Urban Sprawl and Public Transport: A Quantitative Spatial Model for a Railway Policy in Budapest

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Short summary

Investing in suburban public transport is often promoted to encourage mode shift and mitigate the negative impacts of car use. However, improved suburban access may unintentionally drive suburbanization and urban sprawl, introducing unexpected externalities. This study examines these counteracting effects using a spatial computable general equilibrium model calibrated as a quantitative spatial model. The method is applied to a proposed railway tunnel under the Danube in Budapest. Results show an increase in public transport use along the railway, alleviating road congestion in the city center. While no strong evidence of urban sprawl emerges, the model reveals that reduced car congestion may prompt some inner-city residents to revert to car use. These findings suggest that investments in suburban public transport should be paired with traffic calming measures to prevent offsetting behavioral responses and maximize the policy's effectiveness.

Keywords: land use, spatial equilibrium, suburbanization, public transport, urban economics

1 Introduction

This paper examines the relationship between public transport investments and urban sprawl. Both municipal and higher-level governments, along with society at large, seek to reduce car use in urban areas. One potential solution might be investing in public transport, which can encourage the desired transport mode shift by offering reduced travel times, increased comfort, and improved reliability, among other benefits. As commuting costs decrease, it is expected that individuals will be inclined to move to suburban areas that offer higher amenities and greater affordability. This could result in urban sprawl and its associated negative effects. A key question is whether railway-induced sprawl is less harmful to society than car-induced sprawl. Railway infrastructure investment may prompt relocation to areas within the catchment area of stations, resulting in higher population density compared to car-oriented suburbs. The primary objective of this paper is to determine whether suburbanization and a shift towards public transport usage can be observed as a consequence of a large-scale public transport investment and to assess the resulting changes in the city's internal spatial structure. A planned railway tunnel under the river Danube, connecting two railway terminals in Budapest, serves as a case study application of the model.

The research topic is connected to two strands of the literature: (i) the literature on urban sprawl, and (ii) the quantitative spatial modeling (QSM) literature.

Urban sprawl is defined as excessive or inefficient growth of cities (Brueckner, 2000), characterized by low-density outward expansion (Carruthers & Ulfarsson, 2003; Hortas-Rico, 2014; Patacchini et al., 2009). It is associated with negative environmental, social, and economic impacts, including increased pollution (Bart, 2010), racial segregation (Patacchini et al., 2009), and higher costs for public services (Carruthers & Ulfarsson, 2003). Although road infrastructure improvements will likely facilitate sprawl, the relationship between public transport investments and suburbanization is less clear.

Quantitative spatial models (QSMs) are a powerful tool for studying urban spatial structure and evaluating policy interventions. QSMs combine theoretical and empirical approaches to analyze spatial structure with high granularity. They are based on spatial computable general equilibrium (SCGE) models — furthermore, urban QSMs can be interpreted as a subset of SCGE models. As opposed to the additive utility functions incorporated for example in logit models, QSMs use multiplicative utility functions. The idiosyncratic shock — which captures heterogeneity in preferences — is assumed to be Fréchet-distributed. The main distinctive features of QSMs are that (i) there exists a one-to-one mapping between the observed data and the quantitative geographical characteristics of locations, and (ii) the model's structural (or in other words, generic) parameters can be estimated with causal econometric methods. These properties allow the quantitative recovery of location fundamentals (such as amenities and productivities) and ensure robust calibration. In the urban context, this methodology is used, for example, to investigate the structure of European cities using historical data, as in Ahlfeldt et al. (2015), Dericks & Koster (2021), and Heblich et al. (2020). Tsivanidis (2023), Warnes (2021), Velásquez (2023) study the impacts of public transport investments (first of all, the implementation of a bus rapid transit system) in Latin American cities consisting of various unique model extensions. Another group of papers (Delventhal et al., 2022; Miyauchi et al., 2021) is focusing on specific, real-world commuting behaviors. Redding & Rossi-Hansberg (2017) and Redding (2023) provide a great overview of the QSM literature and possible model specifications.

2 Methodology

Theoretical model

The model, including the way in which separate monetary and time budgets and endogenous travel time valuations are defined, is based on Hörcher & Graham (2024) and is expanded with the mode choice specification as in Koster (2024). Regarding the mode choice component, only commuting trips and two travel modes are considered: individual transport by car, and public transport. The model takes three economic agents (households, goods production, and floorspace production) into account. Due to the length limit, this short paper includes an excerpt of the full model only; the latter is available in full length in Doffkay (2024).

