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The Effect of Railway Travel on Urban Spatial Structure

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Abstract:

We examine the effect of railway travel on urban spatial structure in a polycentric urban land use model. We focus on the role of access to the railway network. We find that if the number of train stations is limited, the degree of urbanization is higher around train stations, but the effect of railway travel on road congestion is small. By contrast, if train stations are omnipresent there is little effect on urban spatial structure, but a considerable decrease in congestion. With regard to the supply of train stations, these findings suggest that there is an important policy trade-off between congestion and urbanization.

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1. Introduction

Roads have had a considerable impact on urban spatial structure. Baum-Snow (2007a), for instance, finds that without the interstate highway system there would have been more clustering of population (city growth) in the United States. Highways caused suburbanization. This finding is particularly interesting given the concerns about urban sprawl and, more recently, the decline of certain urban areas (Glaeser, 1998).

In many countries, however, travel by train is an important alternative mode of transport. The yearly passenger-km of rail transport in the EU, for instance, is about 398 billion. Only in India and China the amount of travel by railroads is higher, 978 billion km and 815 billion km, respectively. By contrast, it is only 9.5 billion km in the US (UIC, 2011).

To understand the impact of railroads on urban spatial structure it is important to highlight two aspects of railway travel that differ from travel via roads. First, supply of railway services is discrete by nature. That is, access to the railway network goes through a train station while access to the road network is nearly continuous. Second, the capacity of the railway network is usually thought to be extremely high: although trains can be crowded, there is virtually no congestion.[1] It are these two features of railway travel that result in a different spatial urban economic pattern than if there is only travel by roads.

The aim of this paper is to investigate the effect of railway travel on urban spatial structure. We focus on the effect of different spatial patterns of access to the railway network. We formulate a theoretical model to examine under which conditions and to what extent railway travel leads to urbanization. We measure urbanization by population and job density. The model is based on the computable general equilibrium (CGE) model of Anas and Kim (1996), Anas and Xu (1999), and Anas and Rhee (2006), in the rest of this paper referred to as the Anas model.[2]

The Anas model is a spatial general equilibrium model with an endogenously determined polycentric land use pattern. As such, it is more general than the classical monocentric model

[1] In particular, to cope with capacity constraints, a railway company can alter the time table, train frequency, or the number of carriages, relatively easily.

[2] The Anas and Kim (1996), Anas and Xu (1999), and the Anas and Rhee (2006) papers use a very similar general equilibrium formulation. The Anas model allows for a highly non-linear formulation of consumption, production, and travel behavior (i.e. it is a computable general equilibrium model). As such, it misses the mathematical elegance of the Lucas and Rossi-Hansberg (2002) model, but it allows for a more complex setup with multiple actors, zones, and modes of transport.

with a single business district.[3] We extend the Anas model by including railway travel as a separate mode of transport. Although the Anas model mainly focusses on a typical US (circular) city, the division of economic space into separate zones makes it particularly suitable to model a transport corridor between (European) cities. This is important because railway travel is most commonly used for travel between cities, while other modes of transport (e.g. walking, bike, car, transit) are also used for travel over shorter distances. We include railway travel based on a nested logit formulation of the commuting and transport mode choice, which incorporates the dual (transport mode, commute) multinomial logit approach of Anas and Liu (2007) or, more recently, Tscharaktschiew and Hirte (2012).[4] The key difference with the dual multinomial setup is that the nested logit approach allows the work-residence location choice to be correlated with the transport mode choice.[5]

The results in this paper show that if the supply of train stations is limited, population density around stations is about 5.8 to 6.9 percent higher than when travel only occurs by car. A similar result holds for job density. In addition, there is a 50 to 60 percent increase in commuting flows between those areas with a train station. Only a small part of population uses the train, so the overall effect of railway travel on road congestion is small. Since travel time by train is relatively low, workers have an incentive to reside in a location that is distant from the place of work and in close proximity of a train station. Population clusters because access to the railway network is clustered. If train stations, however, are present in all geographical areas, we do not find a sizeable effect on population density. In essence, travel by train is just like travel by car: access to the railway network is more or less continuous across space. By contrast, we do find a substantial decrease in overall congestion of about 20 percent, which is in line with the idea that public transport can be used as a second-best solution to congestion tolls.[6]

[3] Baum-Snow (2007b), for instance, finds that each additional highway decreases central city population in the US by 10 percent in a monocentric city setup.

[4] Using the Anas model, Tscharaktschiew and Hirte (2012) find that subsidies to public transport result in suburbanization (but no urban sprawl). Instead, our paper specifically focuses on the effect of railway travel on the spatial distribution of jobs and residences in a transport corridor setup.

[5] There is ample evidence which indicates that this is a more realistic approach (e.g. Daly, 1987; Ortúzar and Willumsen, 2001). It also allows the transport mode choice to be correlated within commuting mode nests.

[6] The effects in this paper are quite sizeable, which in part reflects that we take into account changes in the local economy (i.e. the areas with a train station become more attractive places to work and shop), a clear advantage of the approach we use in this paper. Many empirical models are based on the assumption that the economy remains ‘fixed’ between policy alternatives (e.g. highway versus no highway).

The findings in this paper suggest that there is an interesting policy trade-off. To decrease congestion a relatively larger number of train stations, dispersed across economic zones, is most effective. If, however, the purpose is to enhance the accessibility of certain urban areas, to strengthen the economy of those areas, a more strategic placement of stations is necessary.

The potential impact of this trade-off is best illustrated using some examples. France, for instance, has a relatively low density railway network centered around Paris and focusing on the high-speed TGV. There is about 31,000 km of railway track, 3,000 train stations, while the total land area is 640,000 km^2 (UIC, 2011). By contrast, the railway network in eastern Europe is very high density. During the Soviet era it provided transport to the masses. Poland, for instance, has 20,000 km or railway track, many small train stations, but only about half of the land area of France (UIC, 2011). The percentage of total population living in urban areas, a measure of urbanization, is 61% in Poland and 86% in France.[7] By contrast, the INTRIX index, a measure of congestion intensity, is 15.9 in France while Poland is not even in the top 10 of countries with a high level of congestion.[8] [9] Instead, Germany has a hybrid system with a combination of high speed lines and regular lines, a relatively low level of congestion (INTRIX index of 12.2) and a high degree of urbanization (74% of population lives in urban areas). The results in this paper suggest that, at least in part, the differences in urbanization and congestion can be explained by the differences in railway network density and the type of railway network. There seems to be an interesting relationship between the number of stations, their spatial allocation, and congestion versus urbanization. This paper aims to identify the underlying mechanisms that drives these results.

Most previous studies focus on the effect of roads on urban spatial structure, mainly in the US.[10] Two notable exceptions are the empirical studies by Garcia-López (2012) and Baum-Snow et al. (2013). Garcia-López (2012) finds that railroads increase population growth in suburban areas in Barcelona. Baum-Snow et al. (2013) find that, in China, each additional radial railroad decreases central city GDP by 26 percent and each ring railroad results in an additional 50 percent decrease.

[7] World development indicators 2012 (www.worldbank.org).

[8] The INTRIX index measures the percentage increase in average travel time during peak hours. An index value of zero means no congestion (www.scorecard.inrix.com).

[9] At the city level, however, the capital of Poland (Warsaw) is regarded as one of the most congested cities in the world.

