—is technically unattainable, the dynamic fee is set at a level that most closely and effectively balances demand with the available road capacity, preventatively precluding the formation of a queue. This market-clearing tariff mathematically replicates the delay cost structure that would have formed on this section in its absence. Thus, market-clearing replaces the destructive deadweight loss of time (which is pure waste and benefits no one) with a financial payment to the budget, successfully internalizing the shadow price of the scarce space.

Distortions Through Unpriced Roads: A System of Inverted Incentives and Efficiency Degradation

The absence of a pricing mechanism on roads creates a system of distorted incentives, where individual driver utility directly conflicts with the collective efficiency of urban mobility. Since the price for the use of scarce road space for all vehicles is zero, the market receives no signal regarding the efficiency of every square meter of asphalt used. This leads to a situation devoid of any incentives to internalize one's Marginal External Congestion Cost (MECC) or to utilize space more efficiently through strategies such as: *time shifting, modal shift, carpooling, trip chaining, rerouting, and trip cancellation*, etc. This lack of price differentiation essentially constitutes a subsidy for the most spatially inefficient modes of travel at the expense of those who use the resource sparingly. Currently, the only incentive for spatially efficient travel is the Marginal Private Cost (MPC); it is the high MPC of the automotive mode that forces many in Kyiv to use road space more efficiently, albeit as a side effect. However, there is a likelihood that this incentive will weaken if the MPC of spatially inefficient transport falls due to rising purchasing power, cheap fuel, low vehicle costs, etc. The consequence of this would be an intensification of the congestion problem.

The most critical issue is that users of non-segregated public transport (as physical segregation cannot be implemented everywhere) bear disproportionately high losses from the state of congestion relative to their minimal contribution to its creation. On unpriced roads, a bus capable of carrying 50–80 passengers is forced to stand in a collective "queue" (congestion) caused by the deficit of space created by private automobiles, which carry an average of only 1.2 persons. As Alain Bertaud notes, congestion is not merely a queue; it is the physical manifestation of the lack of incentives for the rational use of the city's highly valuable real estate.

Furthermore, the inability to set a price on road space results in low-value trips (e.g., driving for coffee during peak hours) having the same priority as high-value ones (missing a train, an important meeting, or a surgeon traveling for an operation), which is absurd from a scarce asset management perspective (Bertaud, 2018). Thus, a congestion charge acts not as a penalty for drivers, but as a market-clearing mechanism that guarantees travel reliability for those who value their time the most (Sorensen & Taylor, 2006).

Consequences of Congestion

Direct User Costs Direct User Costs are the immediate resource losses incurred by road users due to congestion. They arise from the deviation of actual traffic conditions from the ideal state of free flow. These costs are the most measurable component of the deadweight loss within the transport system and consist of the following key elements:

- Travel Time Loss: Calculated as the difference between travel time in congestion and under free-flow conditions. Monetary valuation is based on the Value of Time (VOT) — the monetization of lost minutes through the hourly wage rate. Congestion effectively extracts human capital from productive activity or leisure.
- Excessive Operational Costs: Determined by the non-steady state of movement and low flow speeds. Beyond acceleration-deceleration cycles, prolonged duration on a route due to congestion generates excess fuel consumption per unit of distance (specific consumption), which would be lower at a stable, optimal speed. This also accelerates vehicle depreciation, increasing the trip's unit cost.

Impact on Logistics Congestion acts as a hidden tax on logistical activity, directly affecting supply chains. Reduced speeds for goods movement increase business operating costs, which, on a national scale, leads to decreased national productivity. A distinct and often underestimated component is Reliability Costs. The unpredictability of the traffic situation forces economic agents to add "buffer time" to their plans. This means that a driver or a logistics company plans a departure significantly earlier than required on average to guarantee timely arrival in case of extreme congestion. Consequently, a vast array of person-hours is withdrawn from productive activity or leisure even on days when actual congestion does not occur. This "reserved but unused" time represents a pure loss of social welfare.

Psychological and Social Consequences The inability to travel at normal speeds causes stress and frustration. Aggression accumulated in traffic does not dissipate after the trip ends; it converts into an increase in interpersonal conflicts at workplaces and within families.

Policy Distortions Under public pressure to "do something about congestion," municipalities direct colossal resources into building interchanges and expanding lanes. In a world dominated by induced demand, such investments are socially sub-optimal, as they only temporarily mask the deficit without addressing its root cause. Capital expenditures on asphalt often "burn" budget funds that could have been invested in other sectors with a much higher social rate of return.

Spatial Distortions and Urban Sprawl Firms and workers attempt to escape congestion by relocating jobs and housing to the periphery. This stimulates Urban Sprawl, which, in turn, only increases average trip distances and creates a new wave of demand for road space (closing the "vicious cycle").

Congestion as a Barrier to Urban Productivity From the perspective of market urbanism, the primary function of a city is to operate as a single, efficient labor market where workers and employers can find each other with minimal "friction" (Bertaud, 2018). When road space, as a scarce resource, is allocated inefficiently, congestion creates a physical barrier to economic opportunities. Congestion effectively "shrinks" the city: if, due to low travel speeds, a resident can reach only a limited number of jobs within an acceptable time (typically 60 minutes), the effective size of the labor market for them is reduced (Tsivanidis, 2023). Unpriced, yet chronically congested roads sever critical agglomeration links:

- Businesses lose access to a wider talent pool, being forced to limit themselves to workers from nearby areas.
- Workers are deprived of the opportunity to find jobs that best match their qualifications, leading to wage stagnation.

As Allen and Arkolakis note, in spatial equilibrium models, congestion acts as a specific "tax on trade and mobility" that reduces the overall efficiency of the urban economy.(Allen & Arkolakis, 2022) Edward Glaeser emphasizes that congestion is not merely an inconvenience, but an existential threat to the city: it turns the primary advantage of a metropolis (proximity) into its primary disadvantage (gridlock).(Glaeser, 2011)

1.2. Dynamic Road Pricing (DRP) as a "First-Best" Option: Comparison with Excises, Duties, and Other Congestion Mitigation Methods ("Second-Best").

In welfare economic theory, a "first-best" solution is defined as one that directly eliminates the cause of a negative externality. Dynamic Road Pricing (DRP), as an adaptive market-clearing mechanism that equates the tariff to individual Marginal External Congestion Costs (MECC) in real-time, represents the best possible solution for addressing these negative externalities. It operates akin to an auction mechanism, compelling drivers to reveal their true willingness to pay and preemptively eliminates dysfunctional queues (hypercongestion) by maintaining flow at maximum throughput capacity. All other transport policy instruments are classified as "second-best," as they attempt to influence congestion indirectly through related markets or administrative restrictions, which inevitably leads to additional economic distortions.

Implementation Barriers: Why the "First-Best" Model Was Not Applied in Practice

Despite the indisputable theoretical consensus among economists regarding the efficiency of marginal cost pricing (as emphasized by William Vickrey as early as the 1960s), the practical implementation of DRP remained an insurmountable challenge for decades. This paradox is explained by two fundamental barriers:

1. Technological Constraints: DRP was not considered a viable option because it was believed that, under legacy technological conditions, the transaction costs would be excessive, rendering implementation pointless—particularly when calculating and collecting dynamic fees based on differentiation by time, location, vehicle type, and network load level. However, current advancements in information and communication technologies, Global Navigation Satellite Systems (GNSS), electronic license plate recognition, and smartphones have reduced these transaction costs to a level where DRP implementation has become highly feasible.
2. Political Economy and Public Acceptability Barriers: Road pricing is often characterized as an "economist's dream that is a politician's nightmare." The practical implementation of this policy is hindered by several factors of public resistance. A key factor is status quo bias: society reacts painfully to the monetization of a resource that has historically been perceived as a free public good. Additional critical hurdles include concerns regarding deepening social inequality, privacy risks, and systemic distrust of government authorities. The latter manifests in citizens' reluctance to bear an additional tax burden, especially when they anticipate that funds will be poorly allocated.

Fiscal Instruments: Ownership Taxes and Excises

Traditional fiscal measures, such as import duties, registration fees, and annual vehicle ownership taxes, aim to limit fleet size, yet they are highly inefficient for managing road usage (Bertaud, 2018). The primary drawback of such charges is that they are sunk costs: once the tax is paid upon vehicle purchase, each subsequent trip costs the driver only the price of fuel, creating no incentive to forgo a trip during peak hours (Glaeser, 2011). Furthermore, ownership taxes are spatially undifferentiated, equally disincentivizing vehicle ownership in the congested center of Kyiv as in rural areas where the automobile is the only viable means of mobility (Small & Verhoef, 2007).

Fuel excises are often viewed as a more progressive tool because they correlate with mileage, yet they also do not constitute a "first-best" solution for combating congestion (Vickrey, 1969). Excises are effective for internalizing externalities related to CO_2 emissions, as emission damage is independent of travel location and time (Parry, 2009). However, a liter of fuel burned at 3:00 AM on an empty highway is taxed the same as a liter burned in a bottleneck on a bridge during peak hours, even though the latter generates Marginal External Costs (MCC) dozens of times higher (Walters, 1961). Consequently, fuel taxes are incapable of ensuring the temporal redistribution of traffic, which is essential for eliminating congestion (Song, 2012).

Administrative Rationing and Access Restrictions

Road space rationing systems, such as entry restrictions based on license plate numbers (e.g., "even-odd" days in Bogotá or Mexico City), are examples of crude administrative intervention that often yield counterproductive results (Montero et al., 2025). Empirical research shows that, in the long term, such measures compel households to purchase a second car—often an older and more polluting model with a different plate number—which only exacerbates congestion and pollution (Glaeser, 2011). The main disadvantage of rationing is the lack of a mechanism to reveal trip value: the system prohibits entry for a driver for whom the trip is critically necessary while allowing entry for someone with a low value of time, generating significant social welfare losses (Bertaud, 2018).

Total license plate quotas (as in Singapore or Shanghai) are more efficient than direct bans because they utilize a market-based auction mechanism; however, they similarly focus on ownership rather than the utilization of a scarce resource (Phang & Toh, 2004). Without an accompanying DRP system, even a limited fleet will concentrate at network bottlenecks simultaneously, creating congestion (Keong, 2002).

The Role of Public Transport and Subsidies

Improving public transport (PT)—through dedicated lanes, network expansion, and increased comfort—is traditionally considered the most socially acceptable alternative to road tolls, yet on its own, it rarely solves the congestion problem (Downs, 2004). According to the "fundamental law of road congestion," any road space vacated by a driver switching to a new bus will be immediately occupied by another motorist due to induced demand

(Duranton & Turner, 2011). Subsidizing PT fares or introducing free travel is a "second-best" policy that attempts to compensate for the underpricing of car trips with an analogously underpriced transit fare (Proost, 2018).

However, without a road price signal (DRP), even the best public transport loses in the competition for time if it is forced to stand in collective congestion (Small & Verhoef, 2007). Moreover, excessive PT subsidization in the absence of motorist charges merely encourages general overconsumption of transport services rather than optimizing modal choice (cf. Singapore ERP, 2021). Only DRP creates conditions where PT gains a natural advantage in speed and reliability, allowing the market to independently determine the optimal share for each transport mode (Tsivanidis, 2023).

Conclusion: The Advantage of DRP as an Integrated Instrument

In conclusion, DRP is the sole instrument that ensures a "first-best" equilibrium, as it acts as a flexible regulator that clears the market of low-value trips precisely when the resource is most scarce (Sorensen & Taylor, 2006). Unlike static taxes or administrative bans, DRP restores a precise price signal to the urban system, enabling the internalization of all negative externalities—from time losses to environmental damage—without disrupting baseline population mobility during off-peak periods (Heller et al., 2019). Implementing dynamic pricing allows for the transformation of the "tragedy of the commons" into a managed asset, where revenues can be reinvested into developing alternatives, thereby creating a sustainable and efficient model of urban management (Small, 1992).

Chapter 2. The Second-Best Problem: Why DRP's Welfare Effects Are Ambiguous

2.1. Market Distortions and Unintended Consequences: The Theory of Second Best

The preceding chapter established Dynamic Road Pricing as a theoretically superior instrument for congestion management — a "first-best" mechanism that, by equating the tariff to the Marginal External Congestion Cost in real time, eliminates the deadweight loss inherent in unpriced road space. The elegance of this result, however, rests on a stringent assumption that is rarely satisfied in practice: that the road market is the *only* distortion in the economy, and that all other markets are functioning at their competitive optimum. Once this assumption is relaxed — once one acknowledges that urban economies are replete with fiscal distortions, regulated markets, agglomeration externalities, and asymmetric information — the welfare case for first-best road pricing becomes substantially more ambiguous. This section develops the theoretical framework that governs welfare outcomes when optimal policy is introduced into a distorted economic environment, drawing on the literature to show that the interaction between DRP and pre-existing market failures can attenuate, invert, or fundamentally reshape the policy's net welfare effects.

The General Theory of Second Best

The foundational insight for this analysis comes from Lipsey and Lancaster (1956), whose General Theory of Second Best demonstrates that, if one of the Pareto optimality conditions cannot be satisfied, it is no longer generally desirable — or even beneficial — to satisfy the remaining conditions. Formally, the theorem states that in an economy characterised by n optimality conditions, the second-best welfare optimum attainable when one condition is violated will not in general be achieved by satisfying any subset of the remaining $n - 1$ conditions. This result has profound implications for transport economics. As Small and Verhoef (2007) observe, the occurrence of second-best constraints is "the rule rather than the exception" in applied transportation pricing: in no real city does congestion constitute the sole market failure, and policy makers who design instruments as if it does risk achieving outcomes far inferior to what a properly calibrated second-best policy would deliver — or, in extreme cases, outcomes that reduce social welfare relative to the counterfactual of no intervention at all.

Applied to road pricing, the Lipsey-Lancaster theorem implies that even a perfectly calibrated first-best congestion charge — one set equal to the full Marginal External Congestion Cost on every link of the network — will not necessarily maximise welfare when the broader economy contains distortions in labour markets, land markets, transit markets, or elsewhere. The welfare effect of the toll is determined not by its relationship to the road-market externality alone, but by the entire configuration of wedges it perturbs across all markets simultaneously. Understanding these interactions is therefore a prerequisite for evaluating any real-world implementation of DRP.