Households are choosing simultaneously a place (i) to live at, a place (j) to work at, and a mode (m) to use for commuting, and they are deriving utility from enjoying leisure time L_{ijm} and from consumption K_{ijm}. The utility function takes the Cobb-Douglas form as follows:

$$U_{ijm} = \left(\frac{L_{ijm}}{1-\gamma}\right)^{1-\gamma} \left(\frac{K_{ijm}}{\gamma}\right)^{\gamma} z_{ijm} \tag{1}$$

where z_{ijm} represents a Fréchet-distributed idiosyncratic taste shock, and the parameter γ captures the relative importance of consumption. Households face a monetary budget constraint:

$$x_{ijm}\left(w_j - \tau_{ijm}\right) = p_i C_{ijm} + q_i H^R_{ijm} \tag{2}$$

where x_{ijm} is the individual labor supply, w_j is the daily income, τ_{ijm} is the monetary price of traveling, p_i is the price of consumption goods, C_{ijm} is the level of goods consumption, q_i is the price of residential floorspace, and H_{ijm^R} is the residential floorspace consumption. The utility maximization is subject to a time constraint as well:

$$\bar{L} = L_{ijm} + x_{ijm}\ \left(T + t_{ijm}\right) \tag{3}$$

where $\bar{L}$ is the time endowment, T is the fixed length of a workday, and t_{ijm} is the travel time. Travel times are considered to be endogenous due to road congestion in case of choosing a car as the mode of transport. Location and mode choice probabilities follow a commuting gravity equation.

In the goods production section, firms are assumed to operate under perfect competition using labor (M_j^W) and commercial floorspace (H_j^W) as input. The production function takes the Cobb-Douglas form

$$Y_j = A_j (M_j^W)^{\alpha} (H_j^W)^{1-\alpha} \tag{4}$$

where A_j denotes the productivity of firms at location j, and α is the share of labor. Firms intend to minimize their costs.

Floorspace H_i is produced using capital input Z_i and land endowment L_i subject to the production function

$$H_i = Z_i^{1-\psi} \left(\phi_i \left(H_i\right) \ L_i\right)^{\psi} \tag{5}$$

where the constraints of floorspace supply are described based on Delventhal & Parkhomenko (2023) as follows:

$$\phi_i \left(H_i\right) = 1 - \frac{H_i}{\bar{H}_i} \tag{6}$$

In the equations above, ψ denotes the share of land in construction, and $\bar{H}_i$ is the density limit at location i.

The following equations together describe the spatial general equilibrium:

$$\lambda_{ijm} = \frac{X_{im} E_{jm} \left(\frac{\upsilon_{ijm}}{p_i^{\beta} \ q_i^{1-\beta}}\right)^{\gamma\epsilon}}{\sum_i \sum_j \sum_m X_{im} E_{jm} \left(\frac{\upsilon_{ijm}}{p_i^{\beta} \ q_i^{1-\beta}}\right)^{\gamma\epsilon}} \tag{7}$$

where λ_{ijm} denotes location and mode choice probabilities, X_{im} is the residential amenity, E_{jm} is the workplace amenity, υ_{ijm} captures the value of time, β is the expenditure share of general goods consumption, and ϵ is the Fréchet shape parameter.

Residential and workplace populations (N_i^R and N_j^W respectively) can be expressed using the total population (N) and choice probabilities (λ_{ijm}):

$$N_i^R = N \sum_j \sum_m \lambda_{ijm} \text{ and } N_j^W = N \sum_i \sum_m \lambda_{ijm} \tag{8}$$

The equilibrium wage can be expressed as follows:

$$w_j = \alpha A_j^{\frac{1}{\alpha}} \left(\frac{1-\alpha}{q_j^W}\right)^{\frac{1-\alpha}{\alpha}} \tag{9}$$

where q_j^W is the price of commercial floorspace.

Residential a commercial floospace demand (H_i^R and H_j^W respectively) can be written as follows:

$$H_i^R = N_i^R \sum_j \sum_m \lambda_{ijm|im} \ H_{ijm}^R = N_i^R \frac{\gamma \bar{L}}{\gamma + 1} \frac{1-\beta}{q_i} \sum_j \sum_m \lambda_{ijm|im} \ \upsilon_{ijm} \tag{10}$$

$$H_j^W = N_j^W \ \bar{x}_j \left[\frac{(1-\alpha) A_j}{q_j^W}\right]^{1/\alpha} \tag{11}$$

where $\bar{x}_j$ is the average labor supply at location j.

Using these conditions, a new set of endogenous variables (equilibrium populations N_{im}^R and N_{jm}^W, wages w_j, and floorspace prices q_i), and thus a new spatial equilibrium can be computed.

Model inversion allows us to quantify location fundamentals capturing, for instance, geographical characteristics, or other determinants of attractiveness. The existence of this one-to-one mapping between the location fundamentals and the observed data is one of the greatest advantages of QSMs, as recovering these fundamentals quantitatively would be challenging using other traditional methodologies. It is assumed that the recovered location fundamentals (residential and workplace amenities, productivities, and local density limits) do not change over time, so they are kept constant during the counterfactual simulations.