[10] See Anas et al. (1998), for an overview of the literature on urban spatial structure. See Baum-Snow et al. (2013) for a thorough literature review on infrastructure investment and the impact of (rail)roads on urban spatial structure.

We add to this literature in two ways. To our knowledge, we are the first to investigate the effect of access to a railway network (spatial allocation of train stations) on urban spatial structure using an urban land use model. As mentioned, we pay particular attention to the mechanisms that lead to changes in urban spatial structure. Second, we do not only focus on population and job density, but also consider the role of congestion. This is essential to understand the differential impact of travel by car versus travel by train on urban spatial structure.

The remainder of this paper is structured as follows. Section 2 presents the model. Section 3 discusses the parameters and solution procedure. Section 4 shows the results. Section 5 contains a discussion of future research. Section 6 concludes.

2. The model

2.1 Spatial structure and actors in the model

We follow Anas and Kim (1996) by modelling a closed economy in a transport corridor setup. In the corridor land is separated into *Z* equally-sized zones (see Figure 1). The distribution of jobs and population across zones is endogenously determined.

Figure 1: The transport corridor

1	2	3	4	5	6	7	8	...	*Z-1*	*Z*

We distinguish between three types of economic actors (workers, firms, the government). There is a population of *N* workers. Each worker lives and is employed in one of the zones.[11] Workers consume goods from each of the zones. Workers travel within and across zones to work or consume. In each zone, firms produce goods that are consumed by workers.[12] The government imposes a head tax on the workers to finance (rail) roads. The three actors interact with each other through the product market, labor market, and land market. The economic behavior of the actors is discussed in the following subsections.

[11] Workers are allowed to both live and work in the same zone.
[12] Each zone produces its own good. As such, goods in the model are assumed to be spatially differentiated.

2.2 Workers

Each worker has a home location (zone) *i*, work location *j*, and commutes using transport mode *t* (car or train) and derives utility U_{ijt} from consumption z_{ijvt}, bought in zone v, lot size (land) q_{ijt}, leisure time l_{ijt}, and an idiosyncratic component u_{ijt}, reflecting heterogeneity in tastes:

$$U_{ijt} = \ln(\varsigma_t) + \alpha \ln(\sum_v z_{ijvt}^{\rho})^{1/\rho} + \beta \ln q_{ijt} + \gamma \ln l_{ijt} + u_{ijt}, \qquad (1)$$

where ς_t is an exogenous mode-specific constant. We assume $\alpha + \beta + \gamma = 1$.[13] Workers maximize utility subject to a budget constraint:

$$\sum_v p_{ijv} z_{ijvt} + r_i q_{ijt} + w_i l_{ijt} = \Omega_{ijt}, \qquad (2)$$

where full endowment income equals $\Omega_{ijt} = w_j H - 2dw_j g_{ijt} + D$, H is the total time in hours in a month available to a worker, w_j is the wage rate, *d* is the number of work days per month, g_{ijt} is the one-way commuting time, and *D* is land revenue, with $D = 1/N \sum_k r_k A_k - h$. A_k denotes the land area at zone *k*, r_k is the land rent, and h is a head tax imposed by the government.

The left hand side of equation (2) captures expenditure on consumption, lot size, and leisure, where p_{ijv} is a composite price: $p_{ijv} = p_v + 2fw_j g_{iv}$, which is the sum of the price of the consumption good p_v and the opportunity costs of travel time $w_j g_{iv}$, where g_{iv} is the one-way travel time between the residential location *i* and shopping location *v* and all shopping occurs by car (i.e. $g_{iv} = g_{iv'car'}$). The term $2f$ scales the cost of travel, where *f* is the exogenous number of trips per year to purchase a unit of consumption.

Given the Cobb-Douglas utility function, the Marshalian demands for consumption z_{ijvt}, lot size q_{ijt}, and leisure l_{ijt} are of the following form:

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[13] This utility function implies a constant elasticity of substitution of consumption equal to $\rho/(1-\rho)$. The model-specific constant captures the disutility of going by train (e.g. as a result of scheduling costs, no privacy, no guarantee that seats are available). The utility function is homogenous of degree one.

$$z_{ijvt} = \alpha \frac{\Omega_{ijt} p_{ijv}^{1/(\rho-1)}}{\sum_n p_{ijn}^{\rho/(\rho-1)}} \;;\quad q_{ijt} = \beta \frac{\Omega_{ijt}}{r_i} \;;\quad l_{ijt} = \gamma \frac{\Omega_{ijt}}{w_j}. \tag{3}$$

The utility function has two interesting features. First, the marginal utility of each good conditional on the commuting arrangement *i, j* and transport mode *t*, $\alpha z_{ijvt}^{\rho-1} / \sum_n z_{ijnt}^{\rho}$, goes to infinity if the consumption of that good goes to zero. As a result, workers consume from each zone. This captures the worker's "taste for variety".[14]

Second, each worker has a specific chance to live in *i*, work in *j*, and use transport mode *t*. To elaborate, the indirect utility is $V_{ijt} + u_{ijt}$, where V_{ijt} is the optimized value of the deterministic part of the utility function. The worker chooses the commuting arrangement *i*,*j* and transport mode *t* with the highest utility. In the nested logit approach these choices are nested. Workers choose the commuting arrangement and within commuting arrangement they make the transport mode choice. The joint choice probability Ψ_{ijt} is modeled in the nested logit form as follows:[15]

$$\Psi_{ijt} = \frac{\exp(\lambda V_{ijt} / \chi_{ij})(\sum_l \exp(\lambda V_{ijl} / \chi_{ij}))^{\chi_{ij}-1}}{\sum_{n,m} (\sum_l \exp(\lambda V_{nml} / \chi_{nm}))^{\chi_{nm}}}, \tag{4}$$

where the parameter χ_{ij} captures the correlation between the random part of utility of each joint commuting arrangement and transport mode choice within a particular transport mode nest. If $\chi_{ij} = 1$, this correlation is zero and the probabilities collapse to multinomial logit probabilities. If the commuting and transport mode probabilities are assumed to be independent, we arrive at the dual multinomial logit structure (Anas and Liu, 2007; Tscharaktschiew and Hirte, 2012). If there

[14] The fact that the consumer shops in every zone is determined by the specification of utility. The commuting arrangement and the amount of shopping (and shopping flows through the conversion factor *f*) are endogenously determined by the model.

