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Transportation Costs in the Age of Road Freight: Evidence from United States 1955-2010

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Abstract

This paper examines the temporal and spatial evolution of road freight transportation costs between 1955 and 2010. For that purpose, we have constructed a new data set of minimal road transport costs for freight transport in every decade between 1955 and 2010 for 3105×3105 county-pairs. We use a methodology which combines the time-evolution of the road network's layout with spatially disaggregated transport-related costs: average driving speeds, fuel consumption, fuel prices, labour costs, and vehicle operating costs. The new data set allows to document main facts about the development of county-pair transport costs since the 1950s and examine their temporal as well as spatial changes.

JEL: N72, N92, O18, R41

Keywords: Transport costs, Interstate Highway System, Road Network, Dijkstra's algorithm

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1 Introduction

The effect of transportation costs on economic activity is a central research question in the quest to understanding the spatial distribution of economic activities. Recent evidence of this is provided in studies analysing their effects on GDP, suburbanization, trade, employment, earnings, housing costs, amenities, road congestion or urban growth.[1] In all these studies, the quantification of transportation infrastructure was crucial. Measures related to the physical layout of the transport network are used most often, such as a categorical variable indicating whether transport infrastructure passes through a geographical unit (e.g. city, county, region), or a stock measure such as the length of infrastructure (e.g. the length of highways, number of highway rays). The high correlation of these measures with unobserved transportation costs then allows spatial and temporal changes in the transport network itself to be directly interpreted as changes in the transportation costs themselves.

Stock measures or categorical variables offer important insights on how the transportation network impacts the economy in the case where one is attempting to assess the impact of a newly built transport network, or the expansion of an existing one. They capture an *extensive margin* of transport costs: a county without an access to a highway or a railway line would see its transportation costs decline once it gained access to them. Transportation costs, however, also include fuel consumption, driving speed, fuel prices, labour costs and vehicle operating costs, which stock measures or categorical variables might not fully capture. Furthermore, stock measures and categorical variables can not capture the time variation of transportation costs when the physical layout of transportation network is near its completion or fully completed, and hence changes little over time.[2]

The purpose of this paper is threefold. First, we construct minimal road freight transport costs in every decade between 1955 and 2010 expressed in 2015 US$. These costs are calculated for the cheapest route on the road network connecting any pair of 3105 US counties. They take into account fuel consumption, driving speeds, fuel prices,

[1] See for instance Baum-Snow (2007); Duranton and Turner (2012); Brinkman and Lin (2019); Jaworski et al. (2020).

[2] This is recognised for example in footnote 17 of Herzog (2021).

labour costs, and what will be referred to as 'vehicle operating costs': tire costs, vehicle maintenance, and vehicle depreciation. This results in a new panel data set comprising 3105×3104×1/2 pairs of transport costs in 2015 US$ between the population centroids of 3105 US counties in 1955, 1960, 1970, 1980, 1990, 2000, and 2010. Second, we document extensively the methdological setup, including the data sources, the data preparation, analytical and algorithmic steps required to obtain the results. This is so that future researchers who wish to refine the underlying reference costs, or want to build counterfactual datasets for *ceteris paribus* analyses can extend the methodology. Third, using this data, we document novel facts about spatial and temporal evolution of these generalized road transport costs over the course of second half of the twentieth century. This analysis focuses on the road freight transport, hence on the trucking sector. Therefore, in the rest of the paper, when we refer to 'minimal transportation costs' or 'transportation costs', we mean transportation costs pertinent to trucks and road freight transport.

The freight transportation sector in the United States underwent profound changes in the post-World War II decades. Improvements in vehicle technology increased the speed and reliability of trucks, lowered their fuel consumption, as well as maintenance and operating costs (Smith, 1957; Barber, 1964; Paxson, 1981; Cummins and Violante, 2002). Large government infrastructure programs initiated in the 1950s led to the construction of the interstate highway system (IHS) which, by building a uniform network of access-controlled highways, improved the pre-World War II roads and facilitated fast speeds across the entire United States. Deregulation of the trucking industry, culminating with the Motor Carrier Act of 1980, led to a decline in labor costs during the 1980s (Rose, 1987; Hirsch, 1988; Hirsch et al., 1998). Conversely, the oil shocks of the 1970s increased fuel prices in the 1970s and early 1980s. As a result of all these changes, it is recognised that transport costs varied considerably over time. An important aspect is that they have also varied across space. For example, the effect of the 1970s oil shocks on fuel prices, were not spatially symmetric across the US and some parts of the US experienced larger price increase than others. Similarly, the intrinsic layout and historical expansion of the IHS was geographically uneven. To account for both this spatial and time variation, we have assembled a novel data set on historical transport costs by manually digitizing historical government reports, research reports of federal highway administration and expert studies. Specifically, we account for the time variation by collecting data for each of the seven cost components in each benchmark year. Furthermore, we account for spatial variation by collecting, for each benchmark year, State-level data on driving speeds, fuel consumption, and petrol prices, as well as by digitizing the IHS at county level.