Data and empirical tasks

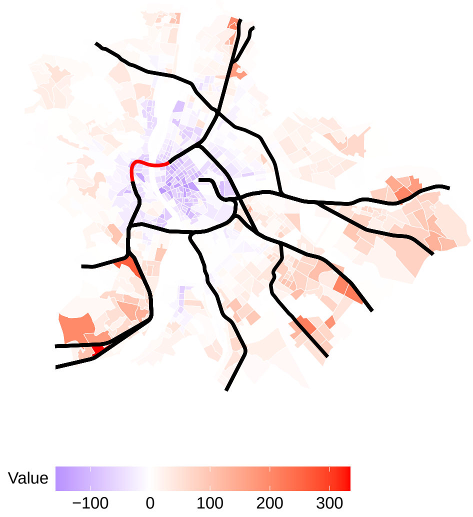
The data used for the calibration of the model, considering 900 zones in Budapest, was obtained from the following sources:

- Initial commuting data (traffic flows, travel times, and distances): BKK Centre for Budapest Transport

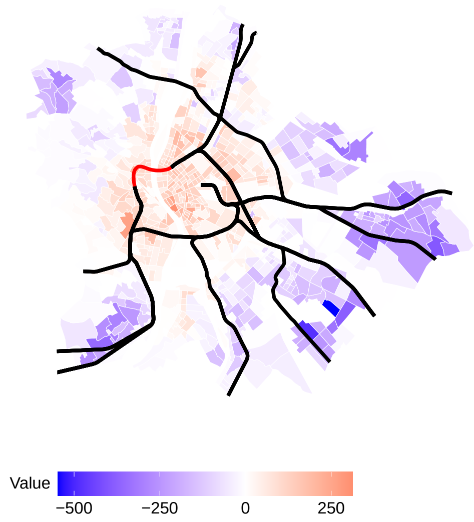
- New travel times by public transport and car: Főmterv
- Housing prices: KSH (Central Statistical Office of Hungary)
- Average annual net wages: GeoX 100×100 Geo-demographic map
- Number of employees working full-time and part-time: KSH (Central Statistical Office of Hungary)

In order to calibrate the model, empirical exercises are required. First, a linear regression is used to predict housing prices for zones with missing data. In order to facilitate endogenous travel times by car, congestion parameters are estimated using regression, considering traffic flow, residential and workplace populations commuting by car, and the total car-commuting population as independent variables. As a structural parameter of the model, the Fréchet shape parameter, which governs location choice dispersion, is estimated using Poisson Pseudo Maximum Likelihood (PPML) estimation. See further details in Doffkay (2024).