[15] The probabilities add up to one. This implies that each worker works and lives within the transport corridor (no inside-outside commuting) and travels either by car or by train (no outside options).

is only one transport mode (i.e. car), the probabilities collapse to the Anas and Rhee (2006) multinomial logit probabilities, where λ is the dispersion parameter.[16]

2.3 Travel time of workers

Assume that travel occurs on a straight line through the zones. Interzonal travel occurs from the center of each zone, while intrazonal travel occurs towards the center of a zone. The formulation of the model for travel (shopping/commuting) by car is taken from Anas and Rhee (2006). The commuting time $g_{ij'car'}$ and the shopping travel time $g_{iv'car'}$ are the same if the origin and destination are the same (i.e. travel time does not depend on the purpose of the trip), and they are fully determined by the time (hours) to travel one kilometer by car $g_{i'car'}$. Specifically, the intra-zonal travel time $g_{ii'car'}$ is $\Delta_i g_{i'car'}/2$, where Δ_i is the length of the zone, and the inter-zonal travel time $g_{ij'car'}$ equals $(\Delta_i g_{i'car'} + \Delta_j g_{j'car'})/2 + \sum_n \Delta_n g_{n'car'}$, where $i \neq j$ and $n = \{i+1, j-1\}$.[17] The time to travel one kilometer by car $g_{i'car'}$ is determined by the congestion function:[18]

$$g_{i'car'} = a\left[1 + b\left(\frac{F_{i'car'}}{K_{i'car'}}\right)^c\right], \tag{5}$$

where $K_{i'car'}$ is the road capacity based on the land allocated to roads $R_{i'car'}$ (i.e. $K_{i'car'} = \zeta R_{i'car'}$), a, b, and c are congestion parameters, and two-way zonal traffic flows $F_{i'car'}$ are defined as:

$$F_{i'car'} = F_{ii'car'} + \sum_{i \neq n}(F_{in'car'} + F_{ni'car'}) + 2\sum_{k=1}^{i-1}\sum_{m=i+1}^{Z}(F_{km'car'} + F_{mk'car'}), \tag{6}$$

where the zonal traffic consists out of three terms: the intra-zonal traffic flows, the flows going to and leaving from the center of zone *i*, and the traffic passing through zone *i* (assumed to travel

[16] In the multinomial model, if $\lambda \to \infty$ choices are deterministic if $\lambda \to 0$ choice are completely random.
[17] Inter-zonal travel is across half a zone in the origin and destination zone plus the travel times through all intermediate zones.
[18] This congestion function does not reflect the effect of peak hour congestion. That is, we do not include the timing of travel during the day in the model.

a full zone length, flows weighted by two).[19] In equation (6), the total daily flow by car $F_{in'car'}$ between some location pair *i*,*n* equals $F^{w}_{in'car'} + F^{s}_{in'car'}$ where the destination zone *n* is either the work location *j* or the shopping location v and the expected number of one-way commuting trips is $F^{w}_{ij'car'} = N\Psi_{ij'car'}$, and the expected number of one-way shopping trips are $F^{s}_{iv'car'} = N\frac{1}{d}\sum_{j,t}\Psi_{ijt}\, fz_{ijvt}$.[20]

If there is a train station in a zone, it is located in the center of the zone. If both zone *i* and *j* have a train station, workers can use the train to commute between these two stations. The intrazonal travel time by train $g_{ij'train'}$ is directly determined by the train speed in kilometers per hour, $train\ speed$, and distance between the origin and destination zone (i.e. no railway traffic congestion):

$$g_{ij'train'} = (\frac{\Delta_i}{\phi} + \frac{\Delta_j}{\phi})/2 + (\frac{\Delta_i}{train\ speed} + \frac{\Delta_j}{train\ speed})/2 + \sum_n \frac{\Delta_n}{train\ speed} + \vartheta Stops_{ij}\ , \quad (7)$$

where $i \neq j$ and $n = \{i+1, j-1\}$ and $(\frac{\Delta_i}{\phi} + \frac{\Delta_j}{\phi})/2$ captures the time to travel to and from the train station (access/egress) by foot/bicycle.[21] Hence, ϕ can be interpreted as a railway accessibility parameter. The term $\vartheta Stops_{ij}$ captures the "waiting time" effect of the number of stops between *i* and *j* on travel time.[22] If a train runs between *i* and *j*, we assume that it stops at all stations that are in between *i* and *j*.

2.4 The government budget

The government finances the land allocated (exogenously) to roads, $R_{i'car'}$, and railways, $R_{i'train'}$, by levying a head tax *h* on the workers:

[19] For the edge zones the third term is zero.
[20] We aggregate consumption over all commuting transport modes and possible work locations. Shopping only occurs during work days and does not take any time (other than travel time).
[21] Workers are allowed to travel to the train station within their zone of residence for working purposes (internal travel). This reflects that work locations are usually close to public transport hubs.
[22] This number excludes the train station at the origin and destination zone.

$$Nh = \sum_i r_i R_{i'car'} + \sum_i r_i R_{i'train'}. \quad (8)$$

2.5 Producers

Goods are sold in the center of each zone. Hence, there are Z goods. Firms produce these Z goods in quantity X_v. Firms maximize profit, $p_v X_v - w_v M_v r_v Q_v$, where M_v is labor input, Q_v is land input, and with $X_v = EM_v^{\delta} Q_v^{\mu}$, where E is a technology parameter and $\delta + \mu = 1$ captures the constant returns to scale production technology. There is perfect competition, every firm is a price taker, and there are a lot of small firms (i.e. the number of firms is indeterminate).[23] [24] In this case, firms make zero profits and the conditional labor and land demands are

$$M_v = \frac{\delta p_v X_v}{w_v}; \quad Q_v = \frac{\mu p_v X_v}{r_v}. \quad (9)$$

2.6 General equilibrium

Product prices p_v , wages w_j, and land rents r_i are determined by the following market clearing conditions:

$$\begin{aligned} &N \sum_{i,j,t} \Psi_{ijt} z_{ijvt} - X_v = 0 \ \text{(product market)} \\ &M_j - N \sum_{i,t} \Psi_{ijt} (H - T_{ijt} - l_{ijt}) = 0 \ \text{(labor market)} \\ &N \sum_{j,t} \Psi_{ijt} q_{ijt} + Q_i + \sum_t R_{i,t} - A_i = 0 \ \text{(land market)}, \end{aligned} \quad (10)$$

[23] Since firms are price takers, supply is fully price elastic. As a result, the level of production is determined by consumption demand. Hence, the location of firms in this model is ultimately determined by consumption.

[24] Note that it is implicitly assumed that consumption and output prices are equal because there are no taxes (for an example with taxes, see Tscharaktschiew and Hirte, 2012) In addition, there is no intermediate use (inter-industry trade) in this model (see Anas and Kim, 1996).

where $T_{ijt} = 2dg_{ijt} + \sum_{v} 2g_{iv} fz_{ijvt}$ is the total travel time (commuting and shopping) and $H - T_{ijt} - l_{ijt}$ is the remaining time available for work. The prices defined by equation (10) are assumed to be independent of the transport mode (i.e. we aggregate over transport modes).

3. Parameters and solution procedure

We use the same parameter values as Anas and Rhee (2006). We choose the parameters related to railway travel (e.g. train speed) in line with what we would expect to find in an European urban transport corridor.[25] The full set of parameter values and exogenous model inputs are reported in the Appendix (Table A1).

There are 5,000 workers in the transport corridor, which consists of 11 equally-sized zones. The horizontal width of these zones is 5 km, the vertical width 0.5 km, and the size of each zone is 2.5 km^2.[26] Hence, the total width of the transport corridor is 55 km and the total land area in the transport corridor is 27.5 km^2. The land in each zone allocated to roads and railroads is 1.5% and 1%, respectively. We normalize the mode-specific constant for trains to 1 and 1.01 for cars. We set λ, the parameter that scales utility in the nested logit probabilities, at 12.[27] In our base analysis, the correlation between the random utilities equals 1 such that the joint commuting, transport mode, probabilities are of the multinomial logit form. The speed to travel towards or from a train station by foot/bicycle is 15 km/hour. Trains run at a 120 km/h. If a train stops in a zone (excluding the origin and destination zone), it waits 1.5 minutes at each stop. Railroads are clustered on the central line going through the zones. If a train station is available in a zone, it is located in the center of the zone. We do not incorporate any cost of constructing/operating the train (stations).[28] Applying Walras law, we normalize the edge zone rents to 0.25 such that monetary income is around 40,000 dollars (30,000 euros).