Labour Market Distortions and the Revenue-Recycling Effect

Among the interactions between road pricing and other markets, the most extensively studied concerns the labour market. Income taxes and consumption taxes create a pre-existing wedge between the marginal social value of labour and the private return to work, reducing employment and output below their efficient levels. A congestion charge, by raising the generalised cost of commuting, further discourages labour supply: it lowers the real wage net of commuting costs and thereby aggravates the deadweight loss already imposed by the tax system (Small & Verhoef, 2007). Parry and Bento (2001) formalise this interaction in a general equilibrium model and obtain results that are striking in their magnitude and their sensitivity to the use of toll revenues. If revenues are returned to households as lump-sum transfers, road pricing can be welfare-*reducing* — the additional distortion to the labour market outweighs the efficiency gain in the road market — because higher non-wage income further discourages work. By contrast, if revenues are used to cut the distortionary labour income tax, welfare gains can be approximately twice the level predicted by a standard partial-equilibrium analysis that ignores this interaction. As Small and Verhoef (2007) summarise this result, "because the revenues are typically large compared to the value of the time savings, inefficient spending of those revenues can completely undo the net benefits of the policy."

Fosgerau and Van Dender (2010) extend this analysis to encompass a range of further complications. They demonstrate that the fiscal interaction between commuting tolls and labour taxes implies that, in a second-best setting, charges for commuting trips should generally be set *below* the marginal external congestion cost — because the toll compounds an already over-taxed activity — while the toll on non-work trips should exceed it. Differentiation of tolls by trip purpose (commuting versus leisure) would partially resolve the tension, but since trip purpose is generally unobservable at the tolling point, the practical scope for such differentiation is limited. The broader implication is that the labour market must be treated as an integral component of any welfare analysis of road pricing: the instrument cannot be evaluated in isolation from the fiscal architecture within which it operates.

Agglomeration Economies and the Productivity Feedback

Cities generate productivity gains through agglomeration: the physical proximity of workers and firms reduces matching frictions, facilitates knowledge spillovers, and enables finer labour market specialisation. These externalities represent a positive market failure — a benefit that accrues to the city as a whole but is not fully priced by any individual agent. Congestion, by raising the effective cost of spatial interaction, suppresses agglomeration and shrinks the accessible labour market for both workers and firms (Tsivanidis, 2023). This creates a second channel through which road pricing interacts with broader welfare. By relieving congestion, DRP should, *ceteris paribus*, restore agglomeration benefits; but if the toll also discourages commuting to the urban core — the dense, high-productivity centre where agglomeration effects are most concentrated — the net effect on agglomeration may be ambiguous. Fosgerau and Van Dender (2010) note that when workers contribute both to congestion and to agglomeration, the socially optimal congestion toll must be reduced by the value of the agglomeration externality generated by each additional commuter, unless a separate instrument is available to stimulate agglomeration directly.

This feedback between transport and productivity also illustrates a broader empirical regularity: transport policy interventions interact with the spatial equilibrium of the entire city, and partial-equilibrium welfare measurement systematically misses the mechanisms — both positive and negative — that operate through the broader urban economy. Tsivanidis (2023), analysing the construction of Bogotá's TransMilenio Bus Rapid Transit system, finds that the standard welfare measure based on the Value of Travel Time Saved accounts for only around half — approximately 54 per cent, though with substantial estimation uncertainty, of total welfare gains. Tsivanidis decomposes the remaining 46% into two sources: approximately one third reflects the large size of the shock — the first-order VTTS approximation performs poorly when the infrastructure change is non-marginal — while the remaining two thirds stem from amenity and productivity externalities that the standard approach ignores entirely . Although this finding pertains to a transit improvement rather than a pricing reform, the mechanism is directly generalisable: transport interventions alter the relative costs of spatial interaction across the whole city, and the resulting reallocation of economic activity generates welfare effects — positive or negative — that the road market alone does not capture.

Distorted Substitutes and the Modal Shift Problem

A further category of second-best concern arises from the condition of the market for the closest substitute to car travel: public transport. In a first-best world, a road toll induces modal shift toward public transit at the social cost of a transit trip, and the aggregate welfare gain reflects the efficient reallocation of demand. But if public transit is itself a distorted market — burdened by low service quality, inadequate investment, or implicit subsidies disconnected from demand signals — the cross-price elasticity between driving and transit will be lower than models assuming efficient substitutes would predict. Some drivers will not shift modes; others will shift to a substitute that imposes its own costs. If transit capacity is inelastic and cannot absorb displaced demand, congestion is not eliminated but relocated — from the road network to an overcrowded transit system — creating a new crowding externality that the toll has not corrected (Pons i Rigat, 2021). Moreover, directing toll revenues toward an already heavily subsidised transit sector may generate negative welfare effects by deepening an existing distortion rather than correcting it, unless the degree of social inequality aversion is very high (Mayeres & Proost, 2001, as cited in Small & Verhoef, 2007).

Land Use Constraints and the Long-Run Spatial Equilibrium

Finally, the longer-run welfare dividend of road pricing depends critically on the responsiveness of the land market. In an undistorted urban economy, a reduction in congestion lowers the effective cost of access to central locations, which induces densification: housing and commercial floorspace supply increases near newly accessible areas, allowing agglomeration benefits to compound and the full spatial equilibrium to re-form around the new transport prices (Redding & Rossi-Hansberg, 2017). When the land market is constrained — by binding building regulations, restrictive zoning, or a discretionary permitting regime — this adjustment cannot occur. Residents and firms cannot relocate in response to changed relative accessibility, and the long-run spatial efficiency gain from pricing is suppressed. Tsivanidis (2023) demonstrates this mechanism in the context of the TransMilenio system: an accommodative zoning policy that allowed housing supply to respond to improved accessibility would have increased welfare gains by approximately 40 per cent — or up to 44 per cent under an optimally targeted scheme that allocates development rights according to predicted changes in market access, illustrating the extent to which rigid land use regulation can truncate the welfare potential of transport policy interventions.

Synthesising the Second-Best Problem

The channels reviewed in this section — network incompleteness, labour market distortions, agglomeration feedbacks, imperfect substitutes, and land use rigidities — share a common structure: each represents a market in which the conditions for efficient allocation are violated, and in each case the violation modifies both the magnitude and the sign of the welfare effects that standard first-best analysis would attribute to DRP. As Fosgerau and Van Dender (2010) observe, the welfare effects of road pricing cannot be determined from road-market data alone: they are settled in the general equilibrium of the city's interconnected transport, labour, housing, and product markets. The aggregate welfare gain — or loss — is the net resultant of direct road-market efficiency improvements and the distortions amplified, attenuated, or introduced in every adjacent market that the pricing reform perturbs.

It follows that the sign and magnitude of DRP's welfare effects in any particular city are questions that cannot be resolved by appeal to first-best theory. This recognition — that the welfare calculus of DRP is determined by the specific configuration of distortions in the city under study — motivates the framework of the sections that follow, where the particular institutional and market conditions of Kyiv are examined as the relevant second-best context within which any road pricing reform must be designed and evaluated.

2.2. DRP in Kyiv's Distorted Urban Environment

The theory of second best is general; its bite depends on the specific configuration of distortions in the city under study. Kyiv is not a frictionless monocentric textbook city, and the welfare consequences of DRP there are shaped by the particular wedges that characterise its transport and land markets. This study examines the interaction between the introduction of DRP and three salient features of Kyiv that may bear directly on the policy's success. Each is introduced below as a deviation from the first-best benchmark, together with the channel through which it alters the expected effect of DRP.

The quality of surface public transport and the subjective cost of switching. In a first-best world, a road toll reallocates trips toward the substitute mode at the social cost of using that mode. In Kyiv, however, surface public transport is itself distorted: chronic under-investment, an ageing and partly informal *marshrutka* fleet, and low service quality impose a large non-monetary disutility on transit users. This functions as an implicit "tax" on the substitute. The practical consequence is that the subjective cost of switching out of the private car is substantially higher than the resource cost of a transit trip, so the cross-price elasticity between driving and public transport is lower than standard congestion-pricing models assume. A toll calibrated as if transit were a clean substitute will therefore fail to achieve the efficient modal split: demand for car trips is weakly shifting to a change in mode of transport. This keeps the DRP paid by motorists higher than under conditions of high-quality transit, and this can result in other ways to ensure a person's optimal well-being, changing the time of departure, place of residence, place of work, which can ultimately reduce both the well-being of a particular person and the general well-being, depending on the situation.

Asymmetric elasticities of road demand and transit supply. DRP is a demand-side instrument: it raises the price of road space and suppresses car trips. Its welfare effect, however, depends on what happens to the diverted trips. If the supply of surface public transport is inelastic — fixed routes, a fleet bounded by a physical ceiling, limited ability to add capacity — then drivers displaced from the road network cannot be absorbed efficiently by transit, and a congestion externality is simply relocated from the road to an overcrowded bus system. The benefit from de-congesting the roads is then can be offset by a new crowding externality on the substitute. This also works as a tax on substitute with welfare consequences analogous to those described above.

Land-use regulation and constrained spatial adjustment. A large share of the welfare gain from congestion pricing in a spatial economy arises not from the day-one change in trips but from the longer-run reallocation of residents and firms across the city as relative location costs change — the mechanism at the centre of the quantitative spatial framework of Redding and Rossi-Hansberg (2017). Kyiv's land market is heavily distorted by building restrictions and a discretionary permitting regime that prevent the supply of floor space from responding to price signals. When the city cannot densify where accessibility improves, the spatial equilibrium cannot fully re-form around the new transport prices, and the long-run welfare dividend of DRP is dampened relative to the first-best case in which land use adjusts freely.

Taken together, these three distortions establish that the welfare effect of DRP in Kyiv is the joint product of conditions in several adjacent markets, whose sign and magnitude cannot be signed a priori. That is precisely why a sound policy analysis must treat DRP not merely as a charge levied on road space, but as a system-wide intervention whose ultimate welfare effect is settled in the general equilibrium of the city's interconnected transport, housing and labour markets — an assessment that, as the next chapter argues, can only be carried out within a quantitative spatial model.

Chapter 3. Model

3.1. Why a Quantitative Spatial Model?

The preceding chapter established that the welfare consequences of Dynamic Road Pricing in Kyiv cannot be assessed in isolation from the broader urban economy. Three identified second-best distortions — the low functional quality of the transit substitute, the inelastic supply of surface public transport, and binding land-use regulations that prevent spatial adjustment — ensure that the net welfare effect of the policy is determined not by the road market alone, but by the simultaneous response of transport, labour, housing, and product markets to a common regulatory shock. This multi-market interdependence carries a direct methodological implication: no analytical framework that treats these linkages as separable, exogenous, or negligible can reliably evaluate the welfare outcome of DRP. The present section surveys the principal methodologies available for evaluating urban transport policy interventions, identifies the theoretical and empirical limitations of each approach relative to the requirements of this study, and argues that a quantitative spatial model (QSM) is the most appropriate framework that satisfies all of those requirements simultaneously.

Limitations of Partial-Equilibrium and Value-of-Travel-Time Approaches

The conventional standard of applied transport economics is welfare evaluation grounded in the Value of Travel Time Saved (VTTS). Under this framework, the benefit of a policy intervention is measured as the product of the reduction in aggregate travel time and the monetised value of time, typically proxied by the wage rate or a fraction thereof (Small & Verhoef, 2007). The VTTS method is computationally tractable, imposes minimal data requirements, and has an established track record in cost-benefit analysis; these qualities have made it the dominant appraisal standard in transport planning worldwide. However, the VTTS framework rests on a theoretically restrictive assumption: it evaluates welfare as if only first-order, direct time savings matter, treating the rest of the urban economy as fixed. This is formally equivalent to the claim that the transport intervention is marginal and operates in an otherwise undistorted economy — precisely the first-best benchmark that Chapter 2 demonstrated to be inapplicable to the Kyiv context.

When a transport intervention is non-marginal and the economy contains pre-existing distortions, the VTTS approach systematically misses general equilibrium welfare effects operating through wages, land rents, residential sorting, and agglomeration externalities. The empirical magnitude of this omission is documented by Tsivanidis (2023), in the previously mentioned study on Bogotá's TransMilenio Bus Rapid Transit where Tsivanidis compared welfare outcomes under a full quantitative spatial framework with those under the standard first-order VTTS approximation . The VTTS approach, it emerged, accounts for only 54% of total welfare gains.

Hörcher, Cusson, and Graham (2026) observe that most transport appraisal frameworks, including current cost-benefit analysis guidelines in force across Europe and North America, are structurally restricted to partial equilibrium, abstracting from location choices and ignoring welfare spillovers in labour and housing markets. The methodological shortcomings of the partial-equilibrium approach have been acknowledged in the policy community for some time, yet progress towards a coherent alternative has been slow — in large part because the general equilibrium modelling tools required have, until recently, lacked both tractability and the ability to connect rigorously to empirical data.

Limitations of Four-Step Transport Models and Agent-Based Simulation

The four-step transport demand model — the traditional planning instrument comprising trip generation, distribution, modal split, and network assignment — adds a layer of behavioural granularity relative to a simple VTTS calculation, but inherits the same fundamental limitation: the spatial distribution of residents, employers, and firms is treated as exogenous and does not respond to changes in transport costs. This means the four-step model cannot capture the long-run welfare gains that arise from residential and employment relocation when relative accessibility changes across the city — a mechanism that Redding and Rossi-Hansberg (2017) identify as central to the welfare economics of transport policy. The framework also lacks a welfare metric grounded in individual utility maximisation, which precludes aggregating its outputs into a theoretically coherent measure of social benefit.

Agent-based simulation platforms, represent a methodologically richer alternative. In such models, individual synthetic travellers optimise their daily activity schedules through an iterative co-evolutionary learning process, enabling detailed simulation of behavioural responses to road pricing schemes with high spatial and temporal resolution. Chakirov and Erath (2012) demonstrate the capability of agent-based simulation for evaluating congestion pricing scenarios in Singapore, highlighting its ability to reproduce heterogeneous agent behaviour and the feedback between individual route choice and network-level congestion. These are genuine advantages for short-run traffic assignment problems. However, agent-based simulation platforms are simulation environments rather than structural economic models: they do not in general endogenise firm location choices, residential sorting, or housing market clearing; they do not satisfy the Lucas critique requirement that structural parameters be invariant to policy interventions; and they do not produce a welfare measure consistent with microeconomic theory. When the research question requires a long-run general equilibrium analysis in which changes in transport costs propagate into wages, land rents, and the spatial distribution of economic activity, agent-based simulation lacks the theoretical architecture to support such an analysis.

Limitations of Reduced-Form Econometric Approaches

Reduced-form econometric methods — exploiting quasi-experimental variation around transport interventions through instrumental variables, difference-in-differences, or event-study designs — have produced a body of credibly identified empirical results on the causal effects of infrastructure changes on employment, population, and property values. Within their domain of application, such methods deliver internally valid estimates with transparent assumptions. However, they face two structural limitations that make them unsuitable as the primary instrument for the analysis undertaken here.

