Strategic Transportation Investment And Policies: Evidence From the U.S. Highway System

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Abstract

Goods and people flow through transportation networks often constructed by multiple jurisdictions. When each decision-maker fails to internalize the full surplus generated by their investment, the resulting network can be inefficient. Coordinating such investments is therefore crucial but also complex: How much should each participant construct, and how much compensation should they receive from others? This paper develops a quantitative spatial model of the U.S. highway network with both goods trade and commuting to study the inefficiencies arising from decentralized, non-cooperative transportation investments. In the model, states choose highway investments to maximize their constituents' utility in a Nash game, given highway subsidy rates set by the federal government. Through the lens of the model, the paper computes the optimal investment and taxes from the federal planner's perspective, and quantifies the efficiency gap between the observed network, the optimal network, and networks under alternative highway fiscal policies.

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1 Introduction

Transportation infrastructure investment constitutes one of the largest categories of public expenditure across countries. By facilitating lower cost in the movement of goods and people, this infrastructure improves the efficiency of production and daily life, while at the same time reallocating economic activities across the space. A salient feature of transportation infrastructure is its far-reaching spatial spillovers. Highway investments in one state benefit not only local users, but also travelers and businesses outside of the jurisdiction. Moreover, transportation infrastructure redistributes economic activities across locations, creating winners and losers as a consequent of investments.

Despite the potential inefficiencies of a decentralized allocation, infrastructure planning and construction are often delegated to multiple governments at lower administrative levels. The US Federal-aid Highway Program is a case in point. State governments plan the routes, and fund highways by tax revenues.[1] As state governments represent the interests of their constituents, they do not fully account for the welfare impact of highways on the rest of the nation in their investment decisions. Absent proper policies to correct incentives, decentralized investment as such will result in inefficiencies in the road network.

Given the tension between substantial spatial spillovers and decentralized policy institutions, this paper investigates the implications of the decentralized investment and federal highway policies in U.S. federal-aid highways. Theoretically, it seeks to shed lights on the economic mechanisms that give rise to inefficiencies in the lack of cooperation between states, and characterizes the optimal transportation network from the perspective of a federal government. In addition to the traditional externality with the usage of transportation network, I show that terms-of-trade externality and fiscal externality, both arising from spatial interactions of economic activities, are also key drivers of inefficiencies in a decentralized network. Taking the theory to the data, the paper quantifies the welfare gains brought by the prevailing federal highway subsidies in the US – including a massive, homogeneous 90% subsidy on the Interstate Highway System – by comparing the status quo to a counterfactual without any subsidies. It further analyzes the welfare implications under two alternative scenarios. First, the optimal network, as would be chosen by a federal government absent the decentralized institution. Second, taking the decentralized institution as given, the paper postulates a constrained-optimal policy, where we only consider simple subsidy plans with a two-tier subsidy structure: one rate for intra-state highways, the other for highway segments crossing state borders.

The paper starts by documenting facts about how crossing state borders increases the

[1] Even today, the share of toll revenue in total receipt of U.S. highway budget is only 10%.

cost of highway travels for trucks. In particular, conditional on geographic factors and traffic volume, it is slower and takes longer detours to ship goods across cities belonging to different states, compared to shipments between city pairs that belong to the same state. This translates to a higher cost in fuel, wages and time to deliver through highways only because the trip passes state borders. Roads are also more rugged when they are close to state borders, suggestive of relatively insufficient maintenance efforts for the infrastructure.

The paper continues by developing a quantitative spatial model with policy competition in Nash to describe the distortions in decentralized highway investment. In the model, transportation costs of goods and people are endogenously determined by state governments who play a non-cooperative Nash game. A state government seeks to maximize her constituents' utility by investing in infrastructure using state fiscal revenue. Federal highway subsidies, administered as a reimbursement of road construction cost by a fixed percentage, influence a state's incentive to invest by providing a discount on the effective cost paid from the state's budget. Federal taxes indirectly influence states' investment plans through the total tax level faced by residents at each state, which also affect migration decisions between states.

I highlight three origins of inefficiencies as a result of the non-cooperative game between states. The first originates from the terms-of-trade effects caused by trade cost reductions. An investment to reduce the import trade cost from a neighbor lowers the local cost of consumption, but also induces more demand to the neighbor, bidding up the price of goods they produce; for the neighbor, this corresponds to a "terms-of-trade appreciation". It in turn inflates the price (net of transportation costs) for the investor's imports, a welfare loss from the local government's perspective. In the eyes of a social planner, however, terms-of-trade adjustments only reallocate income across locations, which partially cancels out between sellers and buyers; in fact, the aggregate effect should be exactly zero in an environment with no differentials in marginal utility of expenditure across locations. This tension leads to insufficient investment from local government's unilaterally optimal plan, as they fail to internalize the positive terms-of-trade externality incurred to neighbors.[2]

The second type of distortion comes from the network nature of highways. Many highways serve transshipment between locations that do not pay tax dollars into the local budget. While road investments simultaneously save import costs for the investor and the buyers who do not pay for roads, benefits to the latter are not internalized by the investor. Due to

[2]The mirror image of under-investment in importing infrastructure driven by terms of trade is an over-investment in exporting infrastructure: lower exporting costs induce an appreciation of terms-of-trade for the investor. However, exporting infrastructure also generates a positive technology spillover to the destination market, where the residents enjoy lower costs of their imported goods; as the investor fail to capture rents from his neighbor's welfare gains, this spillover induces under-investment relative to social optimum. The direction of distortion on exporting infrastructure depends on the net effect from these two channels.

such technology spillover, state investments in a Nash equilibrium are insufficient relative to the total trade cost savings, especially on segments with large shares of external traffic flows.

Third, endogenous local fiscal budgets give rise to fiscal externalities from unilateral infrastructure investments. This becomes relevant for transportation within the same country or across regions with active cross-border migration. Individuals respond to wages, price levels and tax burden in their location choices. Whenever a state raises taxes to improve infrastructure, he may gain or lose taxpayers depending on whether the net effect on local utility per capita is positive or negative. If it loses taxpayers, a state must raise taxes on each remaining resident to maintain the infrastructure spending, which hurts the constituents' utility. However, a marginal investment that incurs a loss of taxpayers at the investor's jurisdiction can improve social welfare overall, as the gain in tax revenue elsewhere partially offsets the local constituents' loss. This creates a wedge between marginal social returns and the state planner's private returns. Because of the wedge, states that would lose local taxpayers following a marginal investment on infrastructure under the optimal allocation have incentives to reduce those investments and deviate from social optimum.

While the distortions discussed above all originate from the use of highways as a trade facility, commuters' benefits account for a significant share in welfare consequences of highways. What are the implications of commuting in investment distortions? Two major effects emerge. First, similar to the technology spillover of trade infrastructure discussed above, highways can serve commuters who do not pay taxes to the investor state. Because the benefits to those commuters are not internalized, decentralized investments are insufficient especially on segments with large shares of external commuting flows. Second, in the presence of agglomeration effect and amenity congestion effect, state governments can improve constituents' welfare by attracting more workers and venting out residents. Driven by such incentives, they increase investments on links towards locations with relatively high amenity, and decrease investments towards those with relatively high productivity. [3]

In observance of these inefficiencies, the network chosen by non-cooperative state planners will be inefficient absent any coordination mechanism, both insufficient in total scale and misallocated due to varying magnitude of externalities across highway segments. How is the incidence of distortions distributed in space? Could alternative federal subsidy policies better align the state governments' incentives with national welfare? By developing a model of the US highway system, I seek to quantitatively answer these two questions. I first quantify the magnitude of externality by each highway link, measured by the dollar amount of changes in

[3]The incentive to repel residents due to amenity congestion partially off-sets the incentive to attract taxpayers so that each constituent pays less tax. Absent amenity congestion, state planners still find investments towards locations with relatively low productivity palatable, as reducing commuting cost between them attracts more workers to the investor's jurisdiction.

national welfare relative to the changes in investor state's welfare in response to the marginal unit of highway investment on a highway link.

Next, I quantify the welfare implications of alternative highway subsidy policies, given states' objectives implied by the observed equilibrium. States may engage in negotiations with one another, which we don't directly observe.[4] To account for these interactions, I use the model to back out the parameters governing the degree to which states' decisions internalized the policy impact on other states. Specifically, I model a state planner's decisions as if he were maximizing an objective function that assigns non-zero weight to the welfare of other states' constituents. This follows the spirit of Adão et al. (2024): instead of modeling specific institutions, which are difficult to observe in this context, I focus on measuring how effectively institutional constraints lead governments to internalize the effects of their policies to other jurisdictions. If two states assign high weight to each other, it may indicate cooperative behavior in their highway planning process. Through the lens of the model, a two-tier subsidy rate that distinguishes intra-state and cross-state highway links would improve welfare from the prevailing federal subsidy formula, which doesn't distinguish between highway links based on their geographic characteristics.

While this paper focuses on U.S. domestic highways, the model applies to broader settings. It is suited to contexts in which multiple non-cooperative authorities make decentralized decisions that jointly determine transportation infrastructure or other trade facilities between them, and where welfare gains cannot be shared across decision-makers.

Contribution to Literature

This paper contributes to several strands of literature. The first studies the effect of transportation infrastructure on local economic performance and general equilibrium outcomes. From reduced-form evidence to quantitative studies, the literature has found strong effects on growth, spatial distribution of population and economic activities from construction of inter-regional Highways (Baum-Snow (2007), Michaels (2008), Faber (2014), Weiwu (2024)) or railroads (Donaldson and Hornbeck (2016), Nagy (2023), Hornbeck and Rotemberg (2024)). These studies leverage exogenous factors that drive the actual location of transportation infrastructure, such as planned, historical or minimum-cost layout of highway network, so as to identify the causal effect of infrastructure construction. My study takes an attempt

[4]In practice, during the planning procedure of Interstate Highway System, state highway departments exchanged ideas through a non-public organization named American Association of State Highway Officials, which mainly facilitates route alignment at state borders (Barrow (1967)). Similarly, when designating the US Numbered Highway System, states held regional group meetings to discuss the routes to be included; Bureau of Public Roads sent representatives to these meetings Federal Highway Administration (2017).

to explain why highways ended up where they are through governments' incentive to invest and to understand the implication for welfare. In particular, it models the formation of highways as a result of Nash game between state governments who represent the welfare of their constituents, mirroring an important institutional feature in transportation policy that prevails in many nations and regions of the world.

To capture the welfare consequence of different investment plans in the network, this paper builds on the literature of quantitative spatial models (e.g., Redding and Sturm (2008), Allen and Arkolakis (2014), Redding (2016), Monte et al. (2018), Allen et al. (2020), Allen et al. (2024); see Redding and Rossi-Hansberg (2017) for a review). Allen and Arkolakis (2022) developed a model with endogenous transportation cost that tractably captures the welfare effects of marginal infrastructure investment for a given link in an interconnected highway network. This study incorporates endogenous transportation cost into a spatial general equilibrium with trade and commuting à la Monte et al. (2018), and solves the problem of network optimization for both a single-planner environment and the case with a Nash game between multiple state planners.

The second strand of related literature develops tools to characterize optimal investment in transportation network. A recent economic literature started tackling the optimal transportation network problem in a general equilibrium with trade or commuting, which features demand and supply endogenous to the network (Fajgelbaum and Schaal (2020), Kreindler et al. (2023), Bordeu (2023)). In my study, the optimal transportation network takes account of benefits in both trade and commuting, reflecting a salient feature of highway usage in the United States.