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[25] Anas and Rhee (2006) model a typical US city using a circular city approach. In the sensitivity analysis, we show that our results also hold in a circular city setup and using European preference parameters.

[26] Distances in the model are in kilometers (Anas and Xu, 1999; Anas and Rhee, 2006, convert the results, ex post, to miles).

[27] Basically, lambda captures the sensitivity of the model to changes in the deterministic part of utility (e.g. travel times). We choose lambda such that we obtained a reasonable distance decay in commuting flows (i.e. a doubling of distance results in a halving of commuting flows). The sensitivity of our results to changes in lambda is discussed in the sensitivity analysis.

[28] We follow Anas and Rhee (2006) by assuming a zero monetary cost of travel.

The model consists of 21 blocks of equations (endogenous variables). A list of the endogenous variables is reported in the Appendix (Table A2).[29] We solve the system of non-linear equations by formulating it as a non-linear programming (NLP) problem in the optimization software GAMS.[30] We use the expected (log-sum) welfare function as the objective function we maximize:[31]

$$welfare = 1/\lambda \ln \sum_{ijt} \exp(\lambda V_{ijt}) \tag{11}$$

4. Results

4.1 Main results

We run three versions of the model. First, we calculate the base equilibrium, which is similar to the equilibrium of Anas and Kim (1995), Anas and Xu (1999), and Anas and Rhee (2006) in which commuting only occurs by car.[32] We use the base equilibrium as benchmark for the version of the model with railway travel as separate mode of transport. Second, we report results of the urban equilibrium in case railway travel is added to the model (train stations in all zones). Finally, we show the result in case access to the railway network is restricted to zones 1, 6, and 11. Table 1 contains the results. We focus on population density, job density, and congestion (time to travel one km), but also report some other urban metrics. We report results specific to zone 1 to 6 (the equilibria are symmetric).

Column 1, labeled 'no trains', shows the base equilibrium results.[33] Disposable income is 42,985 dollars. Workers shop and commute about 45 minutes per day (total is about 1.5 hours).

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[29] The exact total number of endogenous solutions (equations) depend on the i,j and t dimensions of the variables and the restrictions imposed on the model (e.g. normalization prices, number of train stations). In the results section we report the exact number of equations per case.

[30] Alex Anas graciously provided us with the code from Anas and Rhee (2006). Anas and Rhee (2006) use their own iterative procedure, programmed in GAMS code, that minimizes the (maximum) slack in the equations (variables). We rewrote the code to full GAMS code (NLP problem) which allows us to use the built-in algorithms to solve the model. The benefit of our approach is that we utilize the first and second order conditions (Jacobian and Hessian matrices) to find the optimum (using some standard convergence criteria) and the number of iterations before convergence is relatively low.

[31] The algorithm that we use is based on the Generalized Reduced Gradient (GRG) method. The results are robust to changes in starting values.

[32] That is, t={car}, equation (7) is excluded, the mode-specific constant is zero and land allocated to railroads is zero.

[33] There are 3,719 equations in our version of the model (excluding the two land clearing equations that are fixed). The model was solved in 23 iterations. Walras Law, in terms of land market clearing in zone 1 (and 11), holds with a very small value of excess demand (<1*10-3). It confirms that there are no leakages in the model (model closure) and we obtain an appropriate general equilibrium solution.

Table 1: The spatial equilibrium in a transport corridor: urbanization versus congestion

		(1)	(2)	(3)
Main results	Zones	No trains	Train stations in all zones	Train stations in zones 1, 6, and 11
Population density	1	170.2	171.8	182.0
	2	176.0	177.2	172.0
	3	181.7	182.0	177.4
	4	186.6	185.9	182.2
	5	189.9	188.5	185.3
	6	191.1	189.4	202.2
	Tot.	181.8	181.8	181.8
Job density	1	172.0	173.4	183.0
	2	176.9	177.9	173.1
	3	181.8	182.0	177.8
	4	185.9	185.3	181.7
	5	188.6	187.4	184.4
	6	189.6	188.1	200.2
	Tot.	181.8	181.8	181.8
Time (in hours) to travel one km	1	0.015	0.014	0.015
	2	0.020	0.017	0.019
	3	0.026	0.022	0.026
	4	0.032	0.025	0.031
	5	0.036	0.028	0.035
	6	0.037	0.029	0.036
	Tot.	0.030	0.024	0.029

Other urban metrics		Car	Train	Car	Train	Car	Train
Average distance outward commute (in km)	1	18.8		20.0	21.8	19.1	20.7
	2	15.6		16.7	18.3	15.7	
	3	13.8		14.6	15.8	13.8	
	4	12.9		13.4	14.2	12.8	
	5	12.5		12.8	13.2	12.4	
	6	12.4		12.7	12.9	12.4	15.2
Commuting time		0.879		0.745	1.015	0.857	0.849
Shopping time		0.826		0.691		0.812	
Daily commuting flow zone 1 to 6		35		20	17	28	28
Daily commuting flow zone 6 to 1		36		20	17	28	28
Daily commuting flow zone 1 to 11		20		13	13	16	24
Percentage train use				44.7		5.5	
Disposable income (dollars)		42,985		42,658		40,488	
Welfare (utils/worker)		6.955		7.024		6.969	
Walras Law (land market zone 1)		$<\|1*10^{-3}\|$		$<\|1*10^{-3}\|$		$<\|1*10^{-3}\|$	
Number of eq. / iterations		3,719 / 23		5,897 / 68		3,881 / 27	

Note: Population and job density are measured in workers per km^2. The job/population density for the whole transport corridor (total jobs or population divided by total land area) is reported under the line 'Tot.' (time to travel one km is a weighted average). Shopping/commuting time is in hours per day per worker.

Although the differences across zones are small, population density – based on the number of workers living in a particular zone – is relatively high in zones 4, 5, and 6 (hence, also in 7 and

8). Population density is 186.6, 189.9, and 191.9 workers per km^2 in these zones, respectively. This suggests that there is a small agglomeration in the center of the corridor. The population density over the whole transport corridor is 181.8 (5,000/27.5) workers per km^2.[34]

We find a similar spatial pattern with regard to jobs density. Jobs are available in all zones, which reflects the polycentric nature of the urban equilibrium in this model. The job-housing balance ranges between 0.99-1.01, which suggests that jobs and residences are balanced across zones.[35] The clustering of jobs and population in the center reflects that it is relatively easy to reach other zones from the center of the corridor. This is also reflected by the (weighted) average distance of outward commutes, which is 18.8 km in zone 1 versus 12.4 km in zone 6. The commuting flow between zone 1 and 6 is 35 (vice versa 36) and the flow between the edge zones 1 and 11 is about 43% lower, which is consistent with a larger distance (travel time) between these two zones. The attractiveness of zone 6, and the fact that it is centrally located (i.e. a lot of traffic crossing zone 6), results in a relatively high time (in hours) to travel one km in this zone of 0.037, which is equivalent to a car speed of about 27.0 km/h. The edge zones are relatively uncongested with a traffic speed of 66.7 km/h. The free-flow speed is 72.4 km/h and the weighted average speed in the transport corridor is 33.3 km/h. This implies that there is substantial congestion in some parts of the transport corridor.