First, reduced-form approaches cannot be used to evaluate out-of-sample counterfactuals. The estimated elasticities are valid in the neighbourhood of the specific intervention identified, and extrapolating them to the scale, spatial extent, and price structure of a hypothetical DRP scheme in Kyiv would implicitly require precisely the structural assumptions that the reduced-form approach is designed to avoid. Second, and more fundamentally, standard difference-in-differences and instrumental variable estimators are designed to isolate average treatment effects on directly treated spatial units while differencing out effects common to the treatment and control groups. As Redding and Rossi-Hansberg (2017) and Allen and Arkolakis (2022) emphasise, locations within a city are not independent observations but are systematically linked through commuting, trade, and migration flows: a transport shock to one district propagates through these network linkages to all other districts. The differencing procedure eliminates precisely these spatial spillovers — which, as the Tsivanidis (2023) results indicate, account for a substantial share of total welfare effects. Severen (2026) acknowledges this spatial interdependence as a central motivation for QSMs, while noting that it impacts the interpretation of estimands rather than the consistency of parameter estimates — reinforcing the complementary, rather than substitutable, relationship between structural and reduced-form approaches.

Quantitative Spatial Models: Definition and Methodological Properties

The quantitative spatial model framework, systematically reviewed by Redding and Rossi-Hansberg (2017), was developed to overcome the limitations identified above. QSMs are general equilibrium models of the intra-urban spatial distribution of economic activity that are structurally rich enough to match first-order features of observed data — including heterogeneous locations, gravity-equation relationships for commuting and trade, and cross-sectional patterns of wage and rent dispersion — while remaining tractable enough to permit rigorous counterfactual welfare analysis. As Hörcher et al. (2026) summarise, QSMs are "geographically explicit spatial general equilibrium models" that integrate "the interaction between transport and land use," capture "general equilibrium linkages between accessibility, wages, and housing prices," and "endogenise origin-destination matrices through gravity models of location choice." These properties are directly relevant to the requirements of the present study.

Three methodological properties of QSMs are especially consequential. First, QSMs are exactly identified: the model's structural fundamentals — location-specific productivity levels, residential amenities, and transport costs — can be recovered uniquely from the observed spatial equilibrium in wages, employment, commuting flows, and housing prices. This inversion procedure, discussed in detail by Redding and Rossi-Hansberg (2017), means the model can be calibrated so that the observed data constitute an equilibrium of the model, and the recovered fundamentals are, under the model's assumptions, invariant to the policy change being evaluated. This property satisfies the Lucas critique and ensures that counterfactual predictions are structural responses of the model rather than extrapolations of historical correlations.

Second, a calibrated QSM permits the evaluation of counterfactual policy scenarios within a fully specified general equilibrium. A change in a model primitive — such as the effective travel cost imposed by a road toll — is propagated through the complete system of equilibrium conditions to obtain its consequences for wages, land rents, location choices, and welfare in every location simultaneously. Because locations are linked through commuting, trade, and migration, the model captures the indirect, economy-wide repercussions of the policy that extend well beyond the directly tolled links — precisely the general equilibrium spillovers that the partial-equilibrium and reduced-form approaches discussed above are unable to recover. Allen and Arkolakis (2022) demonstrate the value of this property in an urban framework that incorporates endogenous traffic congestion — the market failure that DRP is designed to correct — showing how a change to any single link of the network reverberates through the commuting system to reshape the spatial distribution of economic activity and welfare across the entire city.

Third, QSMs naturally accommodate the multi-market distortions identified in Chapter 2. Labour market wedges enter through the income and wage-determination equations of the model. Agglomeration externalities are incorporated as productivity and amenity spillovers that depend on local employment and residential density. Land market rigidities are modelled through the housing supply elasticity, and the welfare cost of binding land-use regulation can be quantified by comparing equilibria with and without the constraint. Tsivanidis (2023) demonstrates this mechanism explicitly in the context of the TransMilenio evaluation: relaxing Bogotá's land-use restrictions would have increased the total welfare gains from the BRT by between 24 and 44 per cent, depending on the design of the zoning reform, underscoring the quantitative importance of housing market constraints for the welfare economics of transport policy. Monte, Redding, and Rossi-Hansberg (2018) further demonstrate that a QSM incorporating trade and commuting linkages can match observed labour market responses to transport shocks, validating the framework's empirical predictions against plausibly exogenous variation.

The Quantitative Spatial Model as the Appropriate Methodology for This Study

In summary, the research question motivating this thesis — what is the net welfare effect of introducing Dynamic Road Pricing in Kyiv, given the city's particular configuration of second-best distortions across transport, labour, and housing markets — requires a methodology that can: (I) simultaneously account for general equilibrium adjustments across multiple interconnected markets; (II) recover structural fundamentals from the observable spatial equilibrium; (III) evaluate out-of-sample counterfactuals for a policy that has no local historical precedent; and (IV) produce welfare measures consistent with individual utility maximisation. None of the alternative approaches surveyed above — the VTTS framework, the four-step transport model, agent-based simulation, or reduced-form econometric estimation — satisfies all four requirements jointly. A quantitative spatial model, calibrated to Kyiv's observed spatial structure and supplemented with estimated values of the relevant structural parameters, is the appropriate tool for this analysis. The following sections describe the specific model adopted in this study, its component equations, the calibration and estimation strategy, and the DRP counterfactuals it is used to evaluate.

Methodological caveats. While the quantitative spatial model framework satisfies the four requirements identified above, it does so under structural assumptions that must be acknowledged. All standard QSM implementations rely on a Fréchet distribution for idiosyncratic location preferences, which generates analytically tractable commuting probabilities but imposes a specific functional form whose robustness to alternative distributional assumptions has not been exhaustively examined. Commuting and trade costs are typically modelled using the iceberg assumption — a convenient simplification that departs from established practice in transport modelling and restricts the realism of the transport sector representation within the model.

Non-commuting trips, which may account for a substantial share of urban traffic and are arguably more relevant to a road pricing intervention than to a transit improvement, are rarely endogenised in QSMs. Finally, Hörcher, Cusson, and Graham (2026) note that large-scale validation of QSM counterfactual predictions against ex-post causal evidence has not yet been conducted, and Severen (2026) cautions that the precision of QSM outputs can create an impression of certainty that the underlying parameter estimates do not always justify. These limitations do not disqualify the framework for the present analysis — they are properties of the state of the art — but they should be borne in mind when interpreting the counterfactual results reported in subsequent chapters.

3.2. Model Description

General Overview

The section describes a stylized quantitative model of the city's spatial equilibrium, calibrated to Kyiv. The goal is to investigate the consequences of implementing dynamic road pricing under different institutional and technological scenarios. Comparing the results of equilibrium calculations across scenarios is the model's main goal.

Scenario matrix. The study covers four orthogonal policy dimensions, which are combined into a full factor matrix:

- DRP (On/Off): Whether dynamic tolls are charged on congested road network links.
- Building regulations in the center (0/1/2): FAR basic regulations - relaxed regulations - completely free development market.
- Bus fleet elasticity (on/off): Is the number of buses limited by the physical fleet ceiling, or is the PT supply elastic?
- The quality of the bus fleet (standard/improved) allows you to assess the synergy between DRP and investments in comfort in PT.

3.2.1. Spatial environment and preferences of agents

Spatial discretized environment

The city is modeled as a closed spatial system consisting of a spatial set of discrete geographical locations (zones) $i, j \in \mathcal{S} = \{1, 2, \ldots, I\}$, where $I = 25$. The spatial structure is represented as a regular two-dimensional grid of dimension $J \times J$ (where $J = \sqrt{I} = 5$), reflecting the stylized topology of the city graph.

The geographic matrix of Euclidean distances between all pairs of zones d_{ij}^{euclid} is calculated directly from the coordinates of the grid nodes (x_i, y_i):

$$d_{ij}^{\text{euclid}} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

To account for the realistic circuity of the street network, physical distances are scaled by a circuity factor of θ=1.2, which reflects the average excess length of an actual route relative to the straight-line distance. The transport network is formed only between neighbors in the grid: the connection between zones i and j exists if and only if $d_{ij}^{\text{euclid}} \leq 1.5$ grid units, covering both direct (distance = 1) and diagonal (distance ≈ 1.414) neighbors.

Each location $i \in \mathcal{S}$ serves as both a place of residence for the workforce and a center of production activity (jobs). Such an architecture allows endogenously modeling two-way commuting flows between all points of the urban system. The total number of mobile labor in the city is fixed and equal to $\bar{L}$.

Household Preferences and Demand Structure

All individual agents (workers) are spatially mobile and maximize their own utility by choosing a location to live i, a location to work j, and a mode of transport m for daily travel between them. Consumers have heterogeneous preferences for the choice of place to live and work, as well as material goods.

A nonlinear utility function of the Stone-Geary type is used to formalize consumer choice. It allows us to take into account the inelastic demand for housing at low income levels, which is critical for the analysis of urban systems with structural constraints in the real estate market. The utility function of an agent ω living in location i and working in location j is defined over a composite trade good c (which acts as a numerator with a price $p_c = 1$) and the consumption of housing space h as follows:

$$U_{nij}(\omega) = \left(\frac{c_{nij}(\omega)}{1-\gamma}\right)^{1-\gamma} \left(\frac{h_{nij}(\omega) - \bar{h}}{\gamma}\right)^{\gamma} X_i \exp(-\kappa_t \, \tau_{ijm}) \mathcal{B}_{nij}(\omega)$$

where:

- $c_{nij}(\omega)$ — the amount of consumption of a material composite good by an individual ω;
- $h_{nij}(\omega)$ — the amount of consumption of living space (square meters) by an individual;

- $\bar{h} > 0$ — an exogenously given parameter that reflects the minimum physically and socially necessary threshold of housing consumption per person (subsistence housing requirement), below which utility is not determined;
- $\gamma \in (0, 1)$ — a parameter that determines the marginal share of the budget that is directed to housing after satisfying basic needs;
- X_i — the residential attractiveness of location i (residential amenities), which reflects the quality of the local environment, the availability of infrastructure, and consumer factors;
- $\exp(-\kappa_t \tau_{ijm})$ is the spatial friction or discomfort associated with daily commuting from i to j using the transport mode m, where τ_{ijm} is the generalized time or money cost, and $\kappa_t > 0$ is the cost elasticity of commuting;
- $\mathcal{B}_{nij}(\omega)$ is the individual idiosyncratic preference shock of worker ω to a pair of locations (i, j).

Budget Constraint and Discretionary Income

Let v_n be the agent's total income, which includes salary and dividends from land rent redistribution and road tolls. The agent first reserves funds for two mandatory expenses: the cost of subsistence housing $r_i \bar{h}$ and the monetary transportation costs on the route $i \to j$, denoted $\kappa_{ij}^{\text{money}}$. The remainder determines the discretionary income:

$$y_{nij}^{\text{net}} = v_n - r_i \bar{h} - \kappa_{ij}^{\text{money}}$$

The agent's optimization problem is to maximize the utility over the discretionary remainder after reserving mandatory expenses:

$$\max_{c,\, h \geq \bar{h}} \left(\frac{c}{1-\gamma} \right)^{1-\gamma} \left(\frac{h - \bar{h}}{\gamma} \right)^{\gamma} \quad \text{provided} \quad c + r_i (h - \bar{h}) \leq y_{nij}^{\text{net}}$$

where r_i is the market rental value of a unit of residential space in location i.

Optimal demand

From the first-order conditions, we get:

$$h_i = \bar{h} + \frac{\gamma\, y_{nij}^{\text{net}}}{r_i}, \qquad c_i = (1-\gamma)\, y_{nij}^{\text{net}}$$

A fractional share of γ of discretionary income goes to housing above the subsistence level, a share of $(1-\gamma)$ — to a composite good.

Indirect utility function. Substituting optimal demand into a direct function gives:

$$V_{nij}(\omega) = \frac{y_{nij}^{\text{net}}}{r_i^{\gamma}} \cdot X_i \cdot \exp(-\kappa_t \, \tau_{ijm}) \cdot \mathcal{B}_{nij}(\omega)$$

The numerator y_{nij}^{net} is discretionary income after all fixed payments; the denominator r_i^{γ} is the local spatial price index.

Effective share of housing costs

The aggregate costs of the agent for housing consist of a fixed subsistence component and a discretionary one:

$$\text{HousingSpend}^{\text{ind}} = r_i\bar{h} + \gamma \, y_{nij}^{\text{net}}$$

Then the effective (actual) share of housing costs in total income:

$$\gamma_i^{\text{eff}} = \frac{r_i\bar{h} + \gamma \, y_{nij}^{\text{net}}}{v_n}.$$

In contrast to Cobb-Douglas, where $\gamma_i^{\text{eff}} \equiv \gamma$, according to Stone-Geary this fraction is variable and depends on the location. As v_n increases or r_i decreases, it asymptotically approaches γ. If the income approaches the critical level $r_i\bar{h} + \kappa_{ij}^{\text{money}}$, the discretionary income y_{nij}^{net} goes to zero and the agent spends almost the entire budget only on subsisting housing and transport — a key mechanism for sorting poorer households into cheaper zones.

Aggregate demand for housing. Summing up the individual expenses for all NR_i residents of zone i:

$$\text{HousingSpend}_i = r_i\bar{h} \cdot NR_i + \gamma \cdot E_{n,i}$$

where $E_{n,i} = y_i^{\text{net}} \cdot NR_i$ is the aggregate discretionary income of residents of the zone. The first term is the costs of the subsistence minimum, the second is the market surplus above it. This formula is a direct input argument of the housing market: on its basis, developers form an equilibrium offer (subsection 4.1.4).

Idiosyncratic heterogeneity and spatial sorting

The city is inhabited by heterogeneous workers, each of whom is characterized by an individual vector of idiosyncratic preferences for each combination of residence i and workplace j. According to the canonical approach of quantitative spatial economics, individual preference shocks $\mathcal{B}_{nij}(\omega)$ are independently and identically distributed according to the Fréchet law (Fréchet / Type II Extreme Value distribution). The distribution function of these shocks:

$$F(B) = \exp\left(-B^{-\varepsilon}\right), \quad \varepsilon > 1$$

where ε is the shape parameter of the distribution (inverse variance of Frechet shocks in terms of the model code), which regulates the degree of heterogeneity of agents and acts as the elasticity of spatial labor reallocation.

High values of ε correspond to low variability of individual tastes: agents are similar to each other and very sensitive to economic signals - wages, housing prices, and transit fares. This leads to intensive spatial sorting and concentration of labor in the most productive areas.

On the contrary, low values of ε indicate a high importance of intangible, subjective factors of attachment to a particular area of the city. Migration flows become less elastic to price changes, particularly to the introduction of dynamic pricing for road space use.

Due to the mathematical properties of the Fréchet distribution, idiosyncratic shocks ensure the smoothness of aggregated migration flows and allow us to obtain closed-form analytical expressions for spatial choice probabilities.