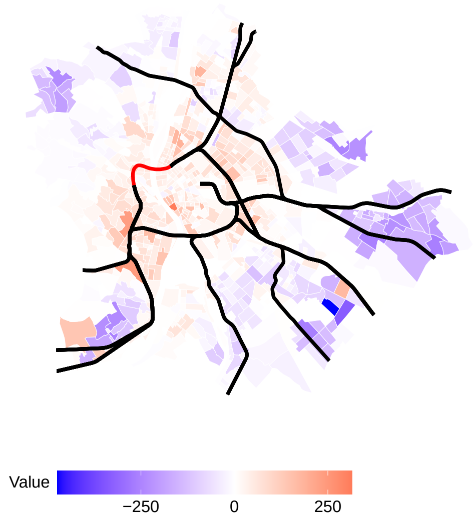
3 Results and discussion



(a) Commuting by public transport

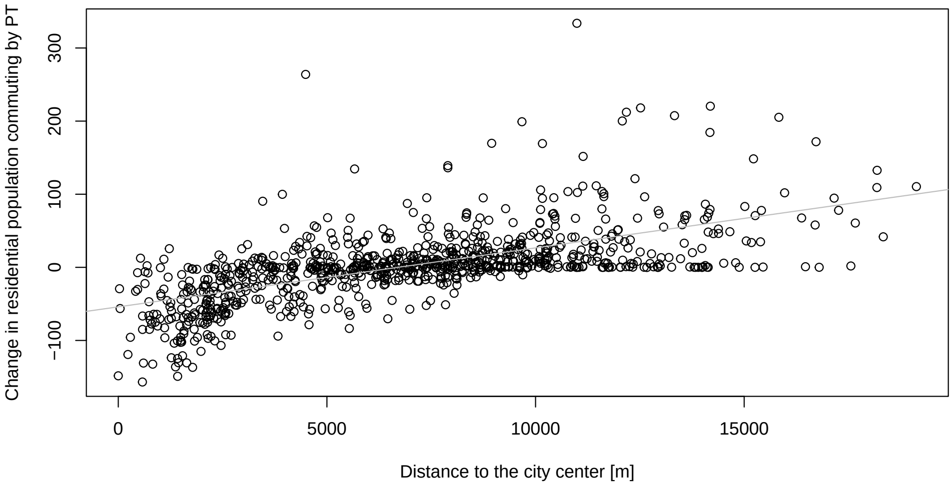


(b) Commuting by car

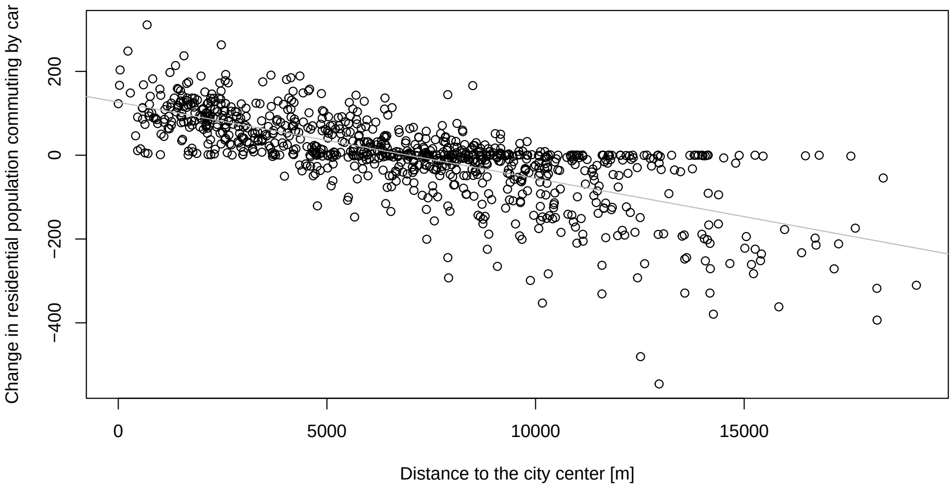


(c) Total

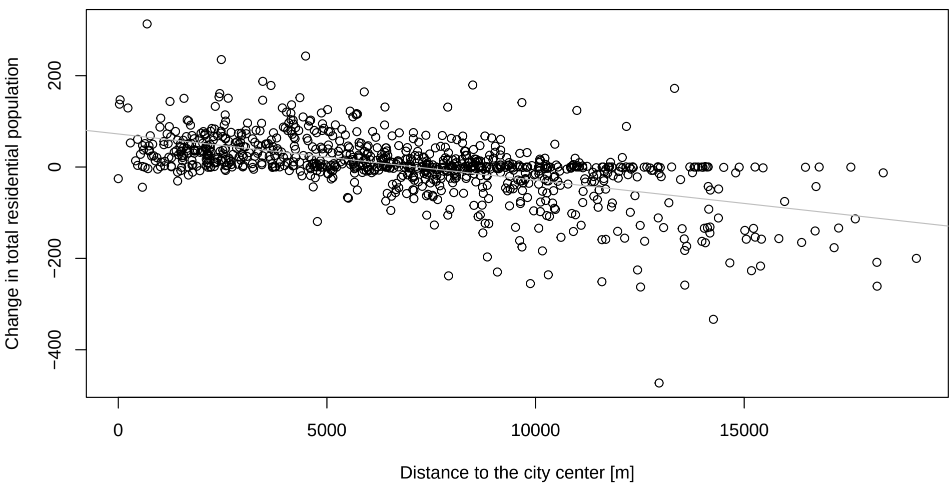
Figure 1: Changes in residential population (persons)



(a) Commuting by public transport



(b) Commuting by car



(c) Total

Figure 2: Changes in residential population (in persons) as a function of distance to the city center

As a counterfactual exercise, it is assumed that the cross-city railway tunnel in Budapest is built resulting in better accessibility by public transport. The main focus is on the change of the residential population in the commuting zones to identify suburbanization, and on the change in modal split. In the figures below, the black lines represent the already existing railway network in Budapest, while the red section is the approximate route of the railway tunnel.

After running the counterfactual simulation, we can observe that the areas around the railway lines are becoming more attractive as places of residence. As shown in Figure 1, the residential population commuting by public transport is growing in the zones from where the railway network is accessible. In contrast, fewer people are commuting from these areas by car. Figure 1 also indicates that the total residential population grows only in a few zones along the railway lines.

The changes in the residential population can also be visualized as a function of the Euclidean distance from the city center as shown in Figure 2. It is shown that the city center attracts more residents who choose to commute by car, which outweighs the change in the number of people using public transport for commuting from outer districts. In other words, suburbanization and sprawling cannot be observed based on the number of residents. Note that since a railway tunnel is examined in this counterfactual exercise, no land over the ground is used in the policy. This means that the capacity of roads is not affected by the railway infrastructure investment, i.e. it is considered to stay constant. In the case of an overground public transport infrastructure improvement, the land allocated to roads might decrease resulting in lower capacity. Due to road congestion, commuting by car would be less attractive, and the city might sprawl.