A burgeoning literature studies the inefficiencies under decentralized investment in transportation infrastructure, including commuting roads (Bordeu (2023), Loumeau (2023)), trade infrastructure (Felbermayr and Tarasov (2022)) and sea ports (Brancaccio et al. (2024)). Other studies examined the origins of suboptimal transportation investment in settings with a centralized planner, including political preferences (Fajgelbaum et al. (2023)) and constraints from historical investment (Santamaria (2021)). US highway system differs from transportation infrastructures in the existing literature by its mixed use for trade and commuting. I contribute to the discussion by accounting for the distortionary effects on non-cooperative investment from both trade and commuting mechanisms and their interactions, and considering the scope for coordinative fiscal policy at a higher level of the government.

In terms of optimal transportation policy to address inefficiencies in a decentralized equilibrium, existing quantitative studies tackle the externalities that atomistic agents create for the aggregate environment – for instance, through congestion externalities or environmental externalities; to the best of the author's knowledge, these studies focused on applications in

urban commuting networks (Almagro et al. (2024), Hierons (2024)). Fajgelbaum and Schaal (2020) theoretically characterized the decentralization of the social planner's optimal network and allocation with taxes and tolls in the competitive market of shippers and monopolistic construction firms. My study departs from existing works in two aspects. First, market failure comes from non-atomistic local governments who do not fully account for the welfare effect of their road construction on neighbors' constituents. Second, due to the differentiation in production, terms-of-trade externality adds to the inefficiencies, a new mechanism relative to the policy recipes on infrastructure without trade in differentiated goods.

Last but not least, this paper contributes to the discussion on implications of non-cooperative government policies. This include discussions on non-cooperative tariffs (Bagwell and Staiger (1999), Ossa (2011), Ossa (2018)), and on tax competition in the presence of population mobility (Kanbur and Keen (1993), Oates (1999), Keen and Konrad (2013), Muñoz (2023)). It is well-understood from the optimal tariff literature that terms-of-trade externality gives rise to inefficient outcomes in non-cooperative tariff policies. My paper reveals an analogy between better trade infrastructure and lower tariffs, and explains how terms-of-trade externality accounts for inefficiencies from non-cooperative transportation investment despite in a very different policy realm.[5] I also show that, since local governments face infrastructure budgets endogenous to the size of population, competition for tax revenues incurs a fiscal externality in unilateral optimal taxes and investments: as taxpayers relocate to jurisdictions with high-paying jobs and lower costs of living, locations losing their tax base must raise taxes on remaining residents to maintain infrastructure spending, a welfare effect neglected by local planners who only represent the interest of their constituents.

2 Motivating Facts

In this section, I present a set of facts illustrating that highway infrastructure conditions in the U.S. tend to be worse on road linkages that cross state borders. I show that traveling between cities across state borders is slower, takes more detour, and roads become more rugged when they approach state borders.

[5]On the government budget side, infrastructure investment differs from cutting tariffs in that it takes real resources away from consumption. In the presence of federal subsidies, the cost of infrastructure is shared among states, hence the amount of resources taken away from a state is lower than the social cost of investment.

Data

MSA Boundaries And Commuting Flows

I obtain city boundaries from maps of March 2020 Metropolitan Statistical Areas (MSA) defined by the U.S. Office of Management and Budget.
A crosswalk between counties and MSAs for years 2013-2023 are obtained from Quarterly Census of Employment and Wages. For each MSA and MSA-pair, I obtain commuting flows by aggregating up county-pair flows from American Community Survey 2011-2015.

Optimal Routes Between Cities

To measure the infrastructure conditions between locations, I obtain optimal routes for trucks that connect the centroids of a pair of "adjacent" MSAs from HERE API. I define a pair of cities to be adjacent if the connection of their geographic centroids do not cross the territory of any other MSA, and at least one of the two is among the 20 nearest MSAs of the other. This restriction helps avoid spurious correlations between state borders and driving costs. Pairs that cross state borders are often also pairs that route through multiple cities. These multi-city routes tend to involve longer detours and potentially more congestion, due to interaction with local commuting flows. Under this criteria, I obtained 1173 non-repetitive pairs. Figure 1 plots all pairs identified as neighbors in the map. Each pair of red dots connected by blue lines are a pair of neighboring cities.[6]

From the optimal truck routing results, I observe the driving distance, estimated time on the road, and elevation at points along the route.

Highway Catalog And Road Condition

Information on highway location, traffic and surface condition is obtained from 2016 Highway Performance Monitoring System (HPMS) published by Federal Highway Administration. It identifies each highway segment by its geo-referenced location, route number (e.g. I-95, US-1), signing system (Interstate, U.S., State, County, etc.), functional system (Interstate, Principal Arterial, Minor Arterial etc.), whether it belongs to the Interstate Highway System, National Highway System, or neither.[7]

[6] Grey lines connect pairs whose centroids connection do not cross a third MSA but does cross an ocean or a lake. I exclude those from neighboring pairs.

[7] All Interstate Highways are part of the National Highway System. National Highway System has broader coverage than Interstate Highway System. The system classification helps determine the eligible subsidy rate from grants dispensed by federal formula funding. The empirical exercise is restricted to roads that at least belong to National Highway Systems, hence controlling for route number automatically controls for subsidy rate.

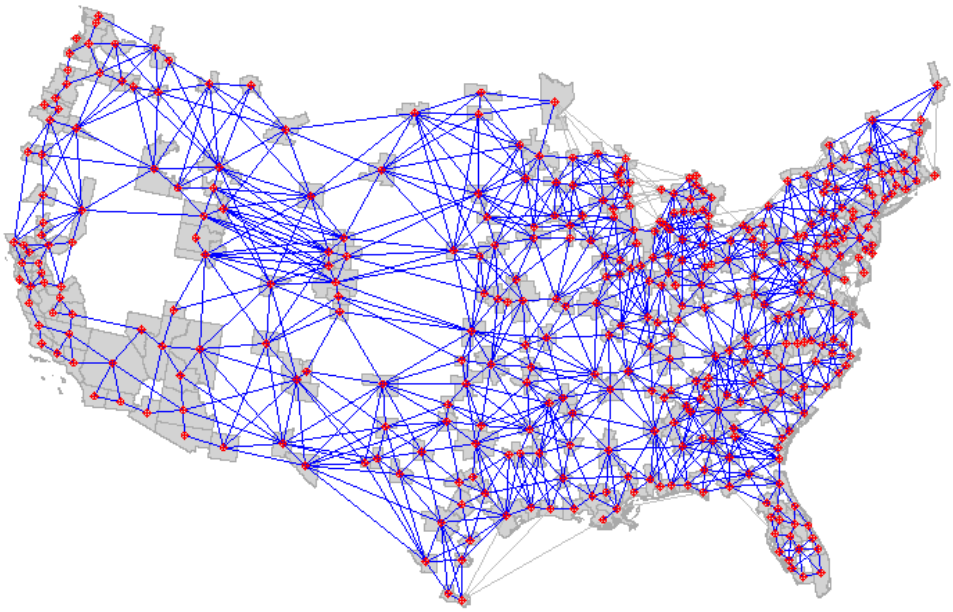


Figure 1: MSA Neighbors

For each segment, the data documents the Annual Average Daily Traffic (AADT), AADT by trucks, and measures for pavement conditions, among other items. In the empirical exercise, I use the International Roughness Index (IRI) from this data to measure the ruggedness of road surface of each segment in space. This statistic has two advantages relative to other measurements of road quality. First, it has relatively complete coverage compared to other pavement condition measures in HPMS. Second, the number comes from an objective measurement procedure, and the index is most commonly used worldwide for evaluating and managing road systems. To be specific, this index is calculated by the inches of suspension movement per mile of travel, and is measured for each 0.1 mile road segment. More suspension movement indicates worse road condition.

Geography

I sourced an elevation raster from DIVA-GIS, which facilitates the measurement for how much terrain ruggedness there is between a pair of cities. I also sourced a shapefile of U.S. rivers from HydroRIVERS data product. This data contains the geo-referenced location of rivers with a catchment area of at least 10 km^2 or an average river flow of at least 0.1 m^3/sec. It also orders all rivers into the main stem river, the tributaries, and the tributaries that flow into tributaries, etc. I use this order to identify the major rivers in the U.S. by rivers of Order 1. These geography features help control for physical factors that may affect the quality and placement of roads.

2.1 Fact 1: Faster Travel Between MSAs of the Same State

Time on the road is a natural measure for trucking costs between a pair of cities. More time spent on the road incurs extra costs for fuel and driver's wage and less timely delivery. In this practice, I examine how such costs vary systematically with the ownership of cities at both ends.

Table 1 shows that travel between MSA pairs within the same state takes shorter time, conditional on distance, traffic and geography. *Link Interior* is a dummy that flags MSA pairs belonging to the same state or partially overlapping with the same state. I control for traffic factors including commuting flows out of the origin, entering the destination, and from origin to destination. Geographic factors that might affect engineering difficulty of the road are controlled by variation in elevations and river crossings: $Log(sd(elev))$ measures the logarithm of standard deviation of elevation on the optimal route, and *Cross River* is a dummy that captures whether the straight-line connection between an MSA pair's centroids crosses a major river.

In the preferred specification (column 4), I additionally control for origin fixed effects and destination fixed effects. This specification accounts for unobserved factors at the city level that may shift the demand for better roads, such as availability of public transit, or cost of road construction, such as local institutional constraints for acquiring right-of-way. Conditional on distance, traffic and geography, time spent on the road is shorter by 2.4% if the city pair belong to the same state. From a back-of-the-envelope calculation, this is equivalent to an average saving of 6.1 km traveled on the road.[8]

2.2 Fact 2: Less Detour Between MSAs of the Same State

Another measurement for the cost of traveling is the directness of road connection between locations. Extra mileages relative to a straight connection incurs extra costs on fuel, wages and time to travel. In this empirical exercise, I examine how indirectness of roads vary with the ownership of cities at both ends. I measure the degree of detour on the optimal path by actual driving distance conditional on the straight-line distance.

After controlling for traffic factors and geographic factors (column 2), I found an average of 2.2% reduction in actual driving distance for a pair of cities within the same state compared to those crossing the state border. To account for unobserved factors at city level that may shift the tortuosity of roads, such as internal geography and local zoning law, column 5 presents the specification absorbing the fixed effects at origin level and destination level. The size of average treatment effect from *Link Interior* increases to 3.2%.

The preferred specification is column 6, where an additional control variable accounts for state borders established by mountains. This variable measures average Terrain Ruggedness Index (TRI) along the straight-line connection between city centroids. In this preferred specification, we observe a significant 3.1% reduction on actual driving distance for city pairs within the same state, which translates to a 5.71 km reduction in straight-line distance and 6.76 km reduction in actual driving distance.[9]

[8] *Link Interior* has an equivalent effect as $0.024/0.859 \times 100\% = 2.8\%$ decrease in driving distance. Multiplied by the average driving distance 218.3 km between adjacent pairs, this is equivalent to a 6.1 km reduction in driving distance.

[9] *Link Interior* has an equivalent effect as $0.031/0.899 \times 100\% = 3.45\%$ reduction in straight-line distance. Multiplied by the average straight-line distance 165.6 km, this is equivalent to a 5.71 km reduction in straight-line distance. Average Actual Distance in regression is 218.3 km, which implies a state border effect equivalent to an actual distance of $218.3 \times 0.031 = 6.76$ km.