3.2.2. The structure of transport networks and technologies of movement

Two-layer architecture of urban transport space

The urban transport infrastructure is formalized as a complex multimodal spatial system consisting of two parallel network layers that are fundamentally distinct in their economic and physical nature: the surface road network ($\mathcal{G}^{\text{road}}$) and a completely isolated network of off-street rail mass transit — the subway ($\mathcal{G}^{\text{metro}}$).

The surface road network $\mathcal{G}^{\text{road}} = (\mathcal{S}, \mathcal{E}^{\text{road}})$ captures the entire topology of city streets, highways, and overpasses. This layer is a non-segregated shared environment where different modal agents (private cars and surface public transport) directly compete for a scarce resource, the used surface area of available road space. The economic feature of this layer is the presence of endogenous negative externalities of congestion, where the marginal private costs of each individual's travel increase non-linearly with the growth of the aggregate load on the links.

In contrast, the mass transit network $\mathcal{G}^{\text{metro}} = (\mathcal{S}^{\text{metro}}, \mathcal{E}^{\text{metro}})$ operates as a spatially segregated, technologically closed system. The physical movement of rolling stock on this layer is completely isolated from street traffic, eliminating the direct dependence of the transit travel speed on traffic congestion. However, this layer is subject to its own specific capacity constraints, in which passenger flows encounter endogenous crowding discomfort and technological barriers to the capacity of station complexes and line segments.

The global choice of agents regarding routing and trip distribution is determined by the vector of generalized spatial costs C_{ijm}, which integrates objective time losses and direct financial costs of travel between each pair of residence locations $i \in \mathcal{S}$ and employment locations $j \in \mathcal{S}$.

Each edge (u, v) of the road graph is characterized by: (i) a free-flow travel time $\tau_{uv}^{\text{free}} > 0$, which corresponds to traffic in the absence of congestion; (ii) a capacity K_{uv} — the maximum flow of vehicles at which traffic conditions do not yet degrade into hypercongestion. For intra-zonal trips (diagonal of the matrix), a separate fixed travel duration τ_{ii}^{free} is set.

Road transport and endogenous congestion

A key feature of the model is the endogenous formation of traffic load and congestion. The time taken for a vehicle to travel along the edge (u, v) is not fixed, but depends on the current flow on it. The volume-delay function is specified in the Bureau of Public Roads (BPR) form:

$$\tau_{uv}^{\text{congested}} = \tau_{uv}^{\text{free}} \cdot \left(1 + 0.15 \cdot \left(\frac{q_{uv}}{K_{uv}}\right)^4\right)$$

where q_{uv} is the current flow of vehicles on the edge (u, v) (total cars and buses), K_{uv} is the capacity of the edge. When $q_{uv} \ll K_{uv}$ congestion is minimal and the time approaches free-flow travel time τ_{uv}^{free}. When the flow approaches or exceeds the capacity, the time increases nonlinearly according to a fourth-power function, which reproduces a realistic transition to the hypercongestion regime.

The adoption of the BPR congestion function departs from the constant-elasticity congestion specifications (e.g., Allen & Arkolakis, 2022) and the linearised structure of Tsivanidis (2023) that admit closed-form or 'exact hat algebra' counterfactuals. Its non-constant elasticity precludes such analytical shortcuts; the counterfactual equilibrium is therefore obtained numerically by fixed-point iteration, in which updated travel costs feed into location-choice probabilities, commuting flows, wages, land rents, and congestion levels until the system converges. This is a deliberate trade-off: the BPR function is the engineering standard for flow-delay modelling and correctly captures the non-linear, threshold character of congestion costs near capacity — the regime in which DRP is both most needed and most consequential for welfare, and the regime documented for major Kyiv arterials in Chapter 1. The cost of this greater empirical fidelity is a requirement for full calibration of free-flow travel times and link capacities, described in Section 3.3. The iterative numerical solution is methodologically standard in the quantitative urban literature: the foundational model of Ahlfeldt, Redding, Sturm, and Wolf (2015) and the full model of Tsivanidis (2023) are solved through analogous procedures.

The generalized travel costs on the edge (u, v) for a car include a time component converted into a monetary equivalent through the agent's value of time, and a direct monetary component:

$$\tau_{uv}^{\text{gen}} = \tau_{uv}^{\text{congested}} + \frac{\ell_{uv}}{\overline{\text{VoT}}} \cdot 10$$

where ℓ_{uv} is the toll rate for travel along the edge (u, v) (DRP toll), $\overline{\text{VoT}}$ is the average value of time in the city, which converts the monetary toll into its time equivalent for the purpose of graph construction. The multiplier of 10 on the right-hand side is related to the scaling of the speed parameter in the numerical implementation and is a technical scaling factor.

The total monetary cost of a car trip from i to j is defined as the sum of the costs along all edges of the optimal route P_{ij}^{*} found by Dijkstra's algorithm:

$$\kappa_{ij}^{\text{car, money}} = \sum_{(u,v)\in P^{ij}} \left(c^{\text{fuel}} \cdot \tau_{uv}^{\text{free}} + c^{\text{idle}} \cdot (\tau_{uv}^{\text{congested}} - \tau_{uv}^{\text{free}})\right) + p_{\text{car}} + p_{\text{park}} + \sum_{(u,v)\in P^{ij}} \ell_{uv}$$

where c^{fuel} is the cost of fuel per unit of free-flow conditions, c^{idle} is the cost of idling in congestion (lower than c^{fuel}, since fuel consumption during slow driving is lower), p_{car} is the fixed cost of the trip, reflecting the costs of maintaining the car (calculated for one trip), p_{park} is the parking fee.

The mode choice function in the nested logit model operates with the effective generalized time $t_{ij}^{m,\text{eff}}$, which converts all components of the trip costs — time and monetary — into a unified time metric through the individual value of the agent's time. For each transport mode, this indicator is determined separately.

For road transport:

$$t_{ij}^{\text{car, eff}} = t_{ij}^{\text{car, phys}} \cdot \omega_0^{\text{car}} + \frac{\kappa_{ij}^{\text{car, money}}}{\mathrm{VoT}_j} + \Delta^{\text{start, car}}$$

where ω_0^{car} is the baseline discomfort weight for private vehicle travel; $\kappa_{ij}^{\text{car, money}}$ is the total monetary cost of a car trip (fuel cost in free traffic and idling in traffic jams, fixed costs of car maintenance, parking fee and DRP toll); VoT_j is the individual value of the agent's time, which depends on the income at workplace j.

Dynamic Road Pricing (DRP) Mechanism

The model implements a Dynamic Road Pricing (DRP) algorithm designed to internalize the negative externalities of congestion. It does this by Walrasian tâtonnement.

The toll rate is calculated according to the rule:

$$\ell_{uv} = \min\left(\bar{\ell},\ \max\left(0,\ \ell_{uv}^{(t)} + \mu \cdot \left(q_{uv}^{(t)} - K_{uv}\right)\right)\right)$$

where $\bar{\ell}$ is the exogenous maximum rate, $\mu > 0$ is the sensitivity parameter (adjustment step size), and $(q_{uv}^{(t)} - K_{uv})$ is the excess traffic flow relative to the target capacity. The toll rate is bounded below by zero (negative tolls are not allowed) and from above by the exogenous maximum value.

Surface public transit

Surface public transit operates on the basis of the road graph shared with cars, and therefore experiences the full impact of traffic congestion symmetrically with them. The time of a bus trip from i to j is physically equal to the time of passing the optimal route on the road graph, but with a speed corresponding to the average city speed of the bus v^{bus}:

$$t_{ij}^{\text{bus, phys}} = t_{ij}^{\text{car, phys}} \cdot \frac{v^{\text{car}}}{v^{\text{bus}}} = t_{ij}^{\text{car, phys}} \cdot 2$$

where $t_{ij}^{\text{car, phys}}$ is the congested car travel time between zones i and j, calculated by Dijkstra on the congested network and converted into physical time through the car's speed coefficient. Both physical times — car and bus — are scaled from the same matrix of congested edge travel times, but with different coefficients.

An essential feature of the specification is the endogenous function of discomfort in buses. Under conditions of limited transit fleet capacity (number of buses $B^{\max}$) and non-zero passenger flows, an endogenous crowding multiplier is formed:

$$\omega^{\text{crowd}} = \begin{cases} 1 + \max\left(0, \frac{q^{\text{pax}}}{B^{\max} \cdot c_B} - 0.8\right)^2, & \text{if } \frac{q^{\text{pax}}}{B^{\max} \cdot c_B} \leq 1 \\ 1 + (0.2)^2 + 5 \cdot \left(\frac{q^{\text{pax}}}{B^{\max} \cdot c_B} - 1\right)^2, & \text{if } \frac{q^{\text{pax}}}{B^{\max} \cdot c_B} > 1 \end{cases}$$

where q^{pax} is the total number of bus passengers in the city, $B^{\max}$ is the total number of buses in the city, c_B is the comfortable capacity of one bus. When the occupancy rate is below 80%, the multiplier remains equal to one; between 80% and 100% grows smoothly; over 100% a quadratic penalty "wall" is used, which effectively prevents unlimited overcrowding of buses and forces passengers to switch to alternative modes of transport.

The effective generalized bus travel time is:

$$t_{ij}^{\text{bus, eff}} = t_{ij}^{\text{bus, phys}} \cdot \omega_0^{\text{bus}} \cdot \omega^{\text{crowd}} + \frac{\kappa_{ij}^{\text{bus, money}}}{\text{VoT}_j} + \Delta^{\text{start, bus}}$$

where $\kappa_{ij}^{\text{bus, money}}$ is the bus fare (fixed, independent of the route), VoT_j is the individual value of time of an agent working in the zone of j, $\Delta^{\text{start, bus}}$ is a fixed initial delay (waiting at a stop, pedestrian approach), ω_0^{bus} is a baseline (structural) discomfort coefficient of the bus, which reflects the constant comparative discomfort of bus transport with respect to the car even with zero-occupancy conditions.

Metro: Independent network, crowding discomfort, and boarding delay

The metro is implemented on a topologically distinct graph that does not share edges with the surface road network. The underground topology is described by a multi-layer structure with $I_{\text{total}} = I \times (1 + N_L)$ nodes, where N_L is the number of line directions (in the model, $N_L = 6$, which corresponds to three lines in two directions). The base layer (nodes $1, \ldots, I$) corresponds to physical regions; layers $k \cdot I + 1, \ldots, (k+1) \cdot I$ for $k = 1, \ldots, 6$ correspond to "tunnel" nodes of each direction of the line.

The adjacency matrix $\mathbf{M}^{\text{metro}} \in \mathbb{R}^{I_{\text{total}} \times I_{\text{total}}}$ encodes three types of edges:

- Tunnel links/edges between successive stations of the same line in one direction;
- Access/egress edges between district i and its station $i + k \cdot I$ (pedestrian approach to the station);
- Transfer edges between different lines at a hub station (zone 13 in the model), including waiting time for a transfer.

The time in the tunnel between the nodes u and v of the line L in the absence of load is determined by the Euclidean distance between the districts, scaled by the speed of the metro v^{metro}. In the presence of passenger traffic, the algorithm successively applies two mechanisms of service quality deterioration.

Mechanism 1: Discomfort in the car (Crowding Discomfort). If the flow of passengers on the tunnel section (u, v) does not exceed the capacity K_{uv}^{metro}, the subjective time multiplier is used:

$$\mu_{uv}^{\text{crowd}} = 1 + 0.3 \cdot \left(\min \left(\frac{q_{uv}^{\text{metro}}}{K_{uv}^{\text{metro}}}, 1.0 \right) \right)^2$$

This mechanism reflects that a full car is perceived by passengers as a 30% longer journey due to the discomfort of compression, even if the physical travel time does not change.

Mechanism 2: Denied Boarding and Queue (Denied Boarding). If the flow exceeds the site capacity ($q_{uv}^{\text{metro}} > K_{uv}^{\text{metro}}$), a penalty waiting time on the platform is added:

$$\Delta_u^{\text{wait}} = \Delta_0^{\text{wait}} \cdot 2 \cdot \left(\max \left(0, \frac{q_{uv}^{\text{metro}}}{K_{uv}^{\text{metro}}} - 1.0 \right) \right)^2$$

where Δ_0^{wait} is the base waiting time (half of the transit headway), which is considered as the minimum wait even in the absence of a queue. The quadratic dependence on overload ensures a sharp growth of the queue when the capacity is exceeded. At a hub station (zone 13), this penalty also applies to transfer flows between all lines intersecting at that station.

After updating the adjacency matrix $\mathrm{M}^{\text{metro, congested}}$ at each iteration, the shortest paths on the full multilayer graph are computed. The resulting subjective metro travel time between districts i and j is extracted from the block $\tau_{ij}^{\text{metro}} = \tau_{ij}^{\text{full}}[1 : I, 1 : I]$ of the extended distance matrix.

Effective generalized time for the metro:

$$t_{ij}^{\text{metro, eff}} = t_{ij}^{\text{metro, phys}} \cdot \omega_0^{\text{metro}} + \frac{\kappa_{ij}^{\text{metro, money}}}{\mathrm{VoT}_j} + \Delta^{\text{start, metro}}$$

where ω_0^{metro} is the basic discomfort factor of the metro, which reflects minor inconveniences of an underground trip in the absence of congestion; at the same time, the dynamic effects of crowding and queuing are already embedded directly inside $t_{ij}^{\text{metro, phys}}$ due to the mechanisms of discomfort in the car and denied boarding capacity; $\kappa_{ij}^{\text{metro, money}}$ is the fixed cost of a metro ticket.

Pedestrian travel

Pedestrian travel is specified as the fourth transport mode with a constant physical speed v^{ped} (the slowest of all modes). Unlike car and bus transport, walking time does not depend on the level of congestion and is calculated directly from the baseline distance matrix τ^{empty}. A critical spatial constraint is the maximum allowable distance for walking trips: trips over a fixed threshold $\bar{\tau}^{\text{ped}}$ are considered infeasible ($t_{ij}^{\text{ped}} = \infty$ for $\tau_{ij}^{\text{empty}} > \bar{\tau}^{\text{ped}}$), which prevents agents from selecting unrealistically long walking distances to and from work in each direction.

Effective generalized time for walking:

$$t_{ij}^{\text{ped, eff}} = t_{ij}^{\text{ped, phys}} \cdot \omega_0^{\text{ped}}$$

where ω_0^{ped} is the elevated baseline discomfort coefficient for walking.