The railway tunnel causes a visible change in the modal split as shown in Figure 3. The share of residents commuting by public transport increases the most (by around 10%) in outer districts, from which the relative change in accessibility of downtown areas is the highest. Simultaneously, people living in the city center choose to commute by car more often, since there is less congestion on the roads due to the aforementioned change in the commuting behavior of people living further away from the city center.

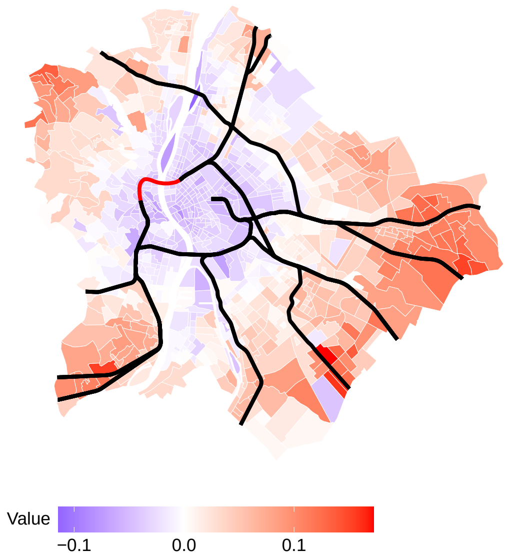
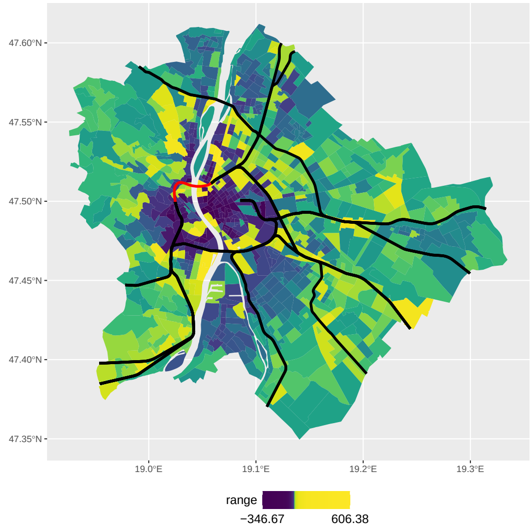
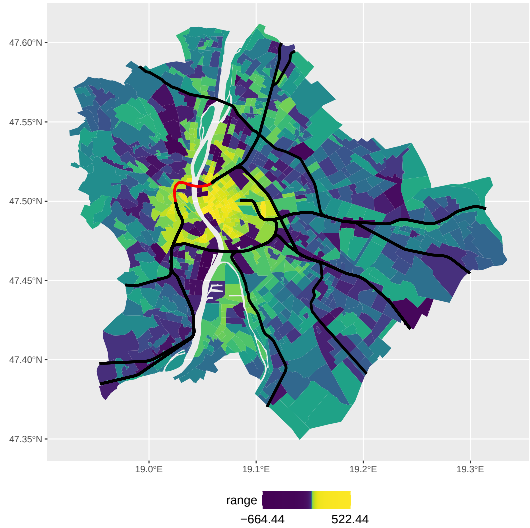


Figure 3: Change in public transport modal split by residence

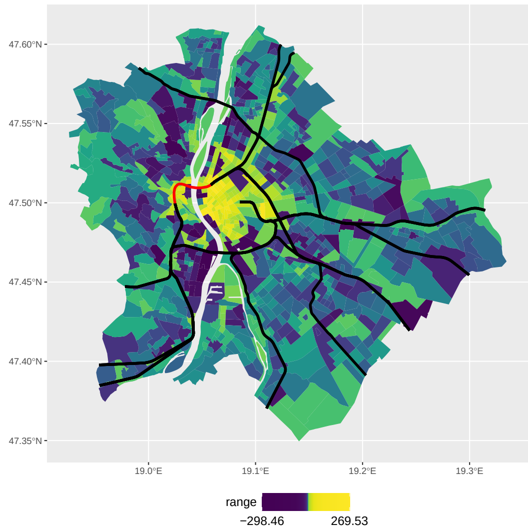
Regarding workplace population, the changes are concentrated around the city center. A significant increase in the number of workers commuting by car can be observed East of the river Danube, in the downtown area. In contrast, more people are commuting by public transport to more northern and southern areas along the Danube. The total change is dominated by the change in commuters choosing a car as travel mode, as shown in Figure 4.