Table 1: Travel Time And City Link Ownership

	Dependent variable:			
	Log(Time on Shortest Path)			
	OLS		*felm*	
	(1)	(2)	(3)	(4)
Link Interior	-0.020^{**}	-0.022^{**}	-0.036^{***}	-0.024^{**}
	(0.008)	(0.010)	(0.008)	(0.010)
Log(Distance on Path)	0.816^{***}	0.828^{***}	0.863^{***}	0.859^{***}
	(0.007)	(0.012)	(0.010)	(0.018)
Log(Commuter Out)	-0.011^{***}	-0.014^{***}		
	(0.003)	(0.004)		
Log(Commuter In)	-0.007^{**}	-0.012^{***}		
	(0.003)	(0.004)		
Log(Commuter o-d)		0.007^{**}		-0.003
		(0.003)		(0.004)
Log(sd(elev))	0.055^{***}	0.057^{***}	0.029^{***}	0.023^{**}
	(0.004)	(0.004)	(0.008)	(0.009)
Cross River	0.059^{***}	0.063^{***}	0.015^{*}	0.031^{***}
	(0.007)	(0.008)	(0.009)	(0.012)
Constant	-0.939^{***}	-1.035^{***}		
	(0.095)	(0.123)		
Origin FE	*No*	*No*	*Yes*	*Yes*
Dest FE	*No*	*No*	*Yes*	*Yes*
Observations	1,148	921	1,173	921
R^2	0.966	0.957	0.993	0.993
Adjusted R^2	0.966	0.957	0.984	0.980

Note: Sd(elev) is the standard error of elevation on the optimal route. Cross River is a dummy that captures city pairs whose centroid connection crosses a major river. Standard errors clustered by origin and destination MSA. *p<0.1; **p<0.05; ***p<0.01.

Table 2: Detour And City Link Ownership

	Dependent variable:					
	Log(Driving Distance)					
	OLS			*felm*		
	(1)	(2)	(3)	(4)	(5)	(6)
Link Interior	-0.036^{***}	-0.022^{**}	-0.017	-0.047^{***}	-0.032^{***}	-0.031^{***}
	(0.008)	(0.010)	(0.010)	(0.009)	(0.011)	(0.011)
Log(Straight-line Distance)	0.900^{***}	0.900^{***}	0.924^{***}	0.918^{***}	0.899^{***}	0.899^{***}
	(0.007)	(0.012)	(0.013)	(0.011)	(0.021)	(0.020)
Log(Commuter Out)	-0.014^{***}	-0.013^{***}	-0.013^{***}			
	(0.003)	(0.004)	(0.004)			
Log(Commuter In)	-0.013^{***}	-0.011^{**}	-0.012^{***}			
	(0.003)	(0.005)	(0.004)			
Log(Commuter o-d)		0.001	0.002		-0.004	-0.003
		(0.003)	(0.003)		(0.006)	(0.006)
Log(sd(elev))	0.060^{***}	0.062^{***}	0.029^{***}	0.051^{***}	0.057^{***}	0.039^{***}
	(0.004)	(0.004)	(0.007)	(0.008)	(0.009)	(0.009)
Cross River	0.040^{***}	0.040^{***}	0.036^{***}	0.015	0.002	0.001
	(0.007)	(0.009)	(0.008)	(0.011)	(0.011)	(0.011)
Log(Avg TRI)			0.038^{***}			0.056^{***}
			(0.007)			(0.016)
Constant	7.779^{***}	7.721^{***}	7.612^{***}			
	(0.062)	(0.068)	(0.070)			
Origin FE	*No*	*No*	*No*	*Yes*	*Yes*	*Yes*
Dest FE	*No*	*No*	*No*	*Yes*	*Yes*	*Yes*
Observations	1,148	921	921	1,173	921	921
R^2	0.969	0.961	0.963	0.991	0.993	0.993
Adjusted R^2	0.969	0.961	0.962	0.981	0.980	0.981

Note: Sd(elev) is the standard error of elevation on the optimal route. Cross River is a dummy that captures city pairs whose centroid connection crosses a major river. Avg TRI is the average Terrain Ruggedness Index along the centroid connection between MSA pairs. Standard errors clustered by origin and destination MSA. *p<0.1; **p<0.05; ***p<0.01.

2.3 Fact 3: More Ruggedness On Roads Approaching State Borders

A more direct examination for road condition is to look at the physical features of road surface. The International Roughness Index (IRI) captures exactly that: More suspension movement during driving reflects more rugged road surface. How costly would that be? According to calculation by the Federal Highway Administration, for a combination truck traveling at 50 miles per hour on a level, straight road, estimated operating cost per vehicle-mile is 16 percent ($0.167) lower at an IRI of 50 rather than 170, and 11 percent ($0.115) lower at an IRI of 95 rather than 170.[10] Given annual Vehicle-Miles Traveled per lane-mile of 2 million in rural Interstate Highways and about fourth them traveled by trucks, these reductions in IRI translate to a reduction in trucker's operation cost of $83,500 and $57,500 each year per lane-mile, respectively.[11]

I use the information in HPMS dataset to characterize how IRI systematically varies as roads approach state borders. To achieve the most comparable groups of highways, I restrict the sample to highways that are in the Interstate Highway System (e.g. I-95), or part of US Numbered Highways (e.g. US-1), or in any lower systems but explicitly cross state borders (e.g. Massachusetts Route 146 and Rhode Island Route 146). I also drop the ones that restricts commercial vehicles from traveling on the road.

Table 3 illustrates that IRI is on average higher on road segments closer to state borders.[12] In this set of regressions, *State border* is defined as a dummy that captures road segments within 8 km of borders between states. *Coastal Border* flags road segments within 8 km of U.S. coastline, and *Land Border* flags those within 8 km of international land borders. These dummies are mutually exclusive with the *State Border* dummy. Controlling for these borders makes sure we are comparing with the right control group – the highways away from boundaries of states.

In our preferred specification (column 5), controlling for average daily traffic and the most disaggregated set of fixed effects, roads within 8 km of state borderlines are more rugged by 1.3 IRI points. By absorbing this battery of fixed effects, the comparison is restricted to road segments that belong to the same state, functioning system and route number, which partials out the heterogeneity in budget constraint, functional importance and construction standards. The remaining variation is therefore a relatively clean indication of the government's discretion in maintaining the road.

[10] Source: Highway Economic Requirements System. https://www.fhwa.dot.gov/policy/23cpr/appendixa.cfm

[11] Source: Highway Statistics 2022, Table VM-1; National Transportation statistics 2025, Table 1-36.

[12] This exercise used highway networks in New England area plus New Jersey, New York and Delaware. Will be expanded to the whole U.S. in future iterations.

Table 3: Road Roughness and State Borders

	Dependent variable:				
	IRI				
	OLS	*felm*			
	(1)	(2)	(3)	(4)	(5)
Log(AADT)	-4.209^{***}	-6.285^{***}	2.670^{***}	2.267^{***}	2.624^{***}
	(0.260)	(0.326)	(0.332)	(0.380)	(0.383)
State Border	0.803	2.972^{***}	1.566^{***}	1.196^{**}	1.331^{**}
	(0.570)	(0.593)	(0.568)	(0.595)	(0.588)
Coastal Border	11.977^{***}	10.231^{***}	8.231^{***}	14.562^{***}	13.127^{***}
	(0.799)	(0.794)	(0.765)	(0.815)	(0.808)
Land Border	2.774^{**}	1.830	-1.448	0.196	0.122
	(1.378)	(1.364)	(1.300)	(1.356)	(1.345)
Constant	121.161^{***}				
	(2.290)				
State FE	*No*	*Yes*	*Yes*	*Yes*	*Yes*
F SYSTEM FE	*No*	*No*	*Yes*	*Yes*	*Yes*
ROUTE FE	*No*	*No*	*No*	*Yes*	*Yes*
Surface Type FE	*No*	*No*	*No*	*No*	*Yes*
Observations	60,136	60,136	60,136	60,136	59,747
R^2	0.008	0.048	0.136	0.184	0.198
Adjusted R^2	0.008	0.047	0.136	0.183	0.197

Note: AADT represents Annual Average Daily Traffic on each lane; State Border, Coastal Border and Land Border are dummy variables indicating whether the segment is within 8 km of a State border, coastal border and international land border respectively. F SYSTEM represents the functional system of the road. *p<0.1; **p<0.05; ***p<0.01.

3 A General Model

This section presents a general competitive equilibrium. Through this exercise, I show that a local investment in transportation affects welfare of all location options across the whole economy. In particular, locations are exposed to such local changes through (1) network effect in the transportation infrastructure, (2) terms of trade adjustments, (3) changes in fiscal burden due to population mobility, and (4) productivity and amenity spillovers due to worker and resident relocation. This decomposition point to directions in which local planners would distort transportation investments.

3.1 Environment

Production. Each location produces a unique variety and labor is the only factor of production. Denote the mass of workers in j by L_j. Output is potentially non-linear with respect to labor:

$$Y_j = L_j y(L_j).$$

Within each variety, goods are perfectly substitutable. Varieties are transported subject to iceberg trade cost. Denote prices of good j faced by consumer in location i as p_{ji}. Perfect competition implies

$$p_{ji} = p_j \tau_{ji}$$

where p_j is the factory gate price for the variety produced in location j.

Workers' budget. Location choices are defined by a combination of residence and workplace. Individuals consume and pay taxes at their residence, and earn the wage level at their workplace. All choices $\{ij\}_j$ share the same consumption bundle local to the residence i. This implies individuals' budget constraint under choice ij

$$e_{ij} = p_j y_j(L_j) - T_i P_i. \tag{1}$$

In the budget constraint, T_i is a lump-sum government tax per capita, denominated in local consumption bundle at i, and captures the per-resident material expenditure on infrastructure construction. P_i is the price for a unit of consumption bundle at location i. Formally,

it is defined as

$$P_i := \min_{c_{ij,k}} \sum_k c_{ij,k} p_{ik}$$
$$s.t.\, C\left(\{c_{ij,k}\}_k\right) \geq 1$$

where $C(\cdot)$ is a homothetic preference across varieties. By envelope theorem, the derivative of price index at location i with respect to prices of imports from location k is

$$\frac{\mathrm{d}P_i}{\mathrm{d}p_{ik}} = \frac{c_{ij,k}}{C\left(\{c_{ij,k}\}_k\right)} \forall j \tag{2}$$

which says that the derivative of price index with respect to price of any commodity equals the unit demand of commodity. Homotheticity in demand guarantees the homogeneity in price derivatives across workplaces conditional on residence.

Local governments' budget. To achieve a fixed level of total infrastructure, local government for location i collects tax from its residents and invest it in infrastructure. Denote the mass of residents in i by R_i. Local government at i faces the following budget constraint:

$$K_i = T_i R_i \tag{3}$$

where K_i captures the total investment in location i.

Individuals' location choice. Consider the fundamental utility level for choice ij, that is, residing in location i and work in location j. Indirect utility of this choice can be written as

$$U_{ij} = U(e_{ij}, \{p_{ki}\}_k, u_i(R_i), \kappa_{ij})$$

where $\partial U/\partial e_{ij} > 0, u_i(R_i)$ is the local amenity level subject to congestion, κ_{ij} is the disutility by commuting from i tp j, and p_{ki} is price for good k in location i, which doesn't depend on workplace choice. Individuals then choose the utility maximizing location pair subject to their potentially idiosyncratic preference, on top of the fundamental utility U_{ij} offered by economic and amenity conditions.