Column 2 adds railway travel as a separate mode of transport. The high percentage train use and the high number of stops in the transport corridor suggests that travel in this case can be interpreted as travel via local train (light rail) or express metro. Nevertheless, due to the disutility of going by train and the relatively high travel times by train (1.015, on average, in case of commuting), most workers still use the car to commute (55.3 percent).

Table 2 contains a decomposition of the railway travel time by number of stops. Below 9 stops, the largest component of travel time of rail passengers is access/egress time. In case of 10 stops or more, the in vehicle travel time is the largest component in total travel time. At 9 stops they both contribute equally to travel time. Waiting times are also a substantial part of travel

[34] This is relatively low in comparison with the center of a city. In particular, in the circular city of Anas and Rhee (2006) the density in zone 6 is about 1,800 workers per km2. We will show results of the circular city in the sensitivity analysis. It is important to note that the exact density in itself is not that informative since it is defined up to some (arbitrary population) scale. It are the differences in the density patterns across space that are interesting.

[35] Hence, the model does not say much about (changes in) urban sprawl across space (in the model firms follow people and people follow firms). However, Baum-Snow (2013), for instance, finds that each radial highway displaces 16 percent of central city population in the US to suburbs, but the effect on jobs is only 6 percent. This suggests that the transport system also plays an important role in the creation/reduction of urban sprawl.

time. Even though the waiting time in each zone is limited, having a train station in each zone results in an accumulation of waiting times for longer trips. In essence, the result in Table 2 imply that, although railway travel in itself is quite efficient (low net travel time), the access/egress and waiting time associated with railway travel makes this mode of transport relatively unattractive.

Table 2: Decomposition of travel time between train stations by number of stops

stops:	2	3	4	5	6	7	8	9	10	11
nominal										
access/egress	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333
travel time	0.042	0.083	0.125	0.167	0.208	0.250	0.293	0.333	0.375	0.417
waiting time	0.000	0.025	0.050	0.075	0.100	0.125	0.150	0.175	0.200	0.225
total	0.375	0.442	0.508	0.575	0.642	0.708	0.775	0.842	0.908	0.975
percentage										
access/egress	88.8	75.3	65.6	57.9	51.9	47.0	43.0	39.5	36.7	34.2
travel time	11.2	18.8	24.6	29.0	32.4	35.3	37.8	39.5	41.3	42.8
waiting time	0.0	5.7	9.8	13.0	15.6	17.7	19.4	20.8	22.0	23.1
total	100	100	100	100	100	100	100	100	100	100

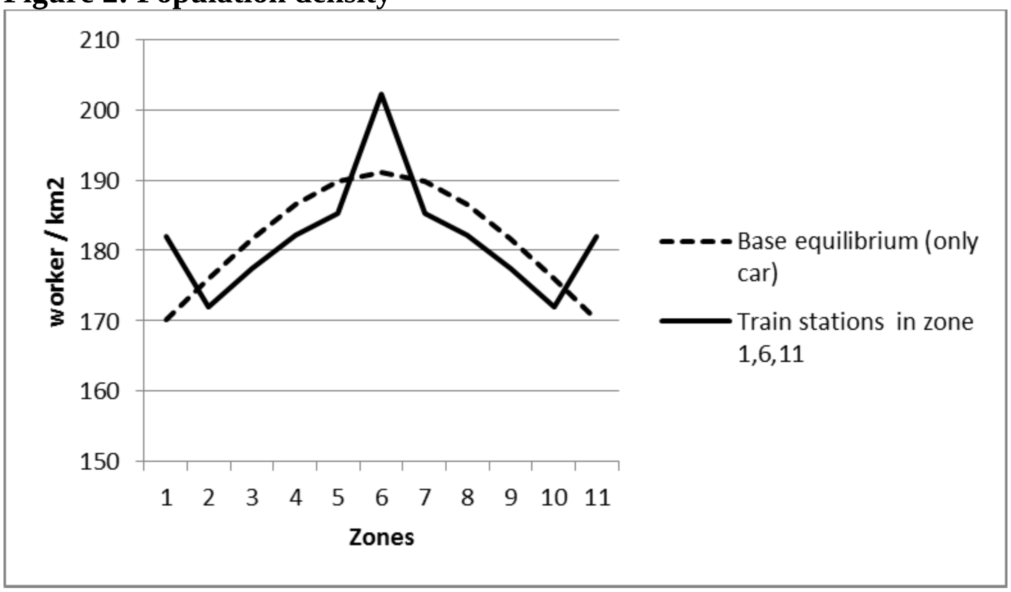
Note: A travel time of 1 is equivalent to one hour. Travel time by train is symmetric by number of stops (i.e. travel time between zone 1 and 3 is equal to travel time between zone 3 and 5).

The results in Table 1, column 2, also demonstrate that shopping and commuting time by car decreases (to 0.691 and 0.745, respectively) in comparison with column 1, which is the result of a substantial decrease in congestion (especially in zones 5, 6, and 7). On average, congestion decreases by 20 percent after the introduction of railway travel. This result implies that public transport (railway travel) may well act as a second-best solution to congestion tolls (the standard solution to reduce congestion, see Anas and Rhee, 2006).

Finally, and most importantly, the results in column 2 imply that the spatial pattern in terms of population and work remains virtually unchanged. At best, population and jobs become a bit more homogenously distributed across space – with a decreased population/job density in zones 4,5, and 6, and an increased density in zones 1,2, and 3 – because the importance of the central zones as areas that have easy access to the relatively closely located peripheral zones decreases due to a decrease in the overall level of congestion. Interestingly, congestion decreases the most in the central zones, but this is not reflected in the urban spatial structure.

Column 3 shows the results when train stations are only available in zone 1,6, and 11.[36] Since travel distances by train are longer relative to column 2, travel can be interpreted as travel via express train. Figure 2 shows the population density in case there is no railway travel (column 1) versus when railway travel is available in zone 1,6, and 11 (column 3). Even with a stylized and simple formulation of railway travel, we see an interesting spatial pattern emerging. Population density peaks in zone 1,6, and 11 in case access to the railway network is limited to those zones. In particular, population density is 5.8 percent higher in zone 6 and it is 6.9 percent higher in zone 1 and 11. These results are economically sizeable. A similar pattern holds with regards to jobs.

Figure 2: Population density



The clustering of population and jobs (into 3 cities/urban areas) has several causes. First, the part of population that wants to use the train, even though this is only 5.5 percent, all clusters around a relatively limited number of train stations (access points). That is, since access to train stations is spatially clustered, the population that uses the train is also clustered. Because train use is relatively low, however, congestion only decreases marginally. Second, the regions with railway access become more attractive places to work and shop, partly due to an increased variety of goods, but also due to a more competitive travel time (0.849 for train versus 0.857 for car). In particular, Figure 3 shows the cumulative commuting flows aggregated by work

[36] In essence, we restrict the travel times and the probability to travel by train such that railway travel is only allowed between zone 1, 6, and 11. In this case, there are 3,881 equations.

destination and Figure 4 the weighted average Marshallian demand (units of consumption) per worker by shopping zone. Both commuting flows and consumption peak in those zones which have access to the railway network. This result implies that train stations (railway travel) have a broader impact on the urban economy than just the effect on population (job) density alone.