(a) Commuting by public transport



(b) Commuting by car



(c) Total

Figure 4: Changes in workplace population

The mean value of time (VOT) by residence increases in the whole city, but the magnitude of the change is the highest in the city center as shown in Figure 5. As expected, the public transport infrastructure investment has a positive impact on productivity in the whole area by ensuring better access to the economic mass. It is important to note that the positive change in firms' productivity is not concentrated in the geometric center of the city, but more around a planned station at Széll Kálmán Square, western from the river, as shown in Figure 6.

As a result of increased productivity, firms can offer higher wages everywhere in the city, as shown in Figure 7. The change is bigger in Buda, the western part of the city. Moderate changes can be observed in the outer districts of Pest, the eastern part of the city. The individual endogenous labor supply is increasing as well since higher wages incentivize working more instead of enjoying leisure time. Furthermore, as a result of shorter commuting times, people can work more without sacrificing their leisure time. The patterns of the change are patchy, as shown in Figure 7. The greatest changes can be observed in outer districts, where the accessibility is significantly improved.

Due to the better public transport connections, land prices are becoming higher in the whole city. The patterns are similar to those of the change in productivity: the peak is near the planned railway tunnel, western from the Danube, and the magnitude of the change decreases with the distance to the new segment, as shown in Figure 8.

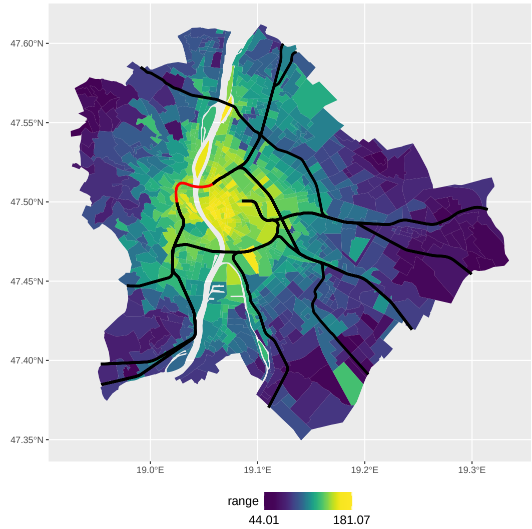


Figure 5: Change in the mean value of time by residence (HUF/hour)

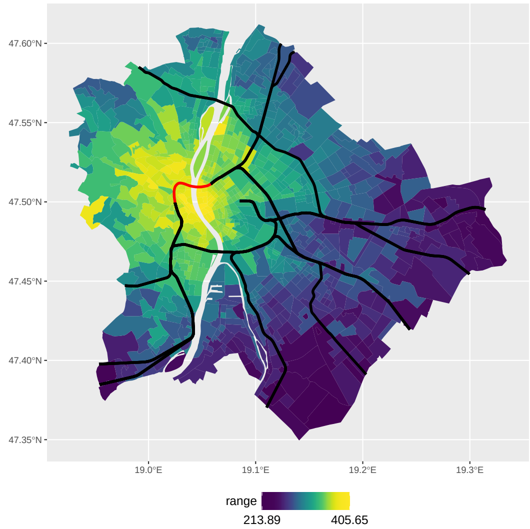
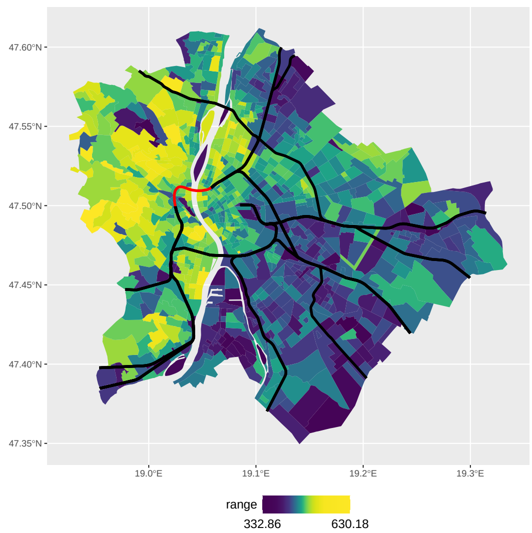
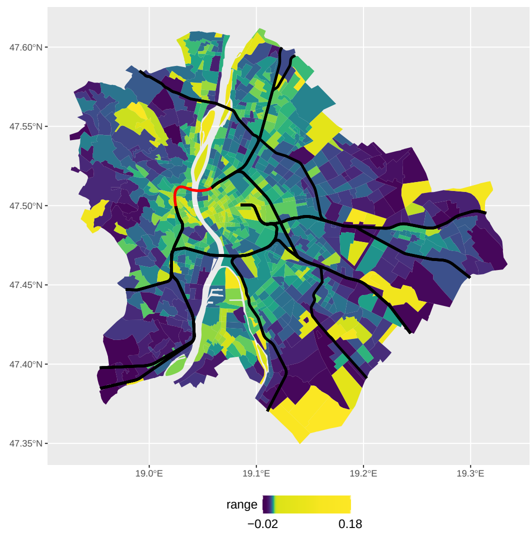