Distribution of workers and residents. Consider the population distribution in equilibrium. Denote mass of individuals commuting from i to j by λ_{ij}. This distribution comes from individual's utility maximizing choice, accounting for the fundamental utility U_{ij} and

their idiosyncratic preference. As fundamental utility adjusts, choice probability on each option reacts, and this affects the distribution of worker and residents following the identity

$$R_i = \sum_j \lambda_{ij}, L_j = \sum_i \lambda_{ij}. \tag{4}$$

Market clearing. Goods market clearing implies

$$Y_j = \sum_{k,l} \tau_{jk} \lambda_{kl} c_{kl,j} (1 + \frac{T_k}{C(\{c_{kl,j}\}_j)}). \tag{5}$$

In words, total production of good j must equal to the total sales towards all individuals who choose location pair kl, gross of shipping cost from production place j to consumption place i. And lastly, labor market clearing implies

$$\sum_i R_i = 1, \sum_j L_j = 1. \tag{6}$$

3.2 Equilibrium Responses to Transportation Investment

Worker's expenditure can be written as a function of indirect utility, prices, local amenity and commuting costs:

$$e_{ij} = e\left(U_{ij}, \{p_{ji}\}_j, u_i(R_i), \kappa_{ij}\right).$$

Let $Y_X = \frac{\partial Y}{\partial X}$ and $Y_{X,ij} = \frac{\partial Y_{ij}}{\partial X_{ij}}$. Take total differentiation and apply Shephard's Lemma,

$$\mathrm{d}e_{ij} = e_U \mathrm{d}U_{ij} + \sum_k c_{ij,k} \left(\tau_{ki} \mathrm{d}p_k + p_k \mathrm{d}\tau_{ki}\right) - U_{e,ij}^{-1} U_{u_i} u_i'(R_i) \mathrm{d}R_i - U_{e,ij}^{-1} U_\kappa \mathrm{d}\kappa_{ij}. \tag{7}$$

On the other hand, differentiate workers' and local governments' budget constraints (1)(3),

$$\mathrm{d}e_{ij} = y_j(L_j)\mathrm{d}p_j + p_j \mathrm{d}y_j(L_j) - P_i\left(K_i \mathrm{d}R_i^{-1} + R_i^{-1} dK_i\right) - T_i \sum_k \frac{\mathrm{d}P_i}{\mathrm{d}p_{ik}} \left(\tau_{ki}\mathrm{d}p_k + p_k \mathrm{d}\tau_{ki}\right). \tag{8}$$

Combining equations (2), (7) and (8), we can rewrite changes in indirect utility U_{ij} as

$$\begin{aligned} U_{e,ij}^{-1}\mathrm{d}U_{ij} = &- \underbrace{\sum_k m_{ij,k} p_k \mathrm{d}\tau_{ki}}_{\text{import technology}} + U_{e,ij}^{-1} \underbrace{U_{comm,ij}\mathrm{d}\kappa_{ij}}_{\text{commuting technology}} - \underbrace{R_i^{-1} P_i \mathrm{d}K_i}_{\text{direct fiscal costs}} \\ &- \underbrace{\sum_k m_{ij,k}\tau_{ki}\mathrm{d}p_k}_{\text{terms of trade}} + \underbrace{(T_i P_i \mathrm{d}R_i)}_{\text{fiscal externality}} + \underbrace{p_j \mathrm{d}y_j(L_j)}_{\text{productivity spillover}} + \underbrace{U_{e,ij}^{-1} U_{amen,ij} u_i'(R_i)\mathrm{d}R_i}_{\text{amenity congestion}} \end{aligned} \quad (9)$$

where $m_{ij,k}$ is the quantity that choice ij imports (exports if negative) from k for each individual, inclusive of consumption and tax contribution:

$$m_{ij,k} = c_{ij,k} + \frac{T_i}{C\left(\{c_{ij,k}\}_k\right)} c_{ij,k} - \mathbb{I}\{j = k\}\, y_j.$$

Note that $\tau_{ij}, K_i, \kappa_{ij}$ are fundamentals which the government can intervene separately with policy; $p_k, m_{ij,k}, y_i, L_i, R_i$ and marginal utility of expenditure $U_{e,ij}$ are equilibrium objects. Each fundamental shock will incur changes in every equilibrium object at every location.

Formula (9) characterizes, to the first order, how the indirect utility for a given location choice responds to shocks in transportation fundamentals. The first two terms capture the technological benefits of improved transportation: lower trade costs reduce spending on iceberg trade cost on imported goods, while lower commuting costs decrease the disutility from commuting. To fund such infrastructure improvements, each current resident must make more fiscal contributions, reflected in the third term. Together, these three terms represent the trade-offs when treating transportation infrastructure as a production technology: resources are invested to reduce the costs of moving goods and people.

The second row captures general equilibrium effects on location utility. For production site k, reduced export costs towards external markets improve its terms of trade, as increased demand makes variety k more scarce relative to other varieties. An individual choosing pair ij benefits if the appreciation in goods produced in j outweighs the appreciation of goods consumed and taxed in i.

The final three terms reflect the effect from population mobility. Individuals relocate in response to changes in fiscal burden (term 3), cost of living, and wages (terms 1 and 4); furthermore, a fall in commuting costs attracts more dwellers to the residence and workers to the workplace (term 2). As residents relocate, locations losing residents face a shrinking tax base, hence each remaining resident must pay a higher tax to sustain infrastructure spending. Finally, productivity spillover and amenity congestion imply that an influx of workers may raise productivity, while more residents may diminish the attractiveness of local amenity.

3.3 Distortions In Local Planner's Investment From Social Optimal

In what follows, we show how local and national planners evaluate infrastructure projects differently, and associate the direction and magnitude of distortion with margins of externalities above.

Local planner$i$ choose investments and the tax $\left\{\{I_{ij}\}_{j\in\mathcal{N}(i)}, T_i\right\}$ within his jurisdiction, recognizing that these investments affect costs in the full transportation network $\{\tau_{ij}\}_{ij}$, $\{\kappa_{ij}\}_{ij}$. In particular, assume investments and local tax must satisfy local budget constraint

$$T_i R_i = K_i, \quad K_i \equiv \sum_{j\in\mathcal{N}(i)} \delta_{ij}^I I_{ij} \tag{10}$$

where δ_{ij}^I is a construction cost shifter. Since taxpayers contribute to public budgets only in their place of residence, a local planner maximizes a weighted sum of the indirect utilities of residents within their territory:

$$\mathcal{W}_i = \sum_j \omega_{ij} U_{ij}.$$

In contrast, when a social planner chooses the investments and taxes under the same local budget constraints for all locations, she accounts for the welfare of all individuals in the economy, using the same Pareto weights as those which local planners put on their constituents:

$$\mathcal{W}^{SP} = \sum_{ij} \omega_{ij} U_{ij}.$$

In this section, I assume Pareto weights of the following form for analytical tractability:

$$\omega_{ij} = \lambda_{ij} U_{e,ij}^{-1}$$

which weighs indirect utility of each location pair choice proportional to the population, but discounts those with high marginal utility of expenditure.[13] We can now compare how the objective functions of local planners and social planner respond to a marginal change in infrastructure funded by raising taxes at location i. To fix ideas, consider perturbations around a socially optimal equilibrium. The deviation of local planner's private returns from social returns then informs us of the size of the wedge that causes inefficiency in local planner's unilaterally optimal investments. I will use three examples to illustrate three margins

[13]The analysis in this section remains robust as long as a planner's objective function satisfies

$$W = W\left(\{U_{ij}\}_{i,j}\right) \; s.t. \frac{\partial W}{\partial U_{ij}} = \omega_{ij}.$$

of externality in isolation: the technology externality, the terms-of-trade externality, and the fiscal externality.

Special case 1: Technology externality.

Suppose there are no spillovers in amenity or productivity, individuals make fixed location choices, and investments in roads induce a symmetric reduction in trade cost for both directions; the trade cost on each link is determined by investments made by planners at both ends of the link jointly. Consider the geography illustrated in figure 2a. To shut down terms-of-trade effect, assume that location C has a linear preference and no cost in importing goods:

$$C_c(\{c_k\}_k) = \sum_k \alpha_k c_k, \quad p_{CA} = p_A, \quad p_{CB} = p_B.$$

In addition, the costs of exporting from C to A and B are always higher than the bilateral trade cost between A and B, so that no transshipment flows through C.

Consider the first-order condition for the local planner at location A, holding fixed the investments chosen by B and C. Without loss of generality, consider the condition with respect to investment I_{AB}, which affects both τ_{AB} and τ_{BA}. From utility responses 9 and budget constraint 10, his unilateral optimum must satisfy

$$\underbrace{-M_{AB}p_B\frac{\mathrm{d}\tau_{BA}}{\mathrm{d}I_{AB}}}_{PV_{AB}} = \delta^I_{AB}P_A.$$

In contrast, social optimal condition requires

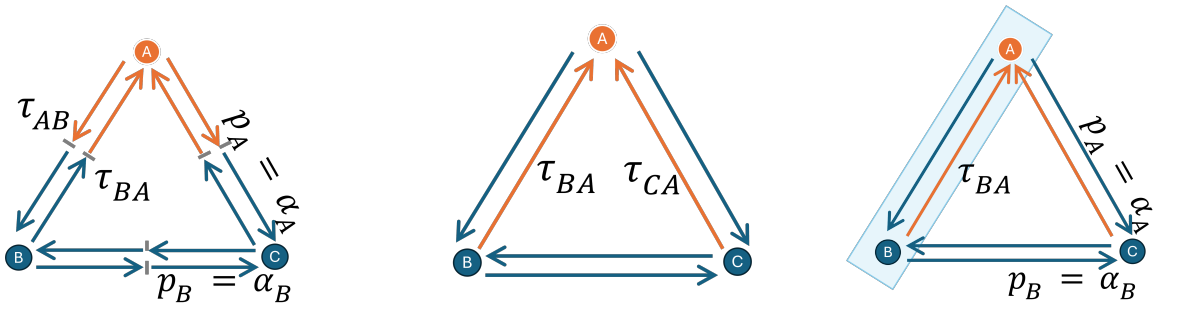
$$\underbrace{-M_{BA}p_A\frac{\mathrm{d}\tau_{AB}}{\mathrm{d}I_{AB}} - M_{AB}p_B\frac{\mathrm{d}\tau_{BA}}{\mathrm{d}I_{AB}}}_{SV_{AB}} = \delta^I_{AB}P_A.$$

For a marginal investment by A on link AB, while social cost equals the private cost on the right-hand side, the additional term in social value (SV_{AB}) compared to the private value (PV_{AB}) reflects that social planner additionally internalizes the import cost reduction for B as a result of A's investment. Comparing these two conditions, we can express the wedge in private optimality condition relative to social optimum as follows:

$$SV_{AB}(1-\kappa_{AB}) = \delta^I_{AB}P_A, \quad \kappa_{AB} = \frac{M_{BA}p_A}{M_{BA}p_A + M_{AB}p_B}$$

The formula for wedge κ_{AB} says that, due to technology externality, local planner underinvests relative to social optimal; furthermore, the wedge between private and social optimal

is proportional to the share of traffic flows destined in external locations, as measured in the value of goods at the factory-gate price.



(a) Technology Externality (b) Terms-of-trade Externality (c) Fiscal Externality

Figure 2: Geographies With Isolated Externality

Special case 2: Terms-of-trade externality.

Suppose there are no spillovers in amenity or productivity, individuals make fixed location choices, and each location invests for reducing importing costs but not the exporting cost, so that technology externality is shut down. Preferences all come with finite price elasticity, so that terms of trade endogenously adjust with respect to trade costs. The modified geography is illustrated in figure 2b.