We document the main temporal and spatial variation trends of the county-pair minimal transportation costs between 1955 and 2010. These can be summarized as follows. First, there was a widespread decline of the county-pair minimal transport costs between 1955 and 2010 ranging from 51% to 57%. This decline varied substantially across decades though. Second, the decline of the minimal transport costs occurred in two main phases: 1955-1980, and 1980-2010. The former was driven mainly by the decline of vehicle running costs, the latter was a combination of lower labor costs, petrol prices and further reductions in vehicle operating costs. Finally, we show that the presence of the IHS is important for minimising transport costs between county pairs, as the share of the IHS miles in cost-minimising routes is greatly in excess of the overall share of IHS miles in the US road network.

Our paper is closely related to the literature on generalized transport costs, which combine all components of transport costs into one measurable index (e.g. Condeço-Melhorado et al., 2011; Koopmans et al., 2013). In that respect, we contribute to it by applying the methodology of Combes and Lafourcade (2005) and calculate generalized road transport costs for the post-World War II US road network. Methodologically, Jaworski and Kitchens (2019) and Herzog (2021) are most closely related to our work. Jaworski and Kitchens (2019) also apply the Combes and Lafourcade (2005) method and Dijkstra's algorithm to obtain pairwise US county transport costs for 1960, 1995 and 2010. Our work extends this in two ways. First, we refine the analysis both in the time dimension, by considering more years, and in the spatial dimension, by using state-level transport cost determinants such as driving speeds, fuel prices and fuel consumption, rather than the US-wide aggregate data used by Jaworski and Kitchens (2019) and Herzog (2021).

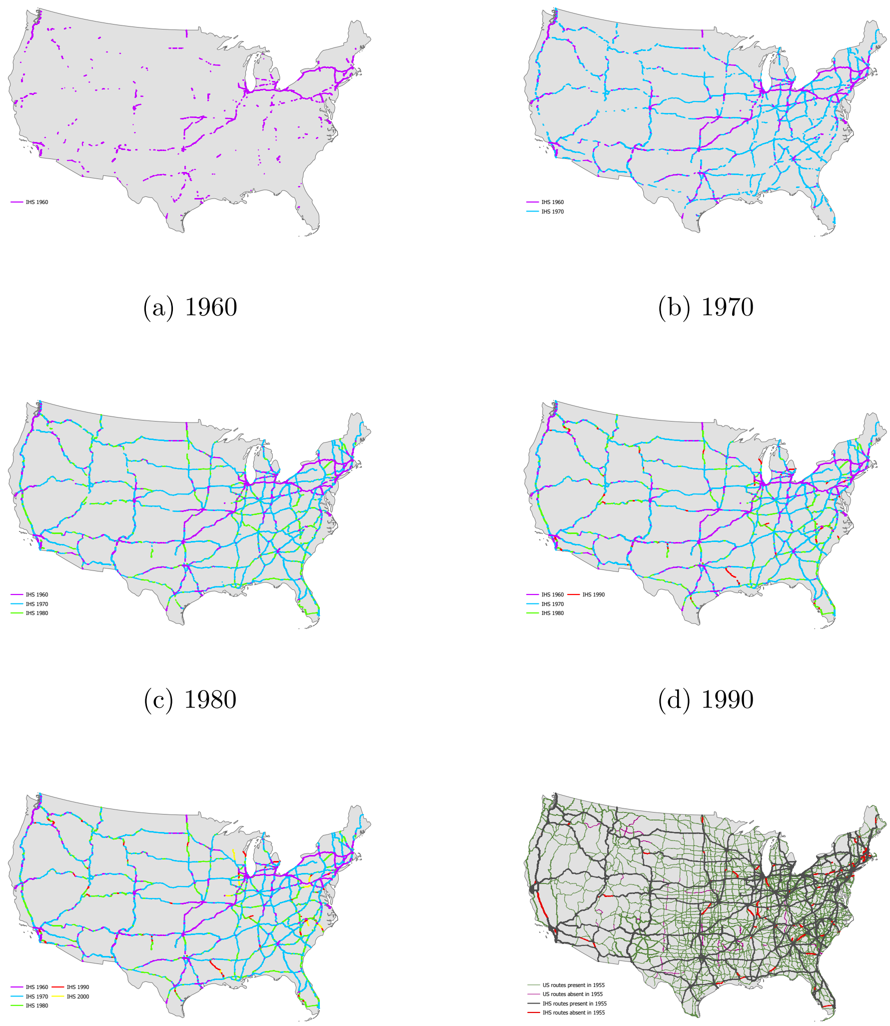
Second, in both these analyses Dijkstra's algorithm is used to first minimise the travel time between counties, with the resulting travel time and distance combined with the cost determinants to obtain the cost for the route. Our approach instead follows Combes and Lafourcade (2005) more closely, by first calculating the time-based and distance-based cost of travelling on each road, and then using Dijkstra's algorithm to identify the routes that minimise the overall cost of travelling. As will be discussed further below, this allows route distance vs. route time trade-offs to be integrated into the decision problem of finding the cheapest route.