Figure 6: Change in firms' productivity



(a) Wages (HUF per day)



(b) Individual labor supply (log)

Figure 7: Changes in wages and individual labor supply

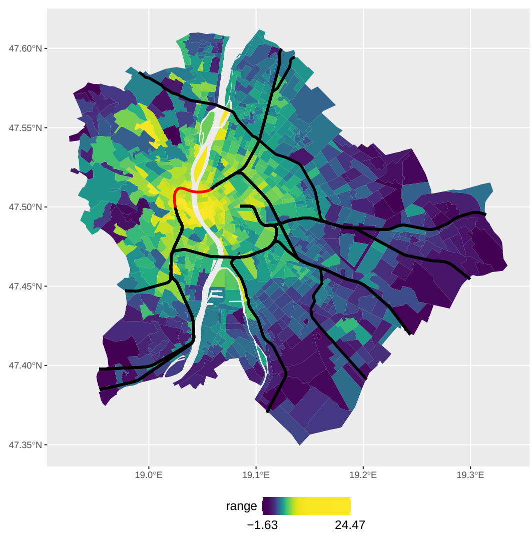
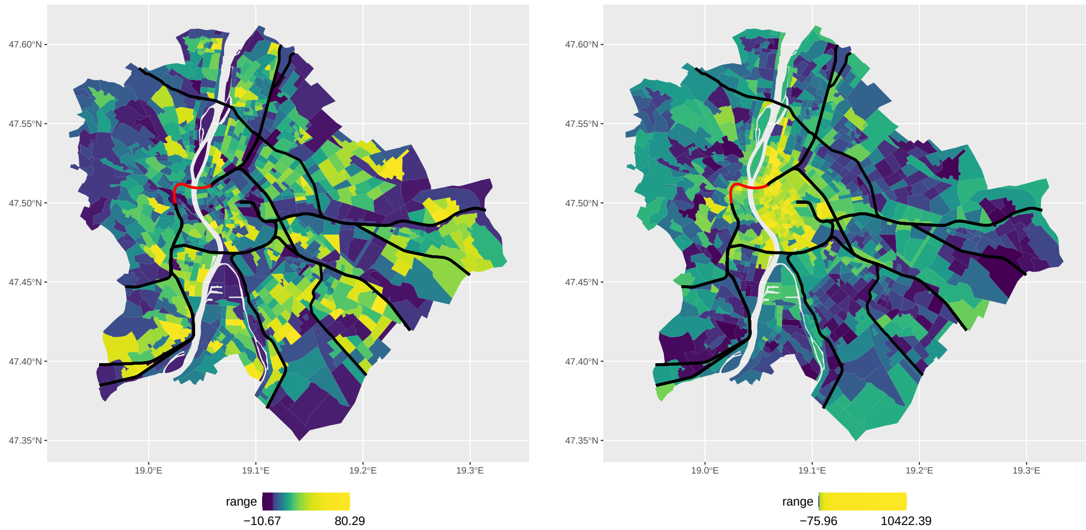


Figure 8: Change in floorspace prices (HUF per day and square meter)

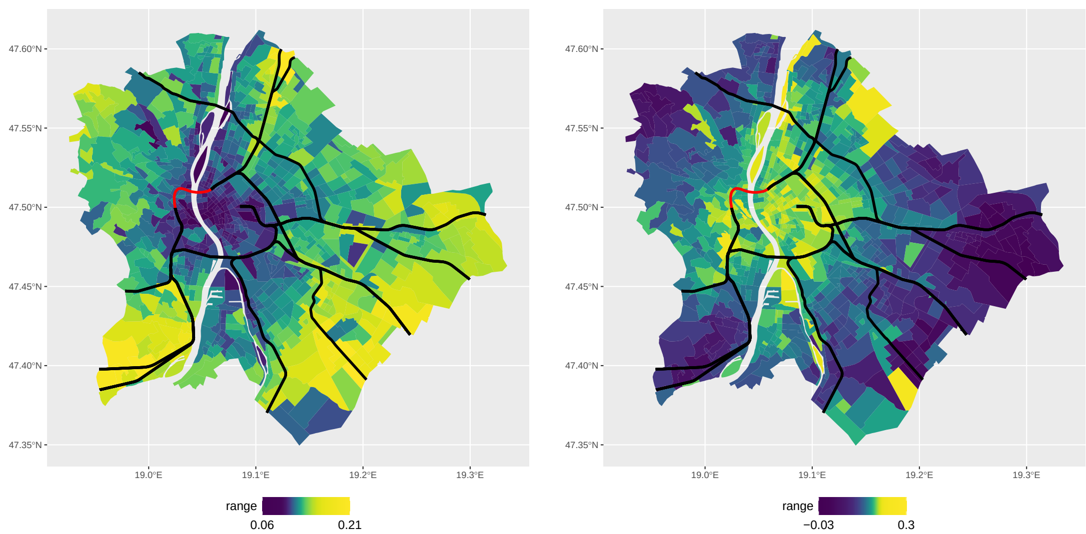
Residential floorspace demand is increasing along the railway lines, as an indicator of a possible railway-induced suburbanization. In contrast, the demand for commercial floorspace gets higher in the city center, as shown in Figure 9. This means that the city center is more specialized in production, while outer districts are more attractive as places of residence.