Consider the first-order conditions for the local planner at location A, in particular for the investment decision to reduce the trade cost from B to A. As τ_{BA} decreases, the import price for good B faced by location A falls due to savings from trade costs, but raises after general equilibrium adjustments as the factory-gate price for good B increases. Perceiving both margins of price responses, unilateral optimum must satisfy

$$\underbrace{-M_{AB}\tau_{BA}\frac{\mathrm{d}p_B}{\mathrm{d}\tau_{BA}}\frac{\mathrm{d}\tau_{BA}}{\mathrm{d}I_{BA}} - M_{AB}p_B\frac{\mathrm{d}\tau_{BA}}{\mathrm{d}I_{BA}}}_{PV_{BA}} = \delta^I_{BA}P_A.$$

However, social optimum requires

$$\underbrace{-M_{AB}p_B\frac{\mathrm{d}\tau_{BA}}{\mathrm{d}I_{BA}}}_{SV_{BA}} = \delta^I_{BA}P_A.$$

The additional term in private value (PV_{BA}) relative to social value (SV_{BA}) reflects the terms-of-trade externality. Terms-of-trade appreciation for B triggered by reduced trade cost $\mathrm{d}\tau_{BA} < 0$ is amount to a transfer from A to B. While a social planner sees no aggregate effect from such a transfer, local planner at A perceives a weakened purchase power of their

constituents' income as the neighbor's good becomes more expensive relative to their own product. As such, they under-invest relative to a socially desirable level. How much do they deviate? We can again express the wedge in private optimality condition as

$$SV_{BA}(1-\kappa_{BA}) = \delta^I_{BA} P_A, \quad \kappa_{BA} = -\frac{\mathrm{d}\ln p_B}{\mathrm{d}\ln \tau_{BA}} > 0$$

The expression for wedge κ_{BA} says that, due to terms-of-trade externality, local planner under-invests relative to social optimal, and the wedge is proportional to the elasticity of the output price at the exporting location with respect to the corresponding iceberg trade cost to import. The rationale is analogous to the one behind unilateral optimal tariffs. Investing less on the infrastructure for importing goods is like charging a tariff. While consumers experience higher cost from the trade cost / tariff, part of the burden is shifted to the exporter, whose product would eventually face a lower price due to shrinkage in demand; the extent to which this burden can be shifted depends on how sensitively exporter's price responds to trade costs/tariffs. An exporter with a large market typically has an inelastic supply curve, which implies limited response of terms of trade respect to trade costs. Towards those markets, the distortion in local planner's optimal investment is mild.

Special case 3: Fiscal externality. Suppose there are no spillovers in amenity or productivity; each location invests for reducing importing costs but not the exporting cost, so that technology externality is shut down; to exclude terms-of-trade externality, assume location C has a linear preference, faces no cost in importing goods, but high exporting costs so that transshipment doesn't happen, as in special case 1. Different from the previous cases, we allow workers to endogenously choose their location between A and B but without the option to commute, and hold fixed the population at location C. The modified geography is illustrated in figure 2c.

Consider the first-order conditions for the local planner at location A, in particular for the investment decision to reduce the trade cost from B to A. As τ_{BA} decreases, the import price for good B faced by location A falls due to savings from trade costs, but this comes at the cost of raising the per-capita tax contribution at location A. While lower costs for consumption attracts taxpayers, higher taxes repels residents and triggers emigration. Observing this trade-off, unilateral optimum must satisfy

$$-M_{AB} p_B \frac{\mathrm{d}\tau_{BA}}{\mathrm{d}I_{BA}} + T_A P_A \frac{\mathrm{d}R_A}{\mathrm{d}I_{BA}} = \delta^I_{BA} P_A, \qquad \frac{\mathrm{d}R_A}{\mathrm{d}I_{BA}} = \frac{\partial R_A}{\partial \tau_{BA}} \frac{\mathrm{d}\tau_{BA}}{\mathrm{d}I_{BA}} + \frac{\partial R_A}{\partial T_A} \frac{\mathrm{d}T_A}{\mathrm{d}I_{BA}}.$$

The term $T_A P_A \frac{\mathrm{d}R_A}{\mathrm{d}I_{BA}}$ reflects the fact that, whenever an investment plan attracts new residents, they generate additional income to local government budget, which alleviates the tax burden for every local taxpayer. On the other hand, social optimal requires

$$-M_{AB} p_B \frac{\mathrm{d}\tau_{BA}}{\mathrm{d}I_{BA}} + (T_A P_A - T_B P_B) \frac{\mathrm{d}R_A}{\mathrm{d}I_{BA}} = \delta^I_{BA} P_A.$$

Unlike local planner A, the social planner notices that taxpayers gained at location A comes at the cost of tax base at location B: each resident at location B now must pay more taxes as a result of the emigration. Therefore, if the investment and associated tax adjustment triggers a relocation of workers from B to A, this project is less desirable in the eyes of the social planner compared to incentives faced by local planner A. But if the relocation happens in the opposite direction, this project generate higher social value than the unilaterally perceived value. The sign of distortion in unilateral investment induced by fiscal externality therefore depends on the direction of population relocation in response to marginal investments and the associated taxes.

General case. Finally, consider the full model with endogenous commuting costs, agglomeration and amenity congestion, and a general geography. Unilaterally optimal investment requires

$$\begin{aligned} -\sum_{j,k} M_{ij,k} \tau_{ki} \mathrm{d}p_k - \sum_{j,k} M_{ij,k} p_k \mathrm{d}\tau_{ki'} + T_i P_i \mathrm{d}R_i + \sum_j U^{-1}_{e,ij} U_{comm,ij} \lambda_{ij} \mathrm{d}\kappa_{ij} \\ + \sum_j p_j L_j \lambda_{ij|j} \mathrm{d}y_j(L_j) + \sum_j U^{-1}_{e,ij} U_{amen,ij} \lambda_{ij} \mathrm{d}u_i(R_i) = P_i \mathrm{d}K_i \end{aligned} \tag{11}$$

and social planner's optimality condition is

$$\begin{aligned} -\sum_{i',j,k} M_{i'j,k} p_k \mathrm{d}\tau_{ki'} + \sum_i T_i P_i \mathrm{d}R_i + \sum_{ij} U^{-1}_{e,ij} U_{comm,ij} \lambda_{ij} \mathrm{d}\kappa_{ij} \\ + \sum_j p_j L_j \mathrm{d}y_j(L_j) + \sum_{i,j} U^{-1}_{e,ij} U_{amen,ij} \lambda_{ij} \mathrm{d}u_i(R_i) = P_i \mathrm{d}K_i. \end{aligned} \tag{12}$$

The difference in local and social returns (left-hand sides of equation (11) and (12)) now involves three additional distortions.

First, the network externality of commuting infrastructure: when commuters cross the jurisdiction of i, local planner i internalizes commuting cost reductions only for workers who reside within her own boundary. This leads to distortions in investment analogous to the ones induced by import technology externality: links hosting more traffic share from external

commuters are more severely under-invested.

Second, productivity spillovers due to worker relocation are only partially internalized. Local planners capture productivity spillovers elsewhere to the extent that their residents commute to those areas. All else equal, local planners favor links that attract workers to destinations towards which its resident already commutes a lot.

Finally, amenity spillovers pushes local planners to reduce the local residents so that each resident enjoys better local amenities; this effect off-sets the fiscal incentive that we discussed in special case 3, and the net effect depends on the net value of a resident: his tax contribution made to the local government less the marginal reduction in local amenity that he causes to all existing residents.

The last two effects trigger competition among local planners to steal workers and, conditional on the distortions from fiscal externality, to repel residents. One effect on unilateral investment distortions is amplifying the distortions on trade infrastructure induced by terms of trade externalities, so that as a workplace, the local planner's jurisdiction offers a higher wage hence attracts workers. The other strategy local planners would adopt is to manipulate commuting infrastructure: invest more towards locations with relatively high amenities, and invest less towards locations with relatively high productivity. This echoes the insight from Bordeu (2023): holding fixed commodity prices, with improved commuting infrastructure, locations with relatively high productivity would attract workers, and those with better amenity would gain residents. In the current setting, the last two spillovers call for more workers and less residents, hence local planner's unilateral investment prioritizes neighbors with lower productivity and better amenity. As such efforts neglects the productivity effects and amenity effects in the rest of the economy, these incentives are distortionary for commuting infrastructure as well.

4 Quantitative Model

4.1 Institutional Background

Before introducing the policy settings in the quantitative model, this subsection briefly introduces the institutional background in the planning and financing procedure of US highways.

State Authority in Highway Planning

Most of the highway expenditures are disbursed by state agencies rather than federal agencies. While federal agencies receive about a third of total road-user tax revenue, they disperse less than 1% of total expenditure on construction and maintenance; the majority of federal re-

ceipts for highways are transferred to state agencies through the Highway Trust Fund. State agencies collect 64% of total road-user tax revenue, and disburse 70% of total construction and maintenance expenditure. The remainder of state highway receipts are transferred to counties, townships and municipalities. [14] [15]

States have considerable discretion in how they spend highway funds appropriated by the Federal government. According to United States Code, "The authorization of the appropriation of Federal funds or their availability for expenditure (on Federal-Aid Highways) shall in no way infringe on the sovereign rights of the States to determine which projects shall be federally financed." Even in the highway system with the highest federal share – 90% – for the cost, routes were selected by the state highway engineers. According to the Federal-Aid Highway Act of 1944, which authorized the designation of the Interstate Highway System (then called "a National System of Interstate Highways"), Interstate Highways shall be selected by "joint action of the State highway departments of each State and the adjoining States" (Federal-Aid Highway Act (1944)). This procedure was described in more detail by Barrow (1967), a policy study on the politics of Interstate route selection:[16]

> "...each of the state highway departments submitted to AASHO for review a list of proposed routes to be included in the Interstate System. After considerable interaction and exchange of views among the several states through their AASHO representatives, the proposals were submitted to the Bureau of Public Roads for final review and approval."

This reflects a persistent feature in the federal-aid highway policies: states control the initiative in selecting the system to be approved, and the federal government has the authority to approve or disapprove. The Secretary of Transportation has the authority to require modifications or revisions, but it was limited to cases where a project violates specific restrictions in law or requires use of certain protected land (Davis (2022)). In fact, it was reported that during the designation of urban Interstate Highway System, Bureau of Public Roads accepted practically every urban belt route proposed by the States (Federal Highway Administration (2023)).

[14] These numbers came from Table HF-2 ahd HF-10, Highway Statistics 1990.

[15] Among the total disbursements from State highway receipts applicable to highways, about 64 percent are spent on state-administered highways. Local roads, streets and grants-in-aid to local governments cost roughly 20 percent of the receipts, and miscellaneous expenditures (administration, highway law enforcement and safety, bond interest) pick up the rest. These statistics are summarized in Table SF-2; numbers computed from 1990 Highway Statistics.

[16] In the quoted text, American Association of State Highway Officials (AASHO) is a non-public organization comprised of highway officials from every state. According to Barrow (1967), the major role of the AASHO in Interstate Highway route selection was to assist in route alignment at state borders.