The remainder of the paper is organized as follows. Section 2 discusses the methodology, and data sources. Section 3 discusses the main transport cost components which enter the calculations. The evolution of the minimal pairwise transport costs are discussed in Section 4, and Section 5 concludes.

2 Data sources and methodology

We broadly follow the methodology developed by Combes and Lafourcade (2005) in order to calculate the cheapest route on the US road network connecting pairs of US county population centroids for seven benchmark years: 1955, 1960, 1970, 1980, 1990, 2000, and 2010. This requires using a network representing the US road system, calculating the cost of travelling on each road segment in the network, then using Dijkstra's algorithm to calculate the cheapest route between pairs of centroids on the network. The size of the US road network and the large number of pairwise county routes involved in the analysis require a preliminary data reduction step in order to make the calculations tractable, which is detailed in appendix B. In order to be able to accurately calculate transport costs given the large geographical and time dimensions involved, we also collected rich, spatially disaggregated data which allow us to model closely both distance and time-related travel costs and thus capture the spatial and time variation of transport cost determinants.

Figure 1: Construction of the Interstate Highway System 1960-2010



(a) 1960

(b) 1970

(c) 1980

(d) 1990

(e) 2000

(f) 1955 routing diagnostics

2.1 The US road network

The first task involves creating a digitized map of the US road system reflecting the state of the road network for each of our benchmark years (1955, 1960, 1970, 1980, 1990, 2000, and 2010). The starting point of our analysis is the digitized National Highways Planning Network 14.05 GIS shape file (henceforth NHPN), which contains the full IHS and US highway system.[3] Every signed road is split into very fine-grained segments, often on the scale of a hundred meters, leading to a large network containing 625,610 road segments. Each segment is assigned a county and state identifier, in addition to information relating

[3]US Federal Highway Administration, 2014

to signage and distance. This allowed state or county level attributes, such as the rural or urban nature of the county to be assigned to each segment. This rural/urban classification, which is detailed further in appendix A, is based on the US Department of Agriculture Rural-Urban Continuum Codes, which allows us to track the progress of urbanisation in the post-war period in the 48 contiguous US states. Combined with a distinction between interstate vs. non interstate roads, we therefore consider 4 categories of roads: urban interstates, rural interstates, urban non-interstate and rural non-interstate. The rationale for this specific classification is that this allowed us to make use of the historical, state-level, average driving speed data discussed further below.

Three data sources were used to determine the time-evolution of the IHS in each benchmark year. First are the 'Interstate Density Maps' which were published by the Federal Highway Administration and show the evolution of the interstate highways every ten years between 1950 and 2000.[4] Second, we used the Federal Highway Administration PR-511 records, which contain information relating to the time when each segment of the IHS was open to public traffic. This data has been used before including the studies by Chandra and Thompson (2000), Baum-Snow (2007), Nall (2015) or Frye (2021). Finally, this was supplemented with historical sources including Interstate-Guide, an online comprehensive guide to the IHS and its history.[5] Given the very fine resolution of the NHPN shape file, we were able to determine very accurately which portion of each highway in every county was open to the public by the end of each decade. The staggered construction of the IHS over the decades of our analysis are shown in Figure 1.