(a) Residential floorspace (b) Commercial floorspace (log)

Figure 9: Changes in residential and commercial floorspace supply (square meter)

After computing the indirect utility for each mode and origin-destination pair, and taking the mean over the destinations, we get the change in the indirect utility at the residence shown in Figure 10. Note that in this calculation we check how local utility is affected just after the policy is implemented, without the relocation of households and firms. When relocation is unlocked by computing the new spatial equilibrium, utility becomes equal again for all origin, destination, and travel mode combinations. It is shown that the utility of living in areas around the railway lines and commuting by public transport is increasing due to the improved connectivity to the city center. At the same time, for commuters choosing the car as the travel mode, living in downtown areas brings more utility due to the reduced congestion and hence, easier and faster commuting.



(a) Public transport (b) Car

Figure 10: Changes in indirect utility at the place of residence

It is shown that due to the decreased congestion, the downtown area attracts more residents commuting by car, than the change of the population in outer districts commuting by public transport. This implies that air pollution in the city center might increase due to the higher mode share of road transport. Moreover, this process interferes with the goal of implementing car-free zones in central areas. On the other hand, public transport might not cause urban sprawl with such negative effects, as car-induced sprawling. Based on the findings of this paper, it can be stated that suburban railway infrastructure improvements should always be combined with traffic-calming policy measures in the center, otherwise, car use will increase in the downtown area. In other words, a trade-off between urban sprawl and higher car use in the downtown area can be observed.

4 Conclusions

In this paper, the QSM methodology was used to evaluate a railway policy in Budapest. The main contribution is the inclusion of travel mode choice and endogenous travel times by car in the model of Hörcher & Graham (2024) who provide a more realistic representation of travel costs considering separate monetary and time costs. As empirical exercises, missing data on housing prices was imputed, and the parameters of the congestion function, as well as the Fréchet shape parameter, were estimated. Model inversion was applied to recover location fundamentals, which were used subsequently in the counterfactual exercise.

In the counterfactual scenario, the cross-city railway tunnel in Budapest is assumed to be built, and its impacts are analyzed. First of all, there is a noticeable change in the modal split. The increase in the population commuting by public transport is concentrated along the railway lines while commuting by car becomes more attractive in the city center due to reduced congestion levels. Additionally, firms' productivity and the wages they can offer increase, and higher land prices are observed throughout the city. A significant finding is that the demand for residential floorspace is increasing in outer districts, indicating potential public transport-induced suburbanization concentrated around the railway lines. Meanwhile, the demand for commercial floorspace is rising in the city center. However, a clear pattern of sprawl is not evident from the results, as the total residential population at the urban fringe is decreasing. Thus, the public transport investment examined does not cause clear urban sprawl based on the findings of this paper.

It is shown that constructing a railway tunnel under the river Danube yields substantial benefits through improved accessibility. The expected utility increases and the monetized benefits over a 50-year period are estimated to be around 3000 billion HUF. However, the railway tunnel and the shift in mode share towards public transport among commuters living in outer districts result in lower congestion levels in the downtown area. Consequently, commuting by car becomes more attractive in the city center, which may have negative impacts such as higher emissions. Therefore, suburban public transport investments should always be combined with traffic-calming policy measures in the city center to mitigate these potential adverse effects.

Although the model performs reasonably well and provides valuable findings, there are several limitations. First, the data sources and the resolution of the data are not optimal in most cases. The model is spatially limited to Budapest, whereas examining urban sprawl would require a broader spatial scope that includes the surrounding agglomeration. Additionally, route assignment data is based on a four-step transport model, which is not integrated into the spatial model, thereby reducing its tractability. In the counterfactual scenario, travel times by public transport are treated as given, but implementing a more transparent and tractable algorithm for calculating travel times could enhance the model's performance. Furthermore, estimating additional structural parameters would ensure a more robust calibration.

Acknowledgements

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