Revenue Sources of State-Administered Highways

For each state's Department of Transportation, the primary revenue source deposited for state-administered highways is highway-user tax. These taxes include motor-fuel taxes, motor-vehicle registration fees and motor carrier-taxes, and tax rates set by states differ across the US. Together, they contribute about 63 percent of total State highway revenues in 1950, when federal aid accounted for 15%. This share declines since the uptick in federal transfer starting from the 1956 Federal-Aid Highway Act. As of 1990, which was close to the completion of the Interstate Highway System, the share contributed by state highway taxes has dropped to 45% of total highway receipts, while the share from federal aid went up to 30%.[17]

The other major revenue source is issue of bonds, which was comparable to federal aid in 1950 but only accounted for 7% of State-administered highway receipts in 1990. Tolls and appropriations from general funds, comparable in scale to one another, together comprise less than 10 percent of the total revenue even in 1990.

Federal Grants Revenue and Subsidy Allocation

The Federal Highway Administration receives highway excise taxes to fund highway spending and intergovernmental transfers. These include motor-fuel taxes, motor-vehicle use taxes, and taxes on tires, tubes, and accessories. They are all specific taxes, i.e. charged by a fixed amount per unit of quantity. Highway Trust Fund, which channels federal receipts to state highway agencies, receives all the revenues from the federal tax on gasoline, diesel and special fuels, which makes up 70-90 percent of Fund receipts depending on the year. The Fund also receives all revenue from the tax on tires, tubes and tread rubber; on new trucks, buses and trailers (except 1956-1962 when the Trust Fund receives half of these tax); and from the annual heavy vehicle use tax.

Before 1991, funds for Federal-Aid Highways were administered into two systems: The ABC System, consisting of the primary, secondary and urban highways, and the Interstate Highway System, as established by the Federal-Aid Highway Act of 1956. The ABC system received a 50% federal subsidy in earlier years and 80% later, and the Interstate Highway System consistently received 90% federal subsidy. After 1991, ABC system was replaced by National Highway System and the Surface Transportation Program, both of which provides 80% subsidy for projects in the system. Noticeably, the rate does not vary based on geographic characteristics conditional on the system classification.

[17]These numbers are reported in Highway Statistics, Table SF-3: Receipts for State-Administered Highways.

4.2 Environment with Exogenous Transportation Costs And Tax

Production

Each location i produces one unique variety. A continuum of firms hire workers to produce and price their output in perfect competition. Each worker provides a unit of labor inelastically conditional on working in location i, produces A_i units of variety i where A_i is the local productivity, and earns wage w_i. Local productivity potentially depends on the measure of local workers due to productivity spillover:

$$A_i = \bar{A}_i L_i^a.$$

This implies factory gate price at location i

$$p_i = \frac{w_i}{\bar{A}_i L_i^a}. \tag{13}$$

Varieties produced at each location can be traded subject to an iceberg trade cost. The cost to ship goods from i to j is τ_{ij}.

Worker's Consumption Preference

Workers value the differentiated varieties with constant clasticity of subsitution, and have idiosyncratic preferences across location pairs of residence and workplace. The welfare of individual ϕ working in location i and living in location j is

$$U_{ji,\phi} = \frac{b_{ji,\phi}}{\kappa_{ji}} \left(\sum_k c_{ji,k}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} u_j$$

where c_{kj} is the per-capita quantity of the variety produced in j and consumed in i, $\sigma \in (1, \infty)$ is the elasticity of substitution across varieties, and u_j is the local amenity. Local amenities are subject to congestion by local residents R_i. In particular,

$$u_j = \bar{u}_j R_j^b.$$

The preference shocks $b_{ji,\phi}$ are independently drawn from a Frechet distribution,

$$G(b) = exp(-b^{-\varepsilon}), \varepsilon > 1.$$

Worker's Location Choice

Workers are geographically mobile and chooses the pair of locations for residence and work that maximize their utility. Their indirect utility when working in i and living in j is

$$\begin{aligned} V_{ji,\phi} &= b_{ji,\phi} w_i (1-t_j) u_j / \left(\kappa_{ji} P_j\right) \\ &= \frac{b_{ji,\phi} p_i (1-t_j)}{\kappa_{ji} P_j} \bar{u}_j \bar{A}_i L_i^a R_j^b \end{aligned}$$

where t_j denote the income tax rate at location j, and local price index P_j is given by optimal consumption choice

$$P_j = \left(\sum_i \left(p_i \tau_{ij}\right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}}. \tag{14}$$

Define fundamental utility for location choice ji as

$$U_{ji} = p_i (1-t_j) \bar{u}_j \bar{A}_i L_i^a R_j^b / \left(\kappa_{ji} P_j\right).$$

This is the level of utility provided by location ji net of idiosyncratic preferences. As a result of workers' optimal location choices, the share of workers working in location i and living in location j is

$$\lambda_{ji} = \frac{U_{ji}^{\varepsilon}}{\sum_{i',j'} U_{j'i'}^{\varepsilon}} \tag{15}$$

which is also the number of workers commuting from j to i by normalizing total labor to 1. The expected utility conditional on optimal location choices is equalized due to population mobility and the Frechet preference shock, and it relates to fundamental utilities by

$$W = \Gamma(\frac{\varepsilon - 1}{\varepsilon}) \left(\sum_{i',j'} U_{j'i'}^{\varepsilon} \right)^{1/\varepsilon}. \tag{16}$$

As an implication of equation 15, distribution of workers and residents satisfy

$$L_j = \sum_i \frac{\left(p_j \bar{A}_j L_j^a / \kappa_{ij}\right)^{\varepsilon}}{\sum_j \left(p_j \bar{A}_j L_j^a / \kappa_{ij}\right)^{\varepsilon}} R_i \tag{17}$$

$$R_i = \sum_j \frac{\left(\left(1-t_i\right) \bar{u}_i R_i^b P_i^{-1} / \kappa_{ij}\right)^{\varepsilon}}{\sum_i \left(\left(1-t_i\right) \bar{u}_i R_i^b P_i^{-1} / \kappa_{ij}\right)^{\varepsilon}} L_j, \tag{18}$$

and average residential income satisfy the following relationship with workplace wages

$$v_j = \sum_i \lambda_{ji} w_i / R_j = \sum_i w_i \frac{(w_i/\kappa_{ji})^{\varepsilon}}{\sum_k (w_k/\kappa_{jk})^{\varepsilon}}, \tag{19}$$

Spatial Equilibrium

The spatial equilibrium is defined by a set of prices and population distribution $\{p_i, L_i, R_i, w_i, v_i\}_i$ that satisfy labor market clearing,

$$\sum R_i = \sum L_j = 1, \tag{20}$$

commodity market clearing,

$$w_i L_i = \sum_j (p_i \tau_{ij}/P_j)^{1-\sigma} (v_j R_j (1 - t_j) + K_j P_j), \tag{21}$$

local price indices P_i given by equation 14, wages w_i given by equation 13, residential income v_i given by equation 19, distribution of workers L_j and residents R_i given by equations 17 and 18, together with the choice of numeraire

$$\sum_i w_i L_i = 1. \tag{22}$$

4.3 Road Investment Technology

Trade Costs

Trade cost for traveling through link ij takes the following form:

$$d_{ij} = \begin{cases} \left((\bar{t}_{ij})^{-\rho_m} + (t_{ij}^{alt})^{-\rho_m} \right)^{-1/\rho_m} & i \neq j, \\ 1 & i = j. \end{cases} \tag{23}$$

where $\bar{t}_{ij}$ captures trade costs by trucks from origin i to destination j, which equals infinity if pair ij do not share territorial borders. It depends on investments made by both ends and a trade cost shifter δ_{ij}^{τ} that varies with distance on the optimal path:

$$\bar{t}_{ij} = \delta_{ij}^{\tau} \exp(\zeta(I_{ij}^{-\gamma} + I_{ji}^{-\gamma})), \qquad \delta_{ij}^{\tau} = \delta_0^{\tau} \text{dist}_{ij}^{\phi} e_{ij} \tag{24}$$

where e_{ij} is an i.i.d. modeling error with respect to δ_{ij}^{τ}. On the other hand, t_{ij}^{alt} describes the cost by alternative transportation modes for each bilateral pair ij, regardless of whether the

pair share territorial borders. I assume the cost takes the functional form

$$t_{ij}^{alt} = \delta_0^{alt} \text{dist}_{ij}^{\psi}. \tag{25}$$

Finally, ρ_m is an elasticity of substitution between modes, which can be microfounded by travelers' discrete choices under *link-specific* Frechet shocks with shape parameter ρ_m.

To compute the bilateral trade costs from the link-specific costs above, I adopt the assumptions in Allen and Arkolakis (2022). Define a route between i and j as a sequence of nodes in the network: $r = (r_0, r_1, r_2, \cdots, r_L)$ where $r_0 = i, r_L = j$. Assume cost of travel accumulates multiplicatively: $\tau_{ij,r} = \prod_{n=0}^{L-1} d_{n,n+1}$. Suppose travelers from i to j makes cost-minimizing *route* choices subject to Frechet shocks with shape parameter ρ. The bilateral trade cost between l, k can be found by

$$\tau_{lk} = \left(\left(I - \widehat{d}^{-\rho} \right)^{-1} \right)_{lk}^{-1/\rho} \tag{26}$$

where $\widehat{d}$ is the matrix of d_{ij}, the cost of traveling link ij; the matrix has value of infinity in the diagonals to prohibit consecutively revisiting the same node.

Commuting Costs

Commuting costs between different destinations follow a similar form as trade costs. Within the same area, commuting comes with non-zero cost. In particular,

$$k_{ij} = \begin{cases} \delta^k \bar{t}_{ij} & i \neq j, \\ \exp(\zeta^k \text{time}_i) & i = j. \end{cases} \tag{27}$$

$$\text{time}_i = \text{radius(city i)} \times I_{ii}^{-\mu}. \tag{28}$$

In the formulation above, local commuting cost is a log-linear function of average commuting time within the same area, which in turn responds to highway investments. $\delta^k \bar{t}_{ij}$ describes the cost of commuting between different locations i and j, where δ^k allows commuters to respond more sensitively to travel costs than truckers do. The bilateral commuting cost between l, k can be found by

$$\kappa_{lk} = \begin{cases} \left(\left(I - \widehat{k}^{-\rho} \right)^{-1} \right)_{lk}^{-1/\rho}, & i \neq j \\ k_{ii}, & i = j \end{cases} \tag{29}$$

where $\widehat{k}$ is the matrix of k_{ij}, the cost of commuting on link ij; the matrix has value of infinite where it denotes pairs that do not share borders and in the diagonal.

4.4 State Planner's Problem

Let $J(g)$ be the set of locations within jurisdiction of state government g, and $\mathcal{N}(i)$ be the set of locations directly connected by a highway link with location i. State governments and the federal government collect income taxes to purchase non-tradable final goods at each location $i \in J(g)$, which can be used to build highways at the location of purchase. States can reallocate tax revenue within its jurisdiction, and the federal government can reallocate tax revenue across states. When procuring final goods in $i \in J(g)$ for highways on link ij, defined as the set of highways connecting neighboring locations i and j, state government g gets s_{ij}^F dollar reimbursed by federal government for each dollar spent. All locations in state g share the same tax rates: $t_i = t_g \, \forall i \in J(g)$, which represent the sum of federal tax t^F and state tax t_g^S.

Each state government values the total welfare of its constituents. They choose investments as if they partially internalize other state governments' value. This can be driven by actual political alliance and/or negotiations in the highway planning procedure that we do not observe. Their objective functions consist of residents' utility across all jurisdictions, weights assigned by such political preferences.