3.2.3. Route, Mode, and Location Choice (Nested Choice Probabilities)

Value of Time and Its Income Elasticity

A key link between agents' transport and consumption decisions is the endogenous Value of Time (VoT), which converts the monetary cost of travel into a time equivalent, rendering it directly comparable with physical travel time. VoT is specified as the fraction of hourly earnings that an agent is willing to spend to save one hour:

$$\text{VoT}_{n,i} = \vartheta \cdot \frac{v_{n,i}}{H_{\text{month}}}$$

where $\vartheta \in (0, 1)$ is the willingness-to-pay coefficient for time savings, $H_{\text{month}} = 176$ is the standard number of working hours per month, $v_{n,i}$ is the monthly income of a resident of zone i.

Since the proportional dependence of VoT on income overestimates the time-money trade-offs of poorer households and underestimates it for the well-off, a correction is applied due to the income elasticity $\xi = 0.72$ (UK DfT WebTAG):

$$\text{VoT}_i^{\text{eff}} = \vartheta \cdot \frac{\bar{v}}{H_{\text{month}}} \cdot \left(\frac{v_{n,i}}{\bar{v}}\right)^{\xi}$$

where $\bar{v}$ is the average monthly income in the city (scale anchor). For $\xi < 1$ the value of time increases with income, but sub-linearly, which is consistent with the condition of diminishing marginal utility of income.

3.2.4. Nested Logit Model

The joint choice of transport mode and routing is formalized using a two-level nested discrete choice framework (Nested Logit).

Lower level. The agent evaluates the attractiveness of each mode of transport available without owning a car: ground transport, walking and metro. The systematic utility of mode $m \in \text{pt}, \text{ped}, \text{metro}$ is determined by the normalized utility:

$$\tilde{V}_{ij}^{m} = \frac{b_m - \kappa_t \cdot t_{ij}^{m,\text{eff}}}{\lambda_{\text{pt}}}$$

where b_m is the modal-specific alternative-specific constant (ASC), $\kappa_t > 0$ is the sensitivity to time costs, $\lambda_{\text{pt}} \in (0, 1]$ is the correlation parameter (dissimilarity parameter).

Effective generalized travel time of mode m:

$$t_{ij}^{m,\text{eff}} = \underbrace{\mu_m \cdot t_{ij}^{m,\text{phys}}}_{\text{discomfort}} + \underbrace{\frac{\text{MC}_{ij}^{m}}{\text{VoT}_{j}^{\text{eff}}}}_{\text{monetary costs}} + \underbrace{s_m}_{\text{starting delay}}$$

where μ_m is the modal-specific discomfort multiplier (μ_{car}, μ_{pt}, μ_{ped}, μ_{metro}); MC_{ij}^{m} is the monetary costs of the trip; s_m is the starting delay (finding parking / waiting at the stop / walking to the station).

The lower-level logsum (expected maximum utility of the public and active transit nest):

$$t_{ij}^{0} = -\frac{\lambda_{\text{pt}}}{\kappa_t} \cdot \ln\left(e^{\tilde{V}_{ij}^{\text{pt}}} + e^{\tilde{V}_{ij}^{\text{ped}}} + e^{\tilde{V}_{ij}^{\text{metro}}}\right)$$

When $\lambda_{\text{pt}} \to 1$ the model collapses into a standard MNL; when $\lambda_{\text{pt}} \to 0$ the choice becomes fully deterministic, with the agent selecting the best PT mode.

Upper Level

At the upper level of the choice hierarchy, car-owning agents choose between driving and the public transit nest:

$$t_{ij}^{1} = -\frac{1}{\kappa_t} \cdot \ln\left(e^{b_{\text{car}} - \kappa_t \cdot t_{ij}^{\text{car,eff}}} + e^{-\kappa_t \cdot t_{ij}^{0}}\right)$$

The conditional probability of a car owner choosing to drive:

$$P(\text{car} \mid \text{own car}, ; i \to j) = \frac{e^{b_{\text{car}} - \kappa_t \cdot t_{ij}^{\text{car,eff}}}}{e^{b_{\text{car}} - \kappa_t \cdot t_{ij}^{\text{car,eff}}} + e^{-\kappa_t \cdot t_{ij}^0}}$$

The conditional probability of selecting a specific non-automobile mode m from the transit nest (lower level) is:

$$P(m \mid \text{PT}, ; i \to j) = \frac{e^{\tilde{V}_{ij}^m}}{e^{\tilde{V}_{ij}^{\text{pt}}} + e^{\tilde{V}_{ij}^{\text{ped}}} + e^{\tilde{V}_{ij}^{\text{metro}}}}$$

Endogenous Car Ownership Decision

The long-term decision to acquire a vehicle is modeled by comparing the expected mobility benefits derived from transport flexibility against the fixed costs of vehicle ownership. The expected travel utility benefit for a resident of zone i:

$$B_i^{\text{car}} = \sum_j \pi_{ij}^{\text{norm}} \cdot \left(t_{ij}^0 - t_{ij}^1\right)$$

where π_{ij}^{norm} — is the normalized probability of a resident of zone i commuting to workplace j (representing the spatial distribution of commute trips).

The net utility from vehicle ownership is expressed as:

$$\Delta U_i^{\text{car}} = B_i^{\text{car}} - \frac{p_{\text{car}}}{\text{VoT}_i^{\text{eff}}}$$

where p_{car} — denotes the fixed monetary costs associated with car ownership (e.g., depreciation, insurance), annualized or scaled appropriately.

The probability of car ownership:

$$P(\text{own car} \mid i) = \frac{1}{1 + e^{-\kappa_{\text{own}} \cdot \Delta U_i^{\text{car}}}}$$

where $\kappa_{\text{own}} > 0$ — is a scale parameter reflecting the sensitivity of the car ownership decision, capturing behavioral inertia (or "stickiness") relative to short-term network fluctuations. In equilibrium, car ownership probabilities $P(\text{own car} \mid i)$ vary across urban zones, endogenously adapting to local PT accessibility, wage levels, and localized traffic congestion.

3.2.5. Transport Friction and the Commuting Probability Matrix

Transport friction between zones i and j is encoded as the exponential of generalized travel costs:

$$d_{ij}^a = e^{\kappa_t \cdot t_{ij}^a}, \quad a \in 0, 1$$

where $\kappa_t > 0$ is the travel time sensitivity parameter from the indirect utility function; $a = 1$ denotes car owners (utilizing the upper-level logsum t_{ij}^1), $a = 0$ denotes transit-reliant agents who do not own a vehicle (utilizing the lower-level logsum t_{ij}^0).

The commuting probability matrix π_{ij} is computed separately for these two population segments and then aggregated:

$$\pi_{ij} = NR_i \left[\underbrace{P_i^{\text{car}} \cdot \frac{(W_j/d_{ij}^1)^\varepsilon}{\text{RCMA}_i^1}}_{\text{car owners}} + \underbrace{(1 - P_i^{\text{car}}) \cdot \frac{(W_j/d_{ij}^0)^\varepsilon}{\text{RCMA}_i^0}}_{\text{only PT}} \right]$$

where $W_j = E_j \cdot w_j \cdot (1 + \zeta^{\text{div}})$ represents the systematic attractiveness of employment zone j (encompassing wages, dividends, and localized employer-specific amenities), ε is the Fréchet distribution shape parameter, and $P_i^{\text{car}} \equiv P(\text{own car} \mid i)$.

The weighted transport friction for the subsequent iteration is defined as:

$$d_{ij} = P_i^{\text{car}} \cdot d_{ij}^1 + (1 - P_i^{\text{car}}) \cdot d_{ij}^0$$

3.2.6. Commuter Market Access (CMA) Indices

Two synthetic indices of spatial accessibility naturally emerge from the model's optimization conditions.

Residential CMA (RCMA) captures the attractiveness of zone i as a residential location, given its accessibility to employment opportunities:

$$\text{RCMA}_i^a = \sum_j \left(\frac{W_j}{d_{ij}^a} \right)^\varepsilon, \qquad \text{RCMA}_i = P_i^{\text{car}} \cdot \text{RCMA}_i^1 + (1 - P_i^{\text{car}}) \cdot \text{RCMA}_i^0$$

where $W_j = E_j \cdot w_j \cdot (1 + \zeta^{\text{div}})$ represents the total attractiveness of employment zone (E_j denotes local employer amenities, and ζ^{div} is the dividend rate).

Firm CMA (FCMA) measures the attractiveness of zone j as a location for firms, reflecting the weighted accessibility of the labor supply:

$$\text{FCMA}_j = \sum_i \underbrace{X_i \cdot r_i^{-\gamma}}_{\Psi_i} \cdot \left[P_i^{\text{car}} \cdot (d_{ij}^1)^{-\varepsilon} + (1 - P_i^{\text{car}}) \cdot (d_{ij}^0)^{-\varepsilon} \right]$$

where $\Psi_i = X_i \cdot r_i^{-\gamma}$ represents the baseline residential attractiveness of zone i (residential amenities adjusted for housing costs).

Zonal Price Indices:

$$\Pi_i = \text{RCMA}_i^{-1/\varepsilon}, \qquad P_j = \text{FCMA}_j^{-1/\varepsilon}$$

3.2.6. Production and Spatial Externalities

Production Function and Wage Formation

A perfectly competitive labor market operates in each zone j. A representative firm employs effective labor H_j and floor space S_j at the prevailing equilibrium rental rate r_j, which is also the market rental rate for real estate for firms and households. The Cobb–Douglas production function with constant returns to scale is:

$$Y_j = A_j \cdot H_j^{\alpha} \cdot S_j^{1-\alpha}$$

where A_j is the total factor productivity (TFP) of zone j, $\alpha \in (0, 1)$ is the labor cost share. Since capital is assumed to be infinitely elastic (perfectly mobile) at the city level given world price, it is endogenously absorbed into the productivity parameter A_j, which allows us to simplify the function to two local factors (labor and real estate). Under conditions of perfect competition and zero profits, the first-order conditions give the equilibrium wage:

$$w_j = \alpha \cdot A_j^{1/\alpha} \cdot \left(\frac{1-\alpha}{r_j}\right)^{(1-\alpha)/\alpha}$$

This formula captures two equilibrium relationships: an increase in r_j reduces w_j — the increase in rental costs compresses nominal wages; an increase in A_j increases both simultaneously. In the long-run equilibrium, w_j is updated endogenously at each iteration.

Effective employment. Effective employment H_j differs from the physical number of workers NW_j: due to the selection effect driven by Fréchet shocks, more accessible zones attract more productive workers, which generates higher effective labor productivity per physical worker. Effective employment is calculated through commuter income flows:

$$H_j = T_g \cdot \frac{\sum_i \left(\pi_{ij}^{\text{car}} \cdot v_{n,i}^{\text{car, raw}} + \pi_{ij}^{\text{pt}} \cdot v_{n,i}^{\text{pt, raw}}\right)}{w_j \cdot (1 + \zeta^{\text{div}})}$$

where π_{ij}^{a} is the flow of commuters from zone i to j by mode a; $v_{n,i}^{a,\text{raw}}$ is the basic (unscaled) expected utility of agents in zone i in regime a, which is a direct mathematical consequence of the Fréchet distribution:

$$v_{n,i}^{a,\text{raw}} = (\text{RCMA}_i^a)^{1/\varepsilon}$$

where $\text{RCMA}_i^a = \sum_j (W_j/d_{ij}^a)^{\varepsilon}$ is the resident labor market access index for group a (defined in Section 4.1.3). This is an analytical result: the expected gain of an agent under the Fréchet distribution is proportional to the ε-root of the size of the available labor market.

The agent's full (actual) expected income is formed by scaling this basic income metric by a global factor: $v_{n,i}^{a} = T_g \cdot v_{n,i}^{a,\text{raw}}$.

T_g is a global normalizing anchor:

$$T_g = \frac{\sum_j NW_j}{\sum_j H_j^{\text{raw}}}$$

which scales units of effective employment to shares of physical workers, ensuring aggregate consistency of the labor market. The denominator $w_j \cdot (1 + \zeta^{\text{div}})$ is the full cost of labor, taking into account the dividend premium that the firm actually pays.

Endogenous Productivity: Spatial Agglomeration Economies

Total factor productivity (TFP) A_j is determined endogenously through spatial productivity spillovers. The density of effective employment across transport-accessible zones enhances the productivity of zone %j%through labor market pooling and knowledge-sharing mechanisms:

$$A_j = a_j \cdot \Upsilon_j^{\lambda}$$

where a_j represents the exogenous component of productivity, λ is the elasticity of TFP with respect to the agglomeration index, and Υ_j is the weighted employment density index:

$$\Upsilon_j = \sum_k e^{-\delta \cdot \hat{d}_{jk}} \cdot \frac{H_k}{L_k}$$

where H_k / L_k denotes the density of effective employment in zone k, $\hat{d}_{jk}$ is the shortest path on the transport graph with edge weights defined by the generalized travel time τ_{uv}^{gen} , δ is the geographic decay parameter.

Endogenous Residential Amenities: Spatial Consumption Externalities

A parallel mechanism operates on the residential housing choice side. The quality of the residential environment in zone i determined not only by exogenous traits, but also by the endogenous population density in transport-accessible neighboring zones:

$$X_i = x_i \cdot \Omega_i^{\chi}$$

where x_i represents the exogenous amenity component, χ is the elasticity of residential amenities with respect to population density, and Ω_i is the weighted residential density index:

$$\Omega_i = \sum_k e^{-\rho \cdot \hat{d}_{ik}} \cdot \frac{NR_k}{L_k}$$

where ρ denotes the decay parameter for amenity spillovers, and $\hat{d}_{ik}$ is the shortest path on the transport graph with weights defined by τ_{uv}^{gen}.

This specification yields a spatial lock-in mechanism: population growth in an attractive district drives up Ω_i, which in turn increases X_i, further attracting new residents. The interaction with the real estate market (Section 4.1.5) determines the equilibrium spatial distribution via the trade-off between self-reinforcing density externalities and rising rental rates.

3.2.7. Real Estate Market and Land Use

Discretionary Income and Aggregate Housing Demand

Before agents generate demand in the real estate market, they sequentially allocate funds toward two non-discretionary expenditures: subsistence housing and transportation. The discretionary (net) income of a resident in zone i is defined as:

$$y_{n,i}^{\text{net}} = v_{n,i} - r_i\bar{h} - \kappa_i^{\text{money}}$$

where $v_{n,i}$ denotes gross income (comprising wages adjusted for dividend payouts from the recirculation of land rents and road-pricing revenues, as defined below), $r_i\bar{h}$ represents the cost of the subsistence housing minimum, and κ_i^{money} is the expected monetary transport expenditure. To preserve numerical stability and reflect a realistic consumption floor, $y_{n,i}^{\text{net}}$ is bounded below at 5% of gross income: $y_{n,i}^{\text{net}} \geq 0.05 \cdot v_{n,i}$.