Figure 3: Aggregate commuting flow by job destination

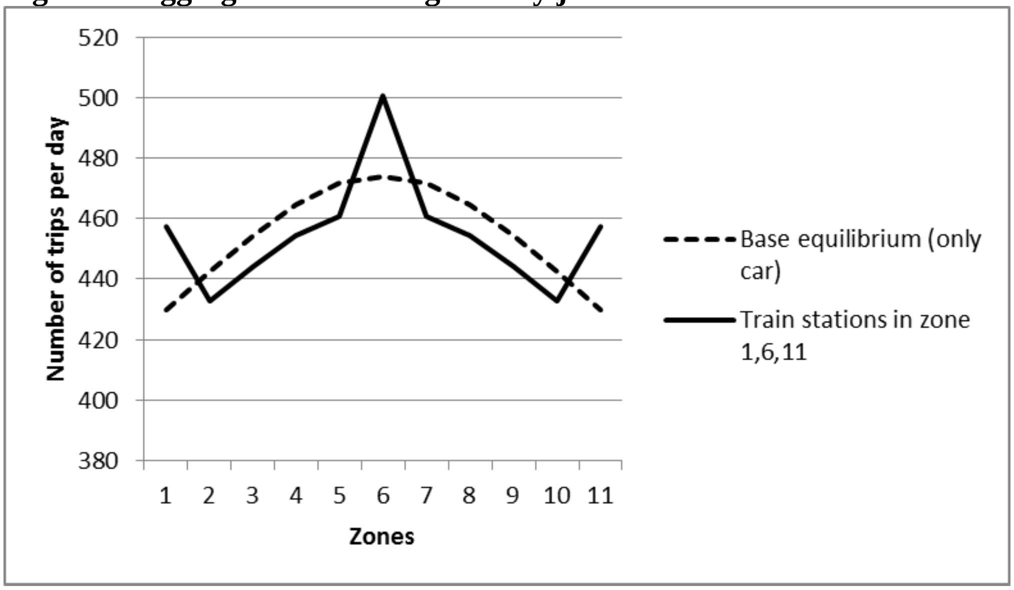
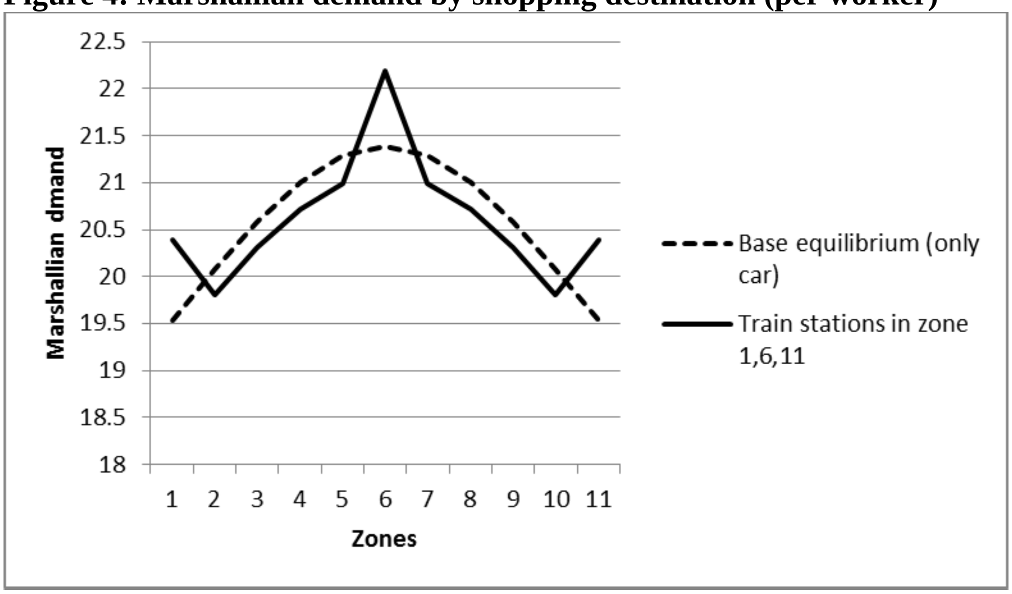


Figure 4: Marshallian demand by shopping destination (per worker)



Finally, the results in column 3 also show that the daily commuting flows between zone 1,6, and 11, increases substantially in comparison with column 1 and column 2. Specifically, the flow from zone 1 to 6 goes up from 35 (37 in column 2) to 56, an increase of 60 percent (51 percent). A similar result holds for the commuting flow between zone 6 and 1. From zone 1 to 11 commuting even doubles relative to the base equilibrium. Moreover, the commuting flows by train, but also by car, increases substantially in comparison with column 2. These result are in line with the idea that railway travel makes cities with access to the railway network more attractive (comparative advantage) as long as the total number of train stations is limited. Due to railroads people find it easier to spatially differentiate where they work versus where they live.

In sum, the above-mentioned findings imply that access to railway travel, at least when this access is limited across space, results in an increase of population and job density (urbanization). The fact that population only clusters when the supply of train stations is limited suggests that, if train stations are used to combat urban decline, they should be used in moderation. Instead, our results indicate that to obtain a decrease in congestion having a relatively large number of access points to the railway network is most useful.

4.2 Sensitivity analysis

Table 3 shows the sensitivity of the results to changes in the parameter values. We report the percentage change of population / job density and congestion relative to the base equilibrium.

First, we change the nested logit coefficient from $\chi_{ij} = 1$ (no correlation between transport modes) to $\chi_{ij} = 0.5$ (moderate correlation). Of course, the base equilibrium in which travel only occurs by car is not affected by this change. In case there are train stations in all zones, the effect on congestion is still negative, but slightly less pronounced (i.e. a decrease of 16.7 percent relative to the base equilibrium). The effects on population and job density are small and similar to the main results reported in this paper. In case access to the railway network is limited to zones 1,6, and 11, however, the effects on congestion, instead of population, are small (overall -3.3 percent, the results are virtually identical to the main results). In addition, the impact on population density becomes somewhat less pronounced and ranges between 2.4 and 3.2 percent.

Second, we change the idiosyncratic preference parameter from $\lambda = 12.0$ to $\lambda = 4.0$ (the circular city parameter value used by Anas and Rhee, 2006). In essence, this decreases the impact of the deterministic part of utility on the probability to work and live in a particular zone. The results again stay in line with our main findings. Interestingly, the effect on population and job density in case access to the railway network is limited to a few zones becomes larger (the positive effect on population density is between 11.1 and 12.0 percent).