In Nash equilibrium, federal government first announces the subsidy rates s_{ij}^F for each highway link ij. At the same time, he commits to satisfy the budget constraint by adjusting the scale of uniform federal tax so that fiscal revenue equals the expenditure on highway subsidies. The level of federal tax therefore depends on the investments chosen by states. Observing the federal policies, states choose their optimal investment on each highway link connected to their territory. They recognize the impact of their investment choices on federal taxes and all states' taxes. State taxes and federal tax are then set to satisfy their respective budget constraints.

Formally, we define the unilateral optimal strategy of state planner g and Nash equilibrium as the following.

Definition 1 (Unilateral Optimal Strategy) *Taking the investments chosen by other state planners* $\{\{I_{i'j'}\}_{i' \in J(h), j' \in \mathcal{N}(i')}\}_{h \neq g}$ *and federal subsidies* s_{ij}^F *as given, the unilateral optimal investments by state government* g *is the set of* $\{I_{ij}\}_{i \in J(g), j \in \mathcal{N}(i)}$ *that solve the following*

problem:

$$\begin{aligned}
\max_{\{I_{ij}\}_{j\in\mathcal{N}(i),i\in J(g)}} \mathcal{W}_g &= \sum_h \Omega_{gh} \sum_{l\in J(h),k} \lambda_{lk} W \\
s.t. \sum_{i\in J(g)} t_g^S v_i R_i &= \sum_{i\in J(g),j\in\mathcal{N}(i)} P_i(1-s_{ij}^F)\delta_{ij}^I I_{ij}, \\
t^F \sum_{g,j\in J(g)} v_j R_j &= \sum_{g,i\in J(g),j\in\mathcal{N}(i)} P_i s_{ij}^F \delta_{ij}^I I_{ij}, \\
I_{ij} &\geq 0,
\end{aligned}$$

road construction technology (23)-(29), and the equilibrium conditions (13), (14), (17)-(22). In equilibrium conditions (13), (14), (17)-(22), taxes and public expenditure correspond to

$$t_i = t_{g(i)}^S + t^F, \qquad K_i = \sum_{j\in\mathcal{N}(i)} \delta_{ij}^I I_{ij}.$$

In this formulation, $\sum_{l\in J(h),k} \lambda_{lk} W$ describes the total utility of constituents in jurisdiction h, which we will refer to as "payoff" of government h. Ω_{gh} are the welfare weights by which planner g values the payoff of planner h relative to his own, so that $\Omega_{ii} = 1\,\forall i$. State planners hold the weights fixed when optimizing their choices.

This objective function formulation indicates that the planner values both the mass of constituents she attracts and the average utility of them. The incentive to attract more constituents can be microfounded by two types of incentives. The first comes from fiscal revenue outside of highway policies: as more residents bid up the land price, state governments can extract more revenue from property taxes and land rents. The second comes from political bargaining power in other federal decisions: as the size of constituents grows, the state gets a larger weight when voting for federal decisions. We explore how the exact relative weight between size of population and average utility affects strategic inefficiency in the appendix. Finally, in the budget constraint, δ_{ij}^I is a construction cost shifter that arises from heterogeneity in engineering difficulties and length of the link.

Definition 2 (Nash Equilibrium) *Let $\sigma_g = \{I_{ij}\}_{i\in J(g),j\in\mathcal{N}(i)}$ denote a set of investment chosen by state g, and $\theta^F = \{\{s_{ij}^F\}_{i,j\in\mathcal{N}(i)}\}_g\}$ denote a set of federal subsidies. The Nash equilibrium under federal policy θ^F is a profile of investments $\{\sigma_g\}_g = \{\{I_{ij}\}_{i\in J(g),j\in\mathcal{N}(i)}\}_g$ such that, for each state g, σ_g solves the problem in Definition 1 given $\{\sigma_h\}_{h\neq g}$ and federal policy θ^F.*

4.5 Federal Planner's Problem

For a benchmark of optimal highway network, consider the tax rates and allocation of highway investment that a federal planner would choose. We maintain the constraint on homogeneous tax rates within each state. Different from Nash equilibrium, the federal planner faces one national budget constraint rather than many state budget constraints. Formally, we define the optimal tax and investment as the following:

Definition 3 (Optimal Allocation) *Socially optimal tax and investment is the set of* $\{\{I_{ij}\}_{i\in J(g),j\in\mathcal{N}(i)}, t_g\}_g$ *that solve the following problem:*

$$\max_{t_g,\{I_{ij}\}_{j\in\mathcal{N}(i),i\in J(g)}\forall g} \mathcal{W}^{federal} = W$$
$$s.t. \sum_{g,i\in J(g)} t_g v_i R_i = \sum_{g,i\in J(g),j\in\mathcal{N}(i)} P_i \delta_{ij}^I I_{ij},$$
$$I_{ij} \geq 0,$$

road construction technology (23)-(29), and the equilibrium conditions (13), (14), (17)-(22).

Federal government's objective is simply the average utility of all population, which is also the total utility generated in the whole country. When a state government is fully altruistic, his objective coincides with that of the federal government.

5 Estimations

There are two primary datasets used in the estimation. The first is Freigh Analysis Framework (FAF) 5.6.1. This data provides the value of bilateral trade flows between 129 domestic destinations in the contiguous US territory, disaggregated by mode of transportation. In particular, we can compute the share of value carried by trucks among all goods shipped for each pair of destinations. The FAF zones together cover the entire contiguous United States. FAF also provides the highway network on which the federal administration estimates the national distribution of truck flows. I use the same highway network to measure highway investments and driving distance between locations.

For commuting flows, I use the county-pair level commuting flows in 2016-2020 American Community Survey (ACS) and aggregate them up to the FAF zone level. Additional data used only for a particular block of estimation will be introduced as we proceed.

To focus on the parameters essential to the inefficiency mechanisms, I calibrate the following parameters to the literature. Following Monte et al. (2018), I set trade elasticity

$\sigma - 1 = 4$, location preference idiosyncrasy $\varepsilon = 3.3$. Following Allen and Arkolakis (2014), I set the agglomeration elasticity $a = 0.1$ and amenity congestion elasticity $b = -0.3$.

5.1 Location-specific Economic Fundamentals

I first use the Head and Ries (2001) method to back out bilateral trade costs from bilateral trade flows X_{ij} between US domestic destinations:

$$\tau_{ij} = \left(\frac{X_{ij}X_{ji}}{X_{ii}X_{jj}}\right)^{-1/2\sigma} \tag{30}$$

Similarly, I back out the bilateral commuting cost relative to geometric average of local commuting cost:

$$\tilde{\kappa}_{ij} = \left(\frac{\lambda_{ij}\lambda_{ji}}{\lambda_{ii}\lambda_{jj}}\right)^{-1/2\varepsilon} = \kappa_{ij}(\kappa_{ii}\kappa_{jj})^{-1/2} \tag{31}$$

I then use the market clearing condition 21 to invert fundamental productivity $\bar{A}_i$ with income $w_i L_i$ given by total value of outbound goods (including towards itself) and expenditure given by total value of inbound goods (including from itself) in FAF data. With the producitivities, I compute local price indices P_i. I then use resident distribution 18 to invert a composite of fundamental amenity and local commuting cost $\bar{u}_j \kappa_{jj}^{1/2}$ given the inferred P_i, observations on L_i, R_i from ACS data, and state tax rates $t_{g(i)}$. We discuss the construction of state tax measures in subsection 5.3. Finally, from the regression

$$\log(\bar{u}_j \kappa_{jj}^{1/2}) = \log \bar{u}_j + \frac{1}{2}\zeta^k(\tilde{\text{time}}_i + \nu_i)$$

where ν_i is an i.i.d. measurement error on time_i, we get the values of $\bar{u}_j$, ζ^k and κ_{jj}. We then obtain κ_{ij} from equation 31.

5.2 Transportation Investment Technology

5.2.1 Measurement of Highway Investment

I measure the investment intensity $I_{ij|i}$ by the mileage-weighted number of lanes on the segments of optimal path connecting centroids of i and j that locate within the territory of i. If a pair of locations share the border but the optimal path between their centroids crosses a third location, I define them as non-adjacent pairs in the network. For cross-state location pairs, the same measuring process also yields the mileage spent in each side of the state border on optimal route between a pair of locations. I use this mileage as the distance

covariate in estimations.

5.2.2 Estimate Trade Costs

From equation 23, we can re-write the link-specific costs as

$$d_{ij} = \delta_0^{other} \text{dist}_{ij}^{\psi} (1 - s_{ij,truck})^{1/\rho_m}, \tag{32}$$

$$s_{ij,truck} = \frac{(\delta_0^{\tau} \text{dist}_{ij}^{\phi} e_{ij} \times \exp(\zeta {I_{ij}}^{-\gamma}))^{-\rho_m}}{(\delta_0^{\tau} \text{dist}_{ij}^{\phi} e_{ij} \times \exp(\zeta {I_{ij}}^{-\gamma}))^{-\rho_m} + (\delta_0^{other} \text{dist}_{ij}^{\psi})^{-\rho_m}}, \tag{33}$$

where $s_{ij,truck}$ is the probability of choosing truck transportation on link ij, which we proxy by the value share of goods from i to j transported by trucks in FAF data. We can then leverage the log-transform of the relationships above to obtain estimation equations for $\delta_0^{other}, \delta_0^{\tau}, \psi, \phi, \rho_m, \zeta, \gamma$:

$$\log d_{ij}^{obs} = \log \delta_0^{other} + \psi \log \text{dist}_{ij} + \rho_m^{-1} \log(1 - s_{ij,truck}) + \log \nu_{ij}, \tag{34}$$

$$\log(s_{ij,truck}^{-1} - 1) = -\rho_m [\log(\delta_0^{other}/\delta_0^{\tau}) + (\psi - \phi) \log \text{dist}_{ij} - (\zeta \times I_{ij}^{-\gamma}) - \log e_{ij}] \tag{35}$$

where ν_{ij} is an i.i.d. measurement error on d_{ij}. We now make two assumptions on the observed data. First, for ij pairs with a direct highway connection, the observed bilateral trade cost τ_{ij} is sufficiently close to link-specific trade cost d_{ij}, which would be true if (1) triangle inequality holds for any trio of adjacent nodes in the network, i.e., $d_{ij}d_{jk} > d_{ik}$ for any i, j, k that are pair-wise adjacent; and (2) the route substitution elasticity ρ is sufficiently high. Second, We assume that e_{ij} follows a log-normal distribution. Given these two assumptions, equation 34 can be estimated by linear regression, and equation 35 can be estimated by maximum-likelihood.

5.3 Mapping Highway Policy to the Model

I use *2017 Highway Statistic* to compute the relevant taxes and subsidies in contemporary highway policies. I first compute the total revenues by each state used for state-administered highways net of any bond issuance, as in table SF-3 of the publication. Subtracting the payments from other governments, I obtain the revenue from each state governments, R_g^S. I also obtain the revenue payed from federal funds, R_g^F. I then compute the federal subsidy rate as

$$s_{ij}^F = s^F = \frac{\sum_g R_g^F}{\sum_g (R_g^F + R_g^S)}.$$

Next, I obtain the county personal income from BEA 2017 release and aggregate up to state total income Y_g. I then compute the state highway tax rate by

$$t_g = R_g^S / Y_g.$$

5.3.1 Estimate Investment Costs

The Highway Economic Requirements System published by Federal Highway Administration provides cost of adding a lane-mile by seven categories of environment for Interstates and other highways.[18] I use the mileage-weighted average between Interstates and Other Principal Arterial on the optimal route as the cost per lane-mile for each highway link. Multiplied by the mileage, this gives us the dollar cost of adding a lane along the optimal route, $\tilde{\delta}_{ij}^I$. We now transform it into the units of local final good in the model. To do this, we leverage the fact that the correct scale of cost should rationalize the observed scale of investment. We therefore estimate state-specific cost shifters δ_g^I by minimizing

$$\frac{1}{N_g} \sum_{i \in J(g), j \in \mathcal{N}(i)} FOC_g(\delta_g^I, I_{ij}; \sigma_g \backslash I_{ij}, \sigma_{-g})$$

where N_g is the number of edges that state g governs in its territory, and $FOC_g(\delta_g^I, I_{ij}; \sigma_g \backslash I_{ij}, \sigma_{-g})$ is state g's first-order condition with respect to his observed investment I_{ij} given other investments by himself, $\sigma_g \backslash I_{ij}$, and all neighbors' choices σ_{-g}, if the state-specific cost shifter were δ_g^I.