This structural setup establishes a direct link between transport policy and the residential housing market: an increase in κ_i^{money} (e.g., due to congestion pricing or deterioration of the comfort of public transit) compresses the total discretionary fund $E_{n,i} = y_{n,i}^{\text{net}} \cdot NR_i$ thereby dampening effective demand in the real estate market.

The aggregate expenditure of zone i residents on real estate consists of both subsistence and discretionary components:

$$D_i^h = r_i \cdot \bar{h} \cdot NR_i + \gamma \cdot E_{n,i}$$

Construction Technology and Free-Market Real Estate Supply

Floor space supply is generated by a perfectly competitive development sector. Construction firms combine land and capital using a Cobb–Douglas production technology, where $\eta_i \in (0,1)$ represents the cost share of land. Under the zero-profit condition, the fraction η_i of aggregate real estate revenue is allocated to land rent. The equilibrium land rent is expressed as:

$$l_i = \frac{\eta_i \cdot D_i^h}{L_i}$$

where L_i denotes the total land area of zone i. The free-market rental price per square meter of floor space is determined via the developer's inverted cost function:

$$r_i^{\text{free}} = \eta_i^{-\eta_i}(1-\eta_i)^{-(1-\eta_i)}\left(\frac{l_i}{\phi_i}\right)^{\eta_i}$$

where ϕ_i represents the exogenous productivity of developers, capturing localized construction technologies and topographic constraints. In the absence of regulatory restrictions, the implied optimal construction volume is given by:

$$H_i^{\text{implied}} = \frac{D_i^h}{r_i^{\text{free}}}$$

Administrative Land Use Regulations and Market Splitting

The maximum allowable floor space in zone i is fixed by the regulator at:

$$H_i^{\max} = \text{FAR}_i^{\text{cap}} \cdot L_i$$

This regulatory threshold splits the real estate market into two distinct regimes:

Free-Market Regime ($H_i^{\text{implied}} \leq H_i^{\max}$): The floor area ratio (FAR) constraint is non-binding, housing supply is elastic, and the equilibrium rental rate equals the developer's marginal cost: $r_i = r_i^{\text{free}}$.

Regulatory Scarcity Regime ($H_i^{\text{implied}} > H_i^{\max}$): Floor space supply becomes perfectly inelastic, fixed at $H_i^{\max}$. The rental price detaches from construction costs, generating a scarcity premium. Under market clearance governed by Stone–Geary preferences (where discretionary demand $\gamma E_{n,i}/r_i$ plus the subsistence minimum $\bar{h}NR_i$ equals $H_i^{\max}$):

$$r_i^{\text{restricted}} = \frac{\gamma \cdot E_{n,i}}{H_i^{\max} - \bar{h} \cdot NR_i}$$

The denominator captures the surplus of regulatory allowable floor space above the aggregate subsistence requirement. An algorithmic safeguard ensures that $H_i^{\max}$ is strictly bounded below by $\bar{h} \cdot NR_i$. As the denominator approaches zero, prices rise rapidly, effectively displacing surplus population to less restricted zones via the Fréchet spatial sorting mechanism.

3.2.8. General Spatial Equilibrium

Equilibrium Definition

The equilibrium state of the model is defined as a vector of prices and an allocation of agents $r_i, w_j, l_i, v_{n,i}, NR_i, NW_j, H_j, \pi_{ij}, d_{ij}, \ell_{uv}$ such that every agent maximizes utility with respect to residential location, workplace, and transport mode choice, while the labor, real estate, and transport network markets clear simultaneously.

Market Clearance Conditions

Labor Market: Since each agent is assumed to supply exactly one unit of labor to a single workplace, the residential and employment spatial distributions must balance globally:

$$\sum_j NW_j = \sum_i NR_i = 1, \qquad NW_j = \sum_i \pi_{ij}$$

Real Estate Market: The real estate market clears in accordance with the dual-regime framework detailed in Section 4.1.5: in zones where the floor area ratio (FAR) constraint is non-binding, the rental rate equals the developer's marginal cost $r_i = r_i^{\text{free}}$; in zones where the restriction binds, the rental price incorporates a scarcity premium $r_i = r_i^{\text{restricted}}$.

Income Recirculation Mechanism

All revenues generated from land rents and DRP are fully recirculated to residents, which constitutes a critical prerequisite for a consistent welfare analysis. Without such recirculation, DRP tolls would function merely as a baseline welfare transfer from drivers to the municipal budget rather than resolving the market failure associated with traffic congestion externalities.

The land rents and road-pricing revenues aggregate into a single citywide dividend fund:

$$\mathcal{D} = \underbrace{\sum_i l_i \cdot L_i}_{\mathcal{R}^{\text{land}}} + \underbrace{\left(\sum_{i,j} q_{ij}^{\text{car}} \cdot \ell_{ij}\right) \cdot 44}_{\mathcal{R}^{\text{DRP}}}$$

where $q_{ij}^{\text{car}} \in (0,1)$ represents the fraction of the population commuting by automobile between i and j, $\ell_{ij} = \sum_{(u,v)\in \text{path}(i,j)} \ell_{uv}$ — is the cumulative road toll along the route from $i \to j$j, and the multiplier 44 scales daily commute trips to a monthly income equivalent.

The dividend rate is defined as the ratio of this aggregate fund to the city's total wage bill:

$$\zeta^{\text{div}} = \frac{\mathcal{D}}{\sum_j w_j \cdot NW_j}$$

Because the dividend fund is redistributed as a uniform citywide flat-rate premium, the gross workplace income is defined as $v_{n,j} = w_j \cdot (1 + \zeta^{\text{div}})$. In the case of DRP revenue recycling, this mechanism can replicate a revenue-neutral policy directed at reducing the personal income tax rate.

Equilibrium Convergence

The general equilibrium is formalized as the fixed point of a mapping that projects the current vector of prices and spatial allocations onto an updated state. Numerical convergence is achieved when the relative change in real estate rental prices r_i, total factor productivity A_j, residential amenities X_i, transport friction d_{ij}, and land rents l_i between successive iterations falls below an infinitesimal threshold. These five state variables serve as sufficient statistics: they comprehensively map all market clearance feedback loops, while the remaining endogenous variables (NR_i, w_j, π_{ij}, etc.) are uniquely determined as their deterministic functions.

3.2.9. Welfare Measurement

Once the general equilibrium converges, social welfare is quantified via the expected utility of a representative agent. Leveraging the analytical properties of the Fréchet distribution and the equilibrium relation $v_{n,i} \propto \text{RCMA}i^{1/\varepsilon}$, the aggregate systemic attractiveness of zone i as a residential location is expressed as:

$$\Phi_i = X_i \cdot r_i^{-\gamma} \cdot v_{n,i}^{\varepsilon}$$

The citywide aggregate welfare is evaluated using a generalized mean function:

$$U^{\text{city}} = \left(\sum_i \Phi_i^{\eta_g} \right)^{1/\eta_g}$$

where $\eta_g \geq 0$ is the spatial migration elasticity parameter, which governs the degree of inequality aversion in spatial aggregation: $\eta_g = 1$ yields a linear aggregation, whereas $\eta_g \to 0$ approaches a logarithmic formulation that assigns a higher weight to disadvantaged or lagging zones.

The relative change in U^{city} between the baseline and counterfactual scenarios serves as the primary metric for evaluating the structural efficiency of integrated transport and land-use policies.

3.2.10. Model limitations

The model is built on a number of simplifying assumptions that provide analytical tractability but also limit the interpretation of the results. The key limitations and their implications for the work's conclusions are listed below.

Long-term spatial equilibrium and the Soviet legacy. The model calculates a state in which households freely sort between zones according to their own utility. This fundamentally diverges from the reality of Kyiv, where settlement is largely determined by Soviet housing planning: residents of peripheral dormitory areas are unable to move easily due to the cost of housing and credit constraints, which limits their mobility. The consequence: the model's base scenario does not reproduce the observed Kyiv but rather a hypothetical market equilibrium for a stylized city. This creates certain distortions, for example, because in this state of equilibrium, people are more concentrated around the metro compared to real Kyiv; therefore, the share of people using surface public transport is smaller than it should be, and the metro is correspondingly in greater demand.

Focus on rush hour and commuting. The model describes only peak commuting between home and work. The following are excluded from the analysis: people who are not working or working remotely, off-peak trips, freight transport, and logistics. Therefore, the results should be interpreted within the conditions I have set.

Time dimension of DRP. Since DRP affects not only the spatial distribution of trips and changes in mode of travel, but also the temporal distribution of these trips, some drivers shift their trips outside peak times. The presented model is static and does not reproduce this mechanism. Thus, the calculated welfare effect of DRP should be interpreted as a lower bound on the policy's full potential: in practice, a temporal shift in demand would further reduce congestion beyond the effect captured by the model.

Transport network and micromobility. The model reproduces four aggregated travel modes without detailing the network's internal structure. A fragmented system of dedicated lanes for GT, low-mobility modes (bicycles, electric scooters), and multimodal travel chains is not modeled. This limitation is acceptable at the 5×5 zone spatial aggregation level, where each zone covers ~25 km2, but it excludes the analysis of local network effects.

Stylized network. The 5×5 grid is a significant coarsening of the real urban topography, and therefore, the influence of specific highways, intersections, and the exact bottleneck effects of crossing the Dnipro River cannot be reproduced accurately.

Implications for interpretation. The listed limitations narrow the scope of the results, but do not undermine the main analytical goal. The model identifies the directions and relative magnitudes of DRP effects in a controlled equilibrium environment — this is the subject of the study. If microdata is available, the model can be recalibrated without changing the structural specification.

3.3. Model metrics and calibration

3.3.1. Spatial network configuration

The city is represented by a regular 5×5 grid ($I = 25$ zones), where each zone corresponds approximately to 25 km² of urban area. Physical distances are Euclidean and scaled by a circuity coefficient $\xi = 1{,}2$, which corresponds to the median value for dense urban street networks (Giacomin & Levinson, 2015). Road links are defined between neighboring grid nodes (distance $\leq 1{,}5$ units); the basic capacity is $K = 4,000$ transport units per link. Free flow speeds are set according to the physical characteristics of the Kyiv network: car — 50 km/h, bus — 25 km/h, metro — ≈38 km/h, walking — 5 km/h.

To reproduce the key geographical feature of Kyiv, a barrier of increased transport resistance is introduced between rows 3 and 4 of the grid: doubled travel time and reduced throughput $K = 2,000$ i.e. — a stylized analogue of the Dnipro River. The metro is represented by three lines that intersect at the central node (zone 13). The time penalty for transferring between lines is ≈5 min; the penalty for accessing the station is ≈21 min (duration of the walk to and from the metro + waiting).

3.3.2. Calibration strategy and targets

The model parameters are divided into two classes. Externally identified parameters are borrowed from theoretical or empirical literature without further adjustment. Calibrated parameters are selected iteratively so that the basic equilibrium state of the model reproduces a number of target landmarks of the Kyiv urban system. The calibration is based on three landmarks that differ in the reliability of the source, and this difference is explicitly stated. The first landmark is a hard empirical moment: the level of traffic congestion during the rush hour, which is a delay of ~76% relative to the free flow ($\text{TTI} \approx 1{,}76$) (Office of Transformation, n.d.).

The second and third benchmarks are range assumptions, not measured data. These are the expected modal choice structure for commuting (car — 35–42%, metro — 25–30%, surface public transport — 20–27%, walking — up to 15%) and the expected average level of car ownership of 40–65%. It should be emphasized that there are currently no representative microsamples of commuting or panel data on car ownership for Kyiv, and the available aggregated indicators describe the entire population of the city, while the model operates only on the segment of workers with an endogenous decision to own a car — these are different distributions, which makes direct comparisons incorrect. Therefore, these two ranges are assumptions about a plausible choice structure adjusted for model bias, and not exact empirical moments. They are used as compatibility constraints: the parameters are chosen so that the equilibrium structure falls within these ranges, without claiming to accurately reproduce the missing observations.

3.3.3. Externally set parameters

Production. The labor share of output is set at $\alpha = 0{,}80$, which is standard for urban quantitative spatial models and reflects the labor share in the non-real estate sector of the urban firm. The variance of the idiosyncratic Fréchet shocks $\varepsilon = 4$ selected within the range typical of spatial-economic literature (Ahlfeldt et al., 2015; Redding & Rossi-Hansberg, 2017); is chosen within the range typical of the spatial-economic literature (Ahlfeldt et al., 2015; Redding & Rossi-Hansberg, 2017); this parameter controls the degree of sorting of agents by location.

Housing. The discretionary share of housing costs in the Stone–Gearey function is $\gamma = 0{,}25$. The subsistence minimum of living space is $\bar{h} = 0{,}35$. The share of land in the developer's costs η = 0,30 is set the same for all zones. This value is somewhat lower than empirical estimates of the share of land in the cost of housing construction in countries with developed real estate markets (~0.35–0.40 according to Davis & Heathcote, 2007), reflecting the assumption of a higher relative weight of capital costs in the stylized network. The increased cost of construction in central zones is given by the reduced productivity of the developer $\phi_{13} = \phi_8 = 0{,}60$, reflecting historical constraints and higher costs of densification of the center. The height and density restrictions in the status quo are set in a stylized manner: $\mathrm{FAR}_{13} = 0{,}03$, $\mathrm{FAR}_8 = 0{,}02$.

Agglomeration. The elasticity of productivity to employment density (production externalities) is set at $\lambda = 0{,}08$. For comparison, Allen & Arkolakis (2022) choose a value of 0.10 in their baseline specification; reviews of the empirical literature (Rosenthal & Strange, 2004; Combes & Gobillon, 2015) indicate a range of city-level agglomeration elasticities of approximately 0.03–0.08. The adopted value of 0.08 corresponds to the upper end of the range. The elasticity of recreational amenities to population density χ = 0,10 reflects positive externalities from density on the demand side of housing: more residents in transport-accessible areas expand the local base of services and social interactions, increasing the attractiveness of the area to new residents. The positive sign of χ corresponds to the "consumer city" hypothesis (Glaeser, Kolko & Saiz, 2001). The specific value of 0.10 is chosen as the minimum that generates a noticeable spatial anchoring effect, while satisfying the condition of the existence of a single equilibrium χ < 1/(2ε) = 0,125

The geographic decay parameters for spatial externalities — $\delta = 4$ for productivity spillovers and $\rho = 2$ for recreational ones — are not borrowed directly from a specific source, but are chosen according to the functional considerations of the stylized model: they specify how quickly the externality weakens with distance on the transport graph. The value $\delta = 4$ means that production spillovers are significant mainly within one grid cell (≈5 km) and are almost exhausted beyond its boundaries; a lower value of $\rho = 2$ allows recreational externalities to spread somewhat wider, while maintaining the distribution of amenities of higher significance than the district one. This hierarchy corresponds to the empirical consensus: production agglomeration effects decay rapidly with distance and are mostly evident within a few kilometers (Rosenthal & Strange, 2004; Combes & Gobillon, 2015), while amenity effects have a wider spatial reach.