Table 3: Sensitivity analysis (% change relative to base equilibrium)

Zones	1		2		3		4		5		6		Tot.	
							Main results							
Train all zones	Pop	Job	Pop	Job	Pop	Job	Pop	Job	Pop	Job	Pop	Job	Pop	Job
Density	0.9	0.8	0.7	0.6	0.2	0.1	-0.4	-0.3	-0.8	-0.7	-0.9	-0.8	0	0
Congestion	-6.7		-15.0		-15.4		-21.9		-22.2		-21.6		-20.0	
Train zone 1,6,11														
Density	6.9	6.4	-2.3	-2.2	-2.3	-2.2	-2.4	-2.2	-2.4	-2.3	5.9	5.6	0	0
Congestion	0		-5.0		0		-3.1		-2.8		-2.7		-3.3	
							Nested logit coefficient: $\chi_{ij}=1$ ➔ $\chi_{ij}=0.5$							
Train all zones														
Density	0.9	0.8	0.6	0.5	0.2	0.1	-0.4	-0.3	-0.7	-0.6	-0.9	-0.7	0	0
Congestion	-6.7		-10.0		-15.4		-18.8		-22.2		-21.6		-16.7	
Train zone 1,6,11														
Density	3.2	3.0	-1.0	-0.9	-1.0	-1.0	-1.1	-1.0	-1.1	-1.0	2.4	2.4	0	0
Congestion	0		-5.0		0		-3.1		-2.8		-2.7		-3.3	
							Idiosyncratic preferences: $\lambda = 12.0$ ➔ $\lambda = 4.0$							
Train all zones														
Density	0.8	0.7	0.6	0.5	0.2	0.1	-0.3	-0.3	-0.7	-0.6	-0.9	-0.8	0	0
Congestion	-6.7		-15.0		-21.4		-25.7		-25.6		-26.8		-21.9	
Train zone 1,6,11														
Density	12.0	11.5	-4.2	-4.1	-4.3	-4.1	-4.3	-4.2	-4.3	-4.2	11.1	10.8	0	0
Congestion	0		0		-3.6		-5.7		-2.6		-4.9		-3.1	
							A European setup: $\alpha = 0.36, \beta = 0.15, \gamma = 0.49, \rho = 0.6$ ➔ $\alpha = 0.40, \beta = 0.21, \gamma = 0.39, \rho = 0.6$							
Train all zones														
Density	0.8	0.8	0.6	0.6	0.1	0.1	-0.3	-0.3	-0.7	-0.7	-0.8	-0.8	0	0
Congestion	-6.7		-14.3		-17.9		-20.6		-23.1		-20.0		-18.8	
Train zone 1,6,11														
Density	5.5	6.1	-1.8	-2.1	-1.9	-2.1	-1.9	-2.1	-1.9	-2.2	4.6	5.3	0	0
Congestion	0		-4.8		-3.6		0		-2.6		-2.5		-3.1	
							A circular city: rectangular zones ➔ circular wedge							
Train all zones														
Density	-0.5	-0.3	0.4	0.2	0.3	0.2	0.2	0.1	0	0	-0.4	-0.2	0	0
Congestion	-6.7		-11.1		-15.8		-17.4		-22.2		-33.3		-20.0	
Train zone 1,6,11														
Density	9.3	13.8	-5.1	-5.2	-5.2	-5.2	-5.3	-5.3	-5.4	-5.3	9.2	14.2	0	0
Congestion	0		0		-5.3		-4.3		-3.7		-6.3		-4.0	

Notes: This table reports percentage changes of the case with train stations in all zones and train stations in zone 1,6,11 relative to the base equilibrium (only car). The base equilibrium may change as parameter values change. Congestion is measured by the time (in hours) to travel one km.

Third, we use preference parameters (consumption shares) that are in line with a European setup instead of a US setup. That is, the income share of consumption and housing increases to 40 and 21 percent ($\alpha = 0.40$, $\beta = 0.21$), respectively, and the share of leisure decreases to 39 percent $\gamma = 0.39$. These parameters are used by Tscharaktschiew and Hirte (2012) and are in line with consumption shares in a typical German city. We again find that, although the spatial patterns shift somewhat, the trade-off between congestion and urbanization is still there.

Finally, we examine the results in a circular city setup (for a full description see Anas and Rhee, 2006). The rectangular patches of land are replaced by two circular wedges originating from the center of zone 6. The angle of each wedge is three degrees. The horizontal width of the zones are 3.22 km (2 miles) and 8.05 km (5 miles) for the edge zones. The land area of the two wedges is 13.3 km^2 and the total area of the circular city is 797 km^2. The percentage of land allocated to roads is relatively high in the center (27.5 percent in zone 6) and low at the edges (0.7 percent in zone 1 or 11). The idiosyncratic preferences are set at $\lambda = 4.0$ and we use the same railway travel parameters as before. The base equilibrium is a replication of the Anas and Rhee (2006) equilibrium.

Interestingly, the results within cities are similar to the results between cities. The railway network with train stations in all zones resembles a (metro / light rail) network in which lines originate from the center, there are many access nodes, and the lines are interconnected by ring lines. Such a network is, for instance, currently present in Moscow. In this case, we do not find large effects on the degree of urbanization in different zones, but we do find a substantial decrease in congestion (on average 20 percent). Instead, if access to the railway network is limited, which resembles the metro network in Los Angeles (i.e. lines still originate from the center, there are not many access nodes, nodes are not clustered), population and job density peaks in zone 1,6, and 11. The effect on both population and job density is higher than in the transport corridor. Apparently, the effects are amplified within cities. Accessibility (travel times) – an essential determinant in the Anas model – is more restricted in cities (cities are more congested) than in the transport corridor, which could potentially explain this result. A further finding is that the effect on job density is higher than on population density. This implies that areas with access to the railway network have a relatively higher job-housing balance, which could be interpreted as a decrease in urban sprawl.

To summarize, the findings in this paper are robust to changes in the parameter values. The sensitivity analysis suggests that the trade-off between congestion and urbanization holds across a wide range of different setups.

5. Future research

In this section, we suggest several directions for future research. First, it is now well appreciated that agglomeration economies play an important role in the formation of cities (Glaeser and Gottlieb, 2009). Although the Anas model incorporates that consumers value the variety of goods, which is in line with Krugman (1991), there are no economies of scale in production. Ogawa and Fujita (1982), or more recently, Lucas and Rossi-Hansberg (2002), use models in which the level of production is directly dependent on the density of firms. In these models, cities form as a result of agglomeration externalities and not necessarily due to differences in travel times. We would expect that the clustering of population and firms as a result of train stations would be more pronounced if there are agglomeration externalities. It would be interesting to examine to what extent cities in this case are affected by public transport, making a distinction between within (metro) versus between (train) city dynamics. In addition, although the model incorporates the negative effect of extra train stations on travel times, there are no direct positive (e.g. cultural heritage) or negative (e.g. crime, environmental) externalities as a result of having a train station in a particular region.[37]

A second direction for future research would be to extend the model using a network approach. In this paper, travel occurs on a line through the transport corridor, which is based on a limited number of zones. However, many cities are accessible through multiple paths (via train, car, airplane, etc). The system of cities approach has been used by Anas and Pines (2013) to examine the role of fiscal and zoning policies to help finance local public goods. Anas and Liu (2007) combine the Anas model with a separate transport model (algorithm) for the Chicago MSA. Anas and Hiramatsu (2013) use this model to examine optimal cordon tolling in Chicago.[38] The main issue is that the network approach increases the dimensionality of the system of equations, especially in case of a large number of nodes, which makes it more difficult to obtain convergence and reliable results. In this case, simplifying assumptions are commonly used, such as the independence of the commuting and transport mode choice, to get results.