5.4 Estimating State Government Preference [IN PROGRESS]

6 Counterfactual

In this section, I present a preliminary counterfactual exercise implemented in New England area, assuming the area forms a closed economy with a fixed total population; the "federal" policy in this case corresponds to a regional agency that collects a uniform tax in New England and reimburse states' highway construction costs with a fixed percentage.

I first generate the baseline equilibrium by feeding the parameters, economic fundamentals and federal policy to the model and solve for investment under Nash equilibrium, assuming that states have zero weights on others.[19] I then compare the investment outcome and

[18] These categories include three terrain ruggedness type in rural area (Flat, Rolling, Mountainous) and four size types for urban area (Small Urban, Small Urbanized, Large Urbanized, Major Urbanized).

[19] Due to time limitation, the following parameters are temporarily set exogenously: $\gamma = 0.13, \zeta = 0.1, \rho_m = 10$ for the construction technology; I also omitted the local commuting cost estimation and set κ_{ii} to 1. The

welfare under the baseline prediction with those under counterfactual federal policies and under federal planner's optimal choice.

6.1 Alternative Subsidies

I compare the baseline equilibrium with two alternative subsidy rates: zero subsidy, which represents a Nash equilibrium with no federal fiscal policy; and an 80% subsidy, which would prevail if the federal government were to additionally subsidize maintenance of highways at the current rate on highway constructions.

Aggregate Changes

Compared to the baseline equilibrium under 34.5% federal highway subsidy, both counterfactual subsidies fail to generate an equilibrium with higher welfare levels. In the case of zero subsidies, investment expenditure as a share of national GDP shrinks by a quarter relative to the baseline, and welfare is lower because of higher trade costs and commuting costs. In the case of 80% subsidies, while investment almost doubles, welfare drops relative to the mediocre subsidy case. This is because tax has raised so much that the gains from lower cost of goods and commuting cannot offset the cost of extra resource that must be taken away from consumption to invest in highways. This explanation is corroborated as we examine the decomposition of equilibrium changes below.

Counterfactual Subsidy	0	80%
$\Delta W/W_{base}$	-0.167%	-0.184%
$\Delta PK/PK_{base}$	-25.2%	92.3%

Table 4: Changes in Welfare and Investment Expenditure Relative to Baseline

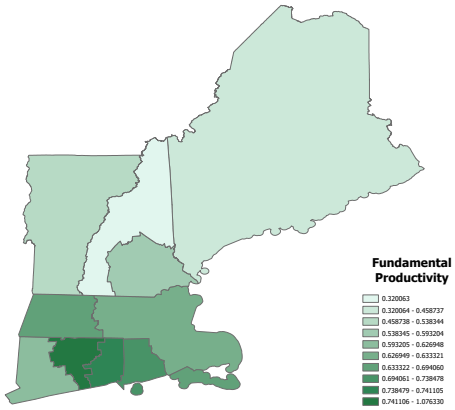
Distributive Changes

Figure 3 shows the economic fundamentals from model inversion, and Table 6 shows the percentage changes of workers, residents, real wages and keep-tax rates at each location in the counterfactual equilibrium. As shown in the last column in Table 6, in an 80% subsidy world, the welfare losses due to a low keep-tax rates are comparable in scale to real wage gains, and in Hartford, Maine, Rhode Island and Vermont, outweighs the gains. This indicates a negative welfare change tied to too much tax burden from infrastructure.

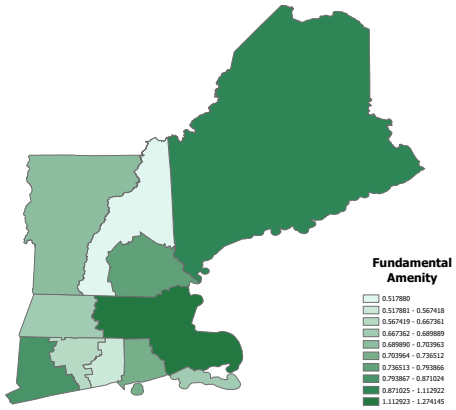
current exercise used distance as the only covariate for highway construction cost. The current model predicts investment levels at the same order of magnitude as the observed investment but the relative distributions are not similar. In later iterations, state preferences for neighbors and more reasonable heterogeneity in construction costs will improve the performance on this aspect.

How does high federal subsidy reallocate economic activities through the endogenous changes in highway network? Figure 4 shows the reallocation of residents and workers in the counterfactual Nash equilibrium under 80% federal highway subsidy. Consistent with Monte et al. (2018), locations with high productivity tends to gain workers with lower transportation costs, as is the case with Hartford and Rhode Island. A new pattern is that places in New Hampshire which rank relatively low in productivity also obtained more workers with high subsidies. Why does that happen? To start with, we examine how investments responded to subsidy raises. Figure 5 shows that high subsidies facilitated more aggressive investments and triggered uneven responses across space. Under 80% subsidy, less productive states in the north increase their investments by a larger fraction than the more productive ones in the south. With subsidies, states can effectively export a share of construction cost to other states, hence afford more highway construction under the same state tax rate. The north states are more sensitive to costs because there are less tax payers, and each unit of highway investment requires a larger contribution per capita from its residents. This accounts for their active response to increased subsidies.

The population reallocation in response to such investments can be explained by the terms-of-trade effects from trade cost reduction. Because northern states increased investments by a larger proportion, they and their neighbors also achieved larger reduction in trade costs. These pairs then divert trade flows from other pairs with less reduction in trade costs, an effect that would improve the terms of trade for the former at the cost of the latter. And because New Hampshire connects with every northern state who increased investment more substantially, they do not suffer from business stealing from external states, whereas Vermont and Maine can lose market share in New Hampshire to one another and to the internal trade within New Hampshire. Improved terms of trade translates to higher relative wages given the same distribution of workers; consequentially, workers migrate towards New Hampshire in response to the wage increase.

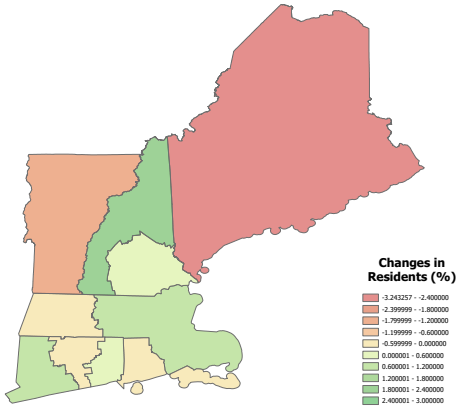


(a) Fundamental Productivity, $\bar{A}_i$

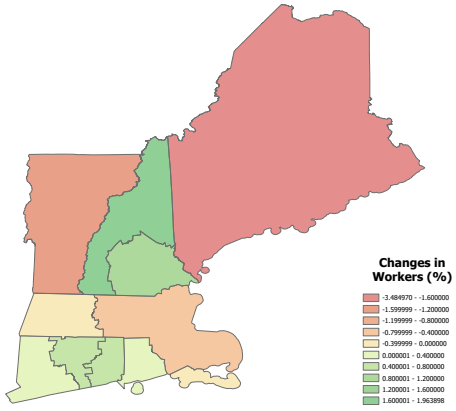


(b) Fundamental Amenity, $\bar{u}_i$

Figure 3: Economic Fundamentals From Model Inversion

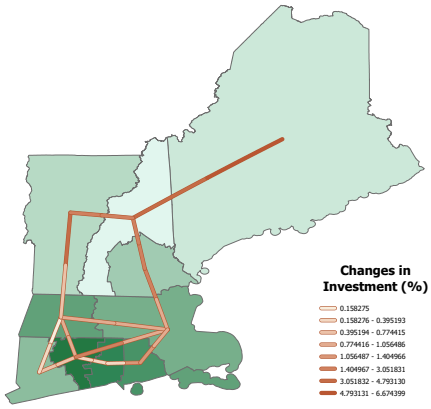


(a) Percentage Changes in Residents

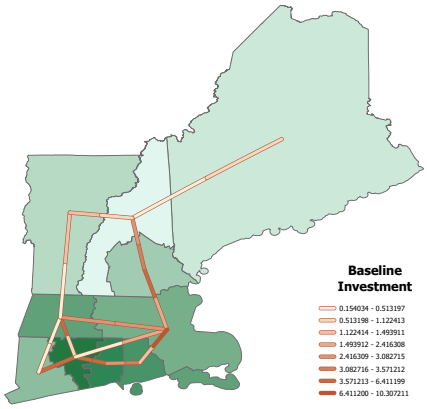


(b) Percentage Changes in Workers

Figure 4: Population Redistribution Under 80% Subsidy



(a) Percentage Changes in Investments



(b) Investment Levels in Baseline Model

Figure 5: Percent Investment Changes Under 80% Subsidy Relative to Baseline

Fundamentals	Z	$\bar{u}$
Hartford, CT	1.076	0.667
New York NY-NJ-CT-PA, CT	0.627	0.871
Rest of CT	0.741	0.567
Maine	0.459	1.113
Rest of MA	0.694	0.690
Boston MA-RI-NH-CT, MA	0.633	1.274
Rest of NH	0.320	0.518
Boston MA-RI-NH-CT, NH	0.593	0.794
Boston MA-RI-NH-CT, RI	0.738	0.737
Vermont	0.538	0.704

Table 5: Economic Fundamentals By Location

	Worker		Residents		Real Wage		Keep-tax	
Counterfactual Subsidy	0	80%	0	80%	0	80%	0	80%
Hartford, CT	0.033	0.652	0.106	-0.349	-0.365	0.809	0.329	-1.352
New York NY-NJ-CT-PA, CT	-0.229	0.302	-0.468	0.689	-0.752	1.541	0.329	-1.352
Rest of CT	-0.736	0.475	-0.619	0.258	-0.792	1.221	0.329	-1.352
Maine	1.590	-3.485	1.499	-3.243	0.115	0.036	0.646	-2.257
Rest of MA	-0.293	-0.016	-0.270	-0.114	-0.770	1.427	0.499	-1.778
Boston MA-RI-NH-CT, MA	0.394	-0.422	0.237	0.660	-0.435	1.883	0.499	-1.778
Rest of NH	-0.516	1.964	-0.568	1.926	-1.127	3.056	0.687	-2.184
Boston MA-RI-NH-CT, NH	0.043	0.879	0.207	0.547	-0.663	2.235	0.687	-2.184
Boston MA-RI-NH-CT, RI	-0.663	0.369	-0.528	-0.017	-0.929	1.585	0.520	-1.893
Vermont	0.781	-1.336	0.777	-1.365	-0.361	1.233	0.704	-2.315

Table 6: Changes Relative to Baseline Equilibrium in Percentages

6.2 Optimal Investment [IN PROGRESS]

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