Value of time. The fraction of salary that an agent is willing to spend on saving time is set at $\vartheta = 0{,}50$ — the upper limit of the range recommended for Central and Eastern European countries by the European Commission's Cost-Benefit Analysis Guidelines (European Commission, 2014) and confirmed by an international meta-analysis of the value of time (Shires & de Jong, 2009). The income elasticity of the value of time $\xi = 0{,}72$ is borrowed from the UK Department for Transport's methodological recommendations (WebTAG Unit A1.3, 2023), which are applied to markets where there are no SP/RP studies of their own; it reflects the fact that the value of time increases subproportionally with income.

Welfare aggregation. The aggregation parameter $\eta_g = 1{,}00$ is a normative choice, not a calibrated value: it specifies a utilitarian public welfare function with equal weights for all residents.

3.3.4. Calibrated parameters

CBD productivity gradient (calibration to TTI). The exogenous productivity components of the central zones (a_{13}, a_8, a_{18}) are selected by direct iteration to reproduce the target congestion level: those values are chosen for which the TTI coincides with the empirical indicator 1.76. Since the congestion level is a monotonically increasing function of the CBD gradient with other fixed parameters, the solution is unique. The calibrated values (1.57 / 1.37 / 1.17) correspond to a CBD productivity premium of 17–57%, which lies in the documented empirical range (Ahlfeldt & Pietrostefani, 2019).

Modal selection parameters (calibration to the split structure). The time sensitivity $\kappa_t = 0{,}30$ and the correlation parameter in the public transport nest $\lambda_{pt} = 0{,}50$ define the shape of the nested logit structure of mode choice. The basic mode attractiveness coefficients—car (normalized to $b_{\text{car}} = 1{,}00$), surface public transport ($b_{pt} = 0{,}45$, or $0{,}55$ in the comfort improvement scenario), metro ($b_m = 0{,}6$) and pedestrian ($b_{\text{ped}} = 0{,}7$) — are chosen so that the equilibrium modal choice structure falls within the given target range. These values are not borrowed from a specific external study: the values of the modes in this model (private car, metro, surface PT, walking) are specific to the Kyiv context, so the attractiveness coefficients are calibrated parameters, not external estimates.

Car ownership parameters. The fixed monthly cost of car ownership $p_{\text{car}} = 0{,}21$ and the sensitivity of the purchase decision $\kappa_{\text{own}} = 15$ are chosen so that the average share of car owners falls within the target range of 40–65%. The parameter κ_{own} provides an S-shaped response of the share of car ownership to the net benefit of ownership, reflecting a gradual, rather than a jump-like, adaptation of the ownership structure to changes in costs.

3.3.5. Notes on interpretation

The limits of the calibration should be clearly understood. Only one of the three benchmarks — the level of congestion — is based on a solid local measurement. The modal choice structure and the level of car ownership are assumptions about plausible ranges to which the corresponding group of parameters is adjusted. This limitation does not undermine the main analytical goal of the work: the model is not intended to provide a point forecast of absolute values, but to identify the directions and relative magnitudes of the effects of dynamic road pricing in a controlled equilibrium environment. Comparisons of equilibria between scenarios — not their absolute levels — are the subject of the study, and it is these comparative statics that are relatively robust to the aforementioned assumptions, as confirmed by the sensitivity analysis (Appendix A). In case of representative microdata on work trips in Kyiv become available, the model parameters can be updated without changing the structural equations and functional forms.

3.4. Results

3.4.1. Experimental Design and Scenario Matrix

This section presents the equilibrium welfare outcomes of a 24-scenario full-factorial experiment across four independent policy dimensions: *dynamic road pricing (DRP)*; *bus fleet architecture* (elastic supply versus a fixed fleet of 3,000 vehicles); *land use regulation* (strict FAR restrictions / partial liberalisation / no restrictions); and *bus quality*. All scenarios are evaluated in the long-run spatial equilibrium with full household and firm re-sorting. Welfare is expressed throughout as a percentage of the *Kyiv status-quo baseline* — Scenario 7 (fixed fleet, standard quality, strict zoning, DRP=0) — which is normalised to 100%. The DRP revenue and all land rents are fully recirculated to residents as a uniform wage supplement, ensuring distributional neutrality of the fiscal mechanism. Table 1 reports the full scenario matrix.

Table 1. Welfare outcomes across all 24 scenarios (% of Kyiv baseline = 100%)

Yellow = Kyiv status-quo baseline (★). Green = peak welfare scenario. ΔW_DRP: percentage change U(DRP=1)/U(DRP=0)–1 within scenario pair.

Configuration	Zoning regime	U, % of baseline (DRP=0)	U, % of baseline (DRP=1)	ΔW_DRP (%)
Elastic fleet, Standard quality	Strict	103.4%	111.4%	+7.7%
Elastic fleet, Better quality	Strict	104.4%	106.1%	+1.6%
Elastic fleet, Standard quality	Partial lib.	125.7%	151.8%	+20.8%
Elastic fleet, Better quality	Partial lib.	127.4%	159.3%	+25.1%

Elastic fleet, Standard quality	No restrictions	150.2%	198.9%	+32.4%
Elastic fleet, Better quality	No restrictions	153.2%	207.1%	+35.2%
Fixed fleet, Standard quality ★	Strict	100.0%	105.6%	+5.6%
Fixed fleet, Better quality	Strict	99.3%	104.0%	+4.7%
Fixed fleet, Standard quality	Partial lib.	121.9%	147.1%	+20.7%
Fixed fleet, Better quality	Partial lib.	121.3%	144.6%	+19.2%
Fixed fleet, Standard quality	No restrictions	143.2%	162.2%	+13.3%
Fixed fleet, Better quality	No restrictions	141.4%	162.9%	+15.2%

3.4.2. DRP in Isolation Under Status-Quo Institutional Constraints

In the status-quo institutional environment — fixed bus fleet, strict zoning, and standard bus quality — the introduction of DRP raises aggregate welfare from 100% to 105.6% of the Kyiv baseline, a gain of +5.6 percentage points. This represents the *lower bound* of DRP's welfare impact in the model, as all complementary reforms are simultaneously absent. The mechanism operates via three primary channels.

First, the DRP toll internalises the marginal external congestion cost, reducing the equilibrium car share from 37.4% to 32.6% — a contraction of approximately 47,000 vehicle trips. Second, cleared road space allows the non-segregated bus network to operate at materially lower effective travel times without any capital investment, generating a transit quality dividend for surface public transport users. Third, the toll revenue, when recirculated as a wage supplement, raises effective disposable income across all residential zones: the DRP dividend adds 2.3 percentage points to workers' wages on top of the existing 13.1% land rent recirculation rate, bringing the aggregate city dividend to 15.4% — a non-trivial fiscal offset against the monetary toll burden.

Despite these gains, the standalone DRP outcome (+5.6%) is modest relative to the feasible policy frontier explored in this study, which reaches 207.1% of the Kyiv baseline in the peak scenario. The key binding constraint is not the DRP mechanism itself, but the institutional environment in which it operates: a supply-constrained housing market and a capacity-constrained transit network limit the spatial reallocation that DRP would otherwise induce.

3.4.3. Land Use Regulation as the Primary Welfare Bottleneck

The zoning regime emerges as the single most powerful determinant of equilibrium welfare in the model — one that unambiguously dominates the direct effect of DRP when evaluated in isolation. In the *absence of DRP*, moving from strict FAR restrictions to full deregulation of construction raises welfare from 100% to 143.2% in the fixed-fleet configuration and from 103.4% to 153.2% with an elastic fleet — welfare gains of +43.2 and +49.8 percentage points respectively, compared to only +5.6 points from DRP alone. These gains stem from two reinforcing general-equilibrium channels.

The first is the *housing cost relief channel*. Under strict zoning, the two central zones (13 and 8) operate in the regulatory scarcity regime, where the market rental price detaches from the developer's marginal cost. In the Kyiv baseline, the maximum zone-level housing expenditure share reaches 72.2%, indicating extreme spatial inequality in housing affordability within a single city. Full deregulation switches central zones to the free-market regime, compressing the maximum expenditure share to 37.5% and the city mean from 33.8% to 30.1%.

The second is the *spatial re-sorting channel*. Under strict zoning, the supply elasticity of central-area housing is effectively zero: households displaced by rising rents cannot be accommodated by new construction and must relocate to peripheral zones, increasing commuting distances and effective transport costs. Deregulation restores supply elasticity, enabling households to co-locate with high-productivity employment zones and activating the agglomeration externality through higher effective employment density within transport reach.

Crucially, zoning liberalisation and DRP exhibit super-additive complementarity. The DRP welfare gain increases monotonically with the degree of liberalisation: from +5.6 percentage points under strict zoning to +20.7 under partial liberalisation and +13.3 under full deregulation in the fixed-fleet configuration, and from +7.7 to +20.8 to +32.4 percentage points in the elastic-fleet configuration. The economic logic is transparent: DRP activates re-sorting toward the city centre by lowering the effective transport cost for transit users; deregulation ensures that this re-sorting demand is accommodated by new supply rather than absorbed into higher rents. Resolving both distortions simultaneously generates an agglomeration dividend that neither reform can achieve alone. In the fixed-fleet configuration the pattern is non-monotonic (+5.6, +20.7, +13.3 percentage points), reflecting the overcrowding penalty that reduces the transit dividend at higher utilisation levels.

3.4.4. Bus Fleet Architecture: The Fixed-Fleet Overcrowding Paradox

The bus fleet architecture produces a structurally counterintuitive result: improving bus quality reduces aggregate welfare in every scenario involving a fixed fleet cap, the sole exception being the combination of DRP with full zoning deregulation, where quality gains marginally outweigh the crowding penalty. In the Kyiv-like baseline configuration, upgrading bus comfort parameters — the base attractiveness coefficient from 0.45 to 0.55 and the structural discomfort weight from 1.5 to 1.4 — lowers welfare from 100.0% to 99.3% without DRP, and from 121.9% to 121.3% with partial liberalisation. This result, which appears to contradict the standard welfare analysis of transit investment, is entirely consistent with the internal mechanics of the model.

The mechanism operates through the endogenous crowding multiplier. When bus quality improves, the utility advantage of surface public transport increases, inducing a modal shift toward buses. However, the total fleet is capped at 3,000 vehicles. The crowding multiplier in the baseline with standard bus quality already reaches ×2.34 at equilibrium. Upon quality improvement, induced demand pushes the vehicle-capacity ratio above unity, triggering the quadratic over-capacity penalty: the effective perceived travel time rises to ×2.16–×4.15 across zoning and DRP configurations, despite the nominally better fleet. The net effect on generalised trip cost becomes negative for bus users, producing a second-round shift back to cars and ultimately leaving both bus passengers and road users worse off.

This mechanism is entirely absent in the elastic-fleet configuration, where quality improvements always yield positive welfare effects. Welfare with an elastic fleet and better bus quality reaches 153.2% without DRP and 207.1% with DRP and full deregulation — the global maximum in the scenario space — compared to 150.2% and 198.9% with standard quality. The policy implication is direct: bus quality investment is only welfare-improving if paired with a commensurate expansion of fleet capacity. Improvements to rolling stock must precede or accompany fleet scaling, or they will be absorbed entirely by overcrowding rather than generating welfare gains for passengers.

A distinct mechanism operates in the elastic-fleet configuration under strict zoning, where DRP's welfare gain contracts sharply from +7.7 percentage points with standard bus quality to +1.6 percentage points with improved quality — despite the absence of any fleet capacity constraint. Here the crowding paradox does not apply: the elastic fleet expands proportionally to absorb induced demand, and bus comfort genuinely improves. The issue lies instead in the housing market. Better buses alone, without DRP, generate a modest welfare gain (from 103.4% to 104.4% of the Kyiv baseline), as the re-sorting pressure on central zones remains limited. However, when better buses are combined with DRP, the two transport improvements act jointly as a stronger residential re-sorting signal: agents simultaneously face lower road congestion costs and more comfortable transit, making central-zone residence disproportionately more attractive relative to the no-DRP baseline. Under strict zoning, where housing supply in central zones is perfectly inelastic, this amplified demand pressure translates entirely into higher rents rather than new construction — mean housing expenditure rises from 35.2% to 36.3% and the peak zone-level share reaches 77.4%, the highest value in the entire scenario space. The housing cost spike under the DRP + better buses combination is materially larger than under DRP alone, and under the strict zoning regime it is large enough to absorb almost the entire transport welfare dividend, leaving a net DRP gain of only +1.6 percentage points. This result underscores that the transit gentrification effect identified in Section 3.4.6 is not only more severe under better service quality, but is specifically a product of the interaction between simultaneous transport improvements and the inelastic housing supply constraint.

3.4.5. Complementarity Structure of the Full Reform Package

The maximum welfare outcome of 207.1% of the Kyiv baseline is achieved by combining DRP, an elastic bus fleet, no zoning restrictions, and improved bus quality. This peak gain is not merely additive: the three reform dimensions are mutually reinforcing through the shared channel of spatial re-sorting. DRP reduces the cost of central-area access for transit users; zoning deregulation ensures that increased access value is captured through residential re-sorting rather than rent extraction; elastic bus supply translates the modal shift into actual fleet expansion and reduced crowding; and better bus quality amplifies the attractiveness of the now-uncrowded transit network. The four reforms constitute a *policy complementarity cluster*: each individual reform raises the marginal return to every other.

A notable feature is the *sharp non-linearity* of DRP effects across zoning regimes. The DRP gain increases from +5.6 percentage points under strict zoning to approximately +32 under full deregulation in the elastic-fleet configuration — a sixfold amplification driven purely by the removal of the housing supply constraint. This non-linearity has a direct implication for the political economy of road pricing reform: advocating DRP as a standalone instrument in a supply-constrained housing market systematically understates its welfare potential. The full case for DRP cannot be made without simultaneously addressing the housing supply constraint.

The contrast between the *minimum and maximum intervention* scenarios is stark. Adding DRP alone to the Kyiv status quo yields 105.6% of baseline welfare. Full deregulation alone (elastic fleet, no restrictions, standard buses, no DRP) yields 150.2%. The combination of DRP with full deregulation and an elastic, improved bus fleet yields 207.1%. The excess of the combined outcome over any sum of isolated effects confirms the super-additive nature of the reform package.

3.4.6. Summary of Findings

The scenario analysis yields the following ordered hierarchy of policy effects:

(I) Land use liberalisation is the single most powerful welfare intervention, raising welfare from 100% to 141–153% of the Kyiv baseline even without DRP, by restoring supply elasticity in constrained central zones and eliminating the housing scarcity premium.