A further research direction relates to the effect of zoning regulations on the urban structure of cities. The model in this paper shows the effects of railway travel on population

[37] The original model of Anas and Kim (1996) does incorporate exogenous shopping externalities.

[38] In addition, the effect of (rail-based) public transport on congestion may depend on the type of highway network between/within cities. Nitzsche and Tscharaktschiew (2013), for instance, find that roads with speed restrictions can have entirely different effects on congestion and welfare than roads without (or just local) restrictions. It would be interesting to examine urbanization and congestion in the context of a system of roads versus a system of railroads.

density and the mechanism through which these effects are obtained. If, at the extreme, zoning regulations are binding in all zones the effects on population would be zero. This suggests a potential overestimation of the changes in population density in our model. A potential solution would be to use a Kuhn-Tucker type of approach and reformulate the system of equations such that it represents a mixed complementarity problem (often used in CGE analysis). Alternatively, Anas and Pines (2013) show a model in which lot size is determined by the government and consumers bid to obtain a particular lot.[39]

Finally, it would be interesting to examine the supply and spatial allocation of train stations in more detail. In particular, the allocation of train stations in this paper is exogenous. It would be interesting to look at different spatial patterns of railway accessibility, including a hybrid system of high-speed and regular lines, the welfare implications of different spatial patterns, and under which conditions such patterns emerge. The general equilibrium framework used in this paper only shows the direction of congestion/urbanization effects, given the railway network, but not the underlying time dynamics. In addition, the local/national government usually plays an important role in the creation of public transport hubs. It would be interesting to investigate whether the supply of public transport should be centralized or decentralized. There is some research in this direction in relation to travel by car (De Borger, Proost, and Dender, 2005; De Borger, Dunkerly, and Proost, 2007). To incorporate this feature, we would need to make a clear distinction between (the cost of) the supply of train stations and the supply of railway services (ticket fares).

6. Conclusions

This paper has investigated the effect of railway travel on urban spatial structure using a polycentric land use model in a transport corridor setup. Urban land use models have mostly been used to analyze the effect of travel by road on the allocation of jobs and residences. Although these models have significantly increased our understanding about urban land use patterns, and in particularly the development of cities, the focus on travel by roads makes these models mainly applicable to countries such as the United States.

The results in this paper show that train stations positively affect the degree of urbanization in the area in which the train station is located if the number of train stations is

[39] For a discussion of different zoning regimes on land use and land prices, see Debrezion et al. (2007).

limited. Because access is limited – emphasizing the discrete nature of railway accessibility – the effects are clustered around train stations. In particular, population density is about 5.8 to 6.9 percent higher in areas with access to railway travel. We find similar results for job density. In addition, we find that commuting flows between areas with a train station is 50 to 60 percent larger in comparison with both the base equilibrium (only car) and the equilibrium with full access to train stations in all geographical zones. This result is in line with the idea that railway travel makes it easier for households to differentiate between the place of residence and the place of work. Limiting the availability of railway travel results in a comparative advantage in terms of goods and travel times for those regions with access to the railway network. However, we do not find large effects on congestion. In contrast, if access to railway travel is relatively abundant, we find a decrease in congestion of about 20 percent, but little effect on the degree of urbanization (urban spatial structure). These results suggest that there is a trade-off between congestion and urbanization. This trade-off seems to hold in a wide variety of setups, including within cities.

These results have several implication for policies regarding (rail-based) public transport. First, it is evident that the accessibility to public transport has broader implications on the urban economy than just the effects on travel time, or population density for that matter, that is the focus of many empirical studies. We find a broader spatial economic pattern related to consumption, jobs, and commuting flows. It is important to take these effects into consideration when deciding to provide public transport in a particular region. Second, there has been a lot of emphasis to reduce congestion by means of congestion tolls. Our results show that public transport (supply of railway travel) may well act as a second-best solution to congestion tolls. Third, public transport is not a goal in itself. The purpose of producing public transport determines how access to public transport is to be allocated across space. Policies aiming to reduce congestion by mains of public transport are best served by a large number of transport hubs. Instead, if the aim is to create a clustering of population or jobs, to mitigate urban decline or, for instance, to foster agglomeration economies, policy makers should carefully evaluate not only the amount of access points, but also the spatial allocation of those points. A limited number of strategically placed stations may be more effective in strengthening the economy in certain areas than a large number of stations randomly allocated across space.

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Appendix

Table A1: Parameters

Transport corridor (symmetric around central zone) Z = 11 zones Length of zones in km 1) 5 2) 5 3) 5 4) 5 5) 5 6) 5 Area in km^2 (vertical width, 500 m) 1) 2.5 2) 2.5 3) 2.5 4) 2.5 5) 2.5 6) 2.5 Land allocated to roads (percentage): 1) 1.5 2) 1.5 3) 1.5 4) 1.5 5) 1.5 6) 1.5
Consumer equations $\alpha = 0.36$ income share of consumption goods $\beta = 0.15$ income share spent on rented lot size q $\gamma = 0.49$ income share of leisure $\rho = 0.6$ relates to elasticity of substitution between commodities $H = 500$ hours per month time endowment $d = 500/24$ work days per month $f = \frac{1}{13}$ the number of trips to purchase one unit of consumption $\lambda = 12.0$ the degree that tastes are idiosyncratic (0 = random) $N = 5{,}000$ workers
Producer equations $\delta = 0.86$ labor cost share $\mu = 0.14$ land cost share $E = 1$ scale factor
Transport equations $a = 1/(45 * 1.6093)$ hours per km, inverse of free of congestion traffic speed $b = 50$ strength of traffic flow to capacity in congestion function $c = 2$ strength of traffic flows to capacity in congestion function $\zeta = 1.1$ parameter that converts roads to road capacity in a zone
Additional parameters for railway travel ς_t mode specific constant (normalized to 1 for train, 1.01 for car) $\chi_{ij} = 1$ captures the correlation between random utilities $\phi = 15$ speed in km/hour to get to the train station by foot/bicycle $train\ speed = 120$ speed in km/hour of travel via public transport (train) $\vartheta = 1.5/60$ time in hours spent on waiting time after each train stop (1.5 minutes) Land allocated to railroads (percentage): 1) 1.0 2) 1.0 3) 1.0 4) 1.0 5) 1.0 6) 1.0

Note that there are no additional parameters necessary for the market clearing conditions and government budget.

Table A2: Endogenous variables

Consumer	
z_{ijvt}	consumption of goods
q_{ijt}	consumption of lot size
l_{ijt}	consumption of leisure
Ω_{ijt}	full endowment income
D	land dividend
V_{ijt}	indirect utility
Producer	
M_v	labor demand
Q_v	land demand
X_v	production of goods
Travel	
g_{ijt}	travel time
Ψ_{ijt}	origin-destination probability matrix
$F_{in'car'}$	total flows by car (shopping and working) between zones
$F_{i'car'}$	total flows by car in a zone (internal, crossing, and ending/beginning in the zone)
$g_{i'car'}$	congestion (time to cross one kilometer) by car
T_{ijt}	total travel time
Government	
h	head tax to finance (rail)roads
Market	
p_v	product prices (effective price)
p_{ijv}	composite price of goods (including travel time)
w_j	wages
r_i	land rents
Objective	
$welfare$	welfare measure