(II) DRP and zoning deregulation are super-additive complements: the combination reaches 207.1% of baseline — far exceeding the sum of standalone effects — because each reform removes a constraint that limits the welfare impact of the other.

(III) DRP in the current Kyiv institutional context yields only modest gains (+5.6 p.p.), principally because the housing supply constraint absorbs the location rent dividend from re-sorting and the fixed fleet absorbs transit quality gains into overcrowding.

(IV) Bus quality investment is welfare-reducing under a fixed fleet cap, due to an endogenous overcrowding paradox in which induced demand exceeds fixed supply capacity. Quality investment must be accompanied by fleet expansion to yield positive welfare effects.

(V) DRP's welfare gains scale strongly with the degree of liberalisation: from +5.6 p.p. under strict zoning to +32.4 p.p. under full deregulation (elastic fleet), a sixfold amplification driven entirely by housing supply elasticity.

Conclusion

This thesis set out to evaluate the net welfare effects of Dynamic Road Pricing in Kyiv under realistic second-best institutional conditions. Three analytical stages were completed: a theoretical case for DRP as the first-best mechanism for internalising marginal external congestion costs; a systematic examination of the second-best distortions — imperfect transit substitute quality, inelastic bus supply, and binding land-use regulation — that modify DRP's welfare impact in the Kyiv context; and a quantitative spatial model calibrated to Kyiv's observed spatial structure, used to run a 24-scenario full-factorial experiment across four policy dimensions.

The central finding is that DRP is welfare-improving under every combination of institutional conditions examined, but its magnitude depends almost entirely on the complementary reforms in place. In isolation, against the stylized Kyiv status-quo baseline of a fixed bus fleet, strict zoning, and standard bus quality, DRP raises aggregate welfare by +5.6 percentage points. In the full-reform scenario — elastic bus fleet, complete zoning liberalisation, and improved bus quality — the DRP gain reaches +35.2 percentage points, bringing the combined policy frontier to 207.1% of the Kyiv baseline.

Two structural results deserve particular emphasis. First, land-use and building regulation emerges as the binding constraint on DRP's welfare potential. Zoning liberalisation alone, even without DRP, raises welfare by more than 40 percentage points — eight times the isolated DRP effect. The economic mechanism is straightforward: DRP activates household re-sorting toward the city centre, but under inelastic housing supply this demand pressure is absorbed into higher rents rather than new construction, generating a transit gentrification effect that partially offsets the transport dividend. DRP and zoning liberalisation are super-additively complementary: the DRP gain is six times larger under full deregulation than under strict FAR restrictions. The full welfare case for road pricing therefore cannot be made without simultaneously addressing the housing supply constraint.

Second, the bus fleet architecture produces a structural paradox under a fixed fleet cap: improving bus comfort reduces welfare, because induced modal shift drives bus occupancy above capacity and triggers a crowding disutility penalty that overrides the quality gain. This result inverts the standard welfare logic of transit investment and points to a policy sequencing requirement — fleet expansion must accompany, or precede, any improvement to rolling stock quality.

The results also confirm the theoretical expectation from the second-best analysis. The welfare cost of operating DRP in a distorted institutional environment is quantitatively large: the difference between the standalone DRP gain (+5.6 pp) and the full-reform frontier (+107.1 pp over baseline) represents value that is structurally inaccessible as long as the complementary markets remain distorted. Standard partial-equilibrium cost-benefit analysis, which evaluates DRP against the road market alone, would systematically understate this constraint.

Several limitations bound the interpretation of these findings. The model is calibrated to a stylised 5×5 grid that cannot reproduce Kyiv's exact network topology, and the modal choice structure rests on range assumptions in the absence of representative microdata on Kyiv commuting behaviour. The static formulation excludes temporal demand redistribution — the shift of trips outside peak hours induced by DRP — meaning the welfare estimates represent a lower bound on the full congestion-relief effect.

In sum, the welfare viability of Dynamic Road Pricing in Kyiv is not a binary question but a function of the institutional environment in which it operates. The model demonstrates that DRP is a consistently positive reform, yet its net effect can range from marginal to transformative depending on whether housing supply and transit capacity are simultaneously liberalised. Policymakers who evaluate DRP in isolation risk both understating its potential and designing it to fail.

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APPENDIX A
Sensitivity Analysis of Model Results to Key Parameters

1. Methodology

Method: ceteris paribus — each parameter is varied while all others are held at baseline. Baseline: ε = 4, p_car = 0.21, λ_pt = 0.5, κ_t = 0.30. Three equilibrium scenarios are compared: (1) DRP = 0 — status quo; (2) DRP = 1 only — dynamic road pricing alone; (3) DRP = 1 + full package — DRP with free zoning (FAR = ∞), elastic bus fleet, and improved buses.

Key performance indicators: ΔW % = [W(DRP=1)−W(DRP=0)]/W(DRP=0)·100; Δ car p.p. = car share(DRP=1)−car share(DRP=0) — negative is desired; Δγ p.p. = mean housing expenditure share(DRP=1)−(DRP=0) — negative is desired.

2. Fréchet Dispersion Parameter (ε)

Inverse variance of idiosyncratic preference shocks. Higher ε = "less mobile" agents. Calibration range: ε ∈ [3; 6] (Ahlfeldt et al., 2015; Tsivanidis, 2023). Baseline: ε = 4.

Table A.1 — Absolute outcomes by ε

Value	Scenario	U	Car, %	Hous. γ, %
4 ★	Status quo (DRP=0)	3.9606	37.4%	33.8%
	DRP=1 only	4.1834	32.6%	34.0%
	DRP=1 + full	8.2030	18.8%	31.8%
3 (high mob.)	Status quo (DRP=0)	6.0073	40.9%	33.2%
	DRP=1 only	6.6494	36.4%	32.7%
	DRP=1 + full	8.7161	20.2%	32.3%
5 (low mob.)	Status quo (DRP=0)	2.7054	34.8%	34.1%
	DRP=1 only	3.0614	29.5%	34.2%
	DRP=1 + full	8.6659	17.5%	31.3%

Table A.2 — DRP welfare effects by ε

Value	ΔW DRP=1, %	Δcar DRP=1, p.p.	Δγ DRP=1, p.p.	ΔW full, %	Δcar full, p.p.	Δγ full, p.p.
4 ★	+5.63%	−4.72	+0.20	+107.12%	−18.57	−2.00
3	+10.69%	−4.50	−0.50	+45.09%	−20.62	−0.90
5	+13.16%	−5.33	+0.10	+220.32%	−17.26	−2.80

Note. ΔW at ε = 5 (+220.3%) is a scale artefact of low baseline welfare (W = 2.71); post-reform values are comparable across all ε. Qualitative conclusions are robust.

3. Fixed Car Ownership Cost (p_car)

Monthly fixed cost of car ownership (insurance, maintenance, depreciation, parking), excluding variable fuel costs. Baseline: 0.21. Range: 0.16–0.26 (±24%).

Table A.3 — Absolute outcomes by p_car

Value	Scenario	U	Car, %	Hous. γ, %
0.21 ★	Status quo (DRP=0)	3.9606	37.4%	33.8%
	DRP=1 only	4.1834	32.6%	34.0%
	DRP=1 + full	8.2030	18.8%	31.8%
0.16 (cheap)	Status quo (DRP=0)	3.9155	44.5%	33.8%
	DRP=1 only	4.7815	39.2%	32.7%
	DRP=1 + full	7.3000	27.5%	31.0%
0.26 (exp.)	Status quo (DRP=0)	3.8952	27.8%	35.4%
	DRP=1 only	4.5623	24.2%	35.0%
	DRP=1 + full	9.7294	11.5%	32.8%

Table A.4 — DRP welfare effects by p_car

Value	ΔW DRP=1, %	Δcar DRP=1, p.p.	Δγ DRP=1, p.p.	ΔW full, %	Δcar full, p.p.	Δγ full, p.p.
0.21 ★	+5.63%	−4.72	+0.20	+107.12%	−18.57	−2.00
0.16	+22.12%	−5.31	−1.10	+86.44%	−17.06	−2.80
0.26	+17.13%	−3.65	−0.40	+149.78%	−16.36	−2.60

Note. At p = 0.16, higher initial car share (44.5%) maximises scope for congestion internalisation; full-package ΔW rises monotonically with p, reflecting complementarity between expensive car ownership and reformed transit.

4. PT Mode Correlation Parameter (λ_pt)

Nesting coefficient in the nested logit: governs independence among public transport modes. λ → 0: perfect substitutes; λ → 1: independent. Baseline: 0.5. Range: 0.3–0.7.

Table A.5 — Absolute outcomes by λ_pt

Value	Scenario	U	Car, %	Hous. γ, %
0.50 ★	Status quo (DRP=0)	3.9606	37.4%	33.8%
	DRP=1 only	4.1834	32.6%	34.0%
	DRP=1 + full	8.2030	18.8%	31.8%
0.3 (substitutes)	Status quo (DRP=0)	4.0118	40.3%	33.2%
	DRP=1 only	4.7504	35.8%	32.6%
	DRP=1 + full	7.7625	22.5%	31.4%
0.7 (independent)	Status quo (DRP=0)	3.8798	33.2%	34.5%
	DRP=1 only	4.4015	29.3%	34.1%
	DRP=1 + full	8.8117	15.2%	32.1%

Table A.6 — DRP welfare effects by λ_pt

Value	ΔW DRP=1, %	Δcar DRP=1, p.p.	Δγ DRP=1, p.p.	ΔW full, %	Δcar full, p.p.	Δγ full, p.p.
0.50 ★	+5.63%	−4.72	+0.20	+107.12%	−18.57	−2.00
0.3	+18.41%	−4.54	−0.60	+93.49%	−17.79	−1.80
0.7	+13.45%	−3.93	−0.40	+127.12%	−18.06	−2.40

Note. Moderate sensitivity: ΔW spread between λ = 0.3 and λ = 0.7 is 5.0 p.p. The full-package ΔW at λ = 0.7 (+127.1%) exceeds baseline (+107.1%), reflecting better PT substitutability under transit reform.

5. Travel Time Sensitivity (κ_t)

Slope of transport disutility: higher κ_t = stronger delay penalty and greater route-choice elasticity. Calibrated via UK WebTAG (VoT income elasticity = 0.72). Baseline: 0.30. Range: 0.22–0.38 (±27%).

Table A.7 — Absolute outcomes by κ_t

Value	Scenario	U	Car, %	Hous. γ, %
0.30 ★	Status quo (DRP=0)	3.9606	37.4%	33.8%
	DRP=1 only	4.1834	32.6%	34.0%
	DRP=1 + full	8.2030	18.8%	31.8%
0.22 (low VoT)	Status quo (DRP=0)	3.9752	47.7%	30.5%
	DRP=1 only	4.6947	41.0%	30.3%

	DRP=1 + full	7.2267	31.4%	28.6%
0.38 (high VoT)	Status quo (DRP=0)	3.8978	28.0%	36.3%
	DRP=1 only	3.9339	24.2%	36.7%
	DRP=1 + full	9.4282	12.6%	33.1%

Table A.8 — DRP welfare effects by κ_t

Value	ΔW DRP=1, %	Δcar DRP=1, p.p.	Δγ DRP=1, p.p.	ΔW full, %	Δcar full, p.p.	Δγ full, p.p.
0.30 ★	+5.63%	−4.72	+0.20	+107.12%	−18.57	−2.00
0.22	+18.10%	−6.71	−0.20	+81.79%	−16.36	−1.90
0.38	+0.93%	−3.74	+0.40	+141.89%	−15.34	−3.20

Note. Strongest uncertainty source. At κ = 0.38, DRP alone yields only +0.93% (demand pre-suppressed); the full package reaches +141.9% via the zoning channel. At κ = 0.22, free zoning induces sprawl, worsening congestion relative to DRP-only.

6. Summary Sensitivity Table

Table A.9 consolidates DRP effects across all four parameters. ★ rows denote the baseline parameterisation.

Table A.9 — Consolidated DRP effects across parameters

Param.	Value	ΔW DRP=1	Δcar DRP=1	Δγ DRP=1	ΔW full	Δcar full	Δγ full
ε	4 ★	+5.63%	−4.72	+0.20	+107.12%	−18.57	−2.00
	3	+10.69%	−4.50	−0.50	+45.09%	−20.62	−0.90
	5	+13.16%	−5.33	+0.10	+220.32%	−17.26	−2.80
p_car	0.21 ★	+5.63%	−4.72	+0.20	+107.12%	−18.57	−2.00
	0.16	+22.12%	−5.31	−1.10	+86.44%	−17.06	−2.80
	0.26	+17.13%	−3.65	−0.40	+149.78%	−16.36	−2.60
λ_pt	0.50 ★	+5.63%	−4.72	+0.20	+107.12%	−18.57	−2.00
	0.30	+18.41%	−4.54	−0.60	+93.49%	−17.79	−1.80
	0.70	+13.45%	−3.93	−0.40	+127.12%	−18.06	−2.40
κ_t	0.30 ★	+5.63%	−4.72	+0.20	+107.12%	−18.57	−2.00
	0.22	+18.10%	−6.71	−0.20	+81.79%	−16.36	−1.90
	0.38	+0.93%	−3.74	+0.40	+141.89%	−15.34	−3.20

Note. All effects measured relative to DRP = 0 of the same parameter variant. ★ = baseline parameterisation.

7. Conclusions

— Sign robustness fully confirmed: $\Delta W > 0$ and Δ car < 0 across all 12 parameter configurations. The qualitative finding in favour of DRP is entirely robust to parametric uncertainty within the tested ranges.

— Primary source of quantitative uncertainty: κ_t. Spread in ΔW (DRP=1 only) between $\kappa\_t = 0.22$ (+18.1%) and $\kappa\_t = 0.38$ (+0.93%) is 17.2 p.p. Priority calibration against travel microdata is recommended.

— ε contributes moderate uncertainty (spread 7.5 p.p.): more mobile agents ($\varepsilon = 3$) respond more elastically to DRP. The inflated ΔW at $\varepsilon = 5$ (+220.3%) is a scale artefact of low baseline welfare.

— p_car and λ_pt contribute lower uncertainty (ΔW spread ≈5 p.p. each). The strongest DRP effect occurs with cheap cars (p = 0.16), maximising the scope for congestion internalisation.

— Caveat for $\kappa\_t = 0.22$: at low value of time, free zoning induces spatial sprawl, increasing total vehicle-kilometres and worsening congestion relative to the DRP-only scenario.

APPENDIX B
Model Source Code

The full model source code (MATLAB/Octave .m files) used to produce all quantitative results reported in this thesis is available upon request from the author or via the project repository at: [https://drive.google.com/drive/folders/1YIU19jzZ77QPX-sM3cE_w379FbYnFFqK?usp=sharing].