The construction of the IHS started in a context where the US Highway system had been in place since mid-1920s, with states raising their own funds and constructing a network of roads. This was reflected in the choice of routing and the new interstate highways were most often built as an upgrade or replacement of exiting US highways, especially in high road density areas on the East coast. Road standards were the fundamental attribute that distinguished the interstate highways from other US highways. These included controlled-access which requires that the traffic across highways is carried

[4] `https://www.fhwa.dot.gov/interstate/densitymap.cfm`
[5] `https://www.interstate-guide.com/`

by overpasses and underpasses, can be access only by ramps, and the traffic is unhindered by traffic signals, intersections, and at-grade crossings with other roads or railways. Technical standards required 12-foot travel lane widths, 10-foot minimum shoulder widths, design speeds of 50, 60, and 90 mph for mountainous, rolling, and flat terrain conditions respectively, and geometric standards for curvature, gradient, width, and number of lanes to allow such speeds. Since the standards dictated controlled-access and unhindered traffic flow, where a road upgrade was not possible, the interstates highways were built either with multilevel crossing or using so-called 'parallel routing' which meant building the interstate highways alongside the existing roads (e.g. Interstate-Guide (2021), Georgia Department of Transportation 2007, Colorado Department of Transportation 2002, Oregon Department of Transportation 2004, California Department of Transportation,[6]). For example, several sections of Interstate 5 in Southern California were constructed prior to the 1956 Federal Highway Act, including the Aliso Street Viaduct (built in 1948), portions of former US 101 Santa Ana Freeway located the south of Los Angeles, and portions of US 101 Montgomery Freeway south of San Diego. These sections were added to Interstate 5 and US 101 was decommissioned in 1964. The rest of the route northward, I-5 parallels and replaces the former US 99, which was decommissioned in stages between 1964 and 1972.[7] Indeed, many parallel routed roads still exist, often as frontage roads, though some roads were decommissioned, such as the well-known US Route 66 which existed from 1926 until 1985.

As a result, the physical layout and direction of the IHS followed the existing layout of state and US routes, which is indeed confirmed by overlaying the interstate highway system map with state and US roads map from 1955. This fact helps us to deal with those segments of the IHS in the NPHN shape files which did not exist in a particular benchmark year. Because of the practices of parallel routing and upgrading of existing state highways, these segments are recoded as non-interstate roads prior to their construction date. In order to ensure this approach was appropriate, we manually checked each signed interstate segment against existing maps of US routes in 1950 and 1955, as well as on Interstate-

[6] `https://www.cahighways.org/itypes-history.html`, accessed on February 15, 2021.

[7] `https://www.interstate-guide.com/i-005/#history`, accessed April 17, 2020

Table 1: Composition of the US road network

	Interstates	US routes	State routes	Other	Total
Total mileage (2014)	45,637.31	132,715.53	209,166.82	49,371.34	436,891.48
	10.45 %	30.38 %	47.88 %	11.3 %	100 %
Roads built pre-1955	92.44 %	97.11 %	94.52 %	-	-

Source: National Highway Planning Network version 14.05.
'Other' category contains county, township, municipal and unsigned roads.

Guide, to establish whether a pre-existing route was present in that location in 1955. As shown in the first column of Table 1 and in Figure 1(f), over 92% of IHS mileage already existed in some form in 1955.

The second row of Table 1 reveals that US and state routes make up most of the remaining roads in the NHPN shapefile, summing up to 78% of the network mileage. As is the case for the IHS, the overwhelming majority of the physical layout of non-interstate highway was in place by 1955, as state and US routes were being built since the 1920s. Indeed, the manual check carried out for US routes against the 1950 map, shown in Figure 1(f) and Table , confirmed that 97.11% percent of the network of US routes present in the 2014 NPHN map already existed in 1955. The network of state routes was also checked using state-level transportation sources to establish the opening date of each signed state route, and again confirmed that around 95% of state routes were open by 1955. [8] The remaining 11% of the network is made up of county, municipal and township routes, which cannot be checked due to lack of signage.[9]

It is important to emphasise that the fact that we use the 2014 NPHN network as the basis of our work does not mean that we ignore the lengthy construction of the IHS itself, nor that construction activity occurred on non-interstate highways between 1955 and 2010. Most of these efforts, however, focused on improving existing roads, by building additional lanes, resurfacing, and building bypasses and tunnels to avoid dangerous segments of the roads. Clearly all this infrastructure investment will impact transport costs and it is therefore crucial to account for this improvement of the road

[8]Because state routes represent nearly half the network, these are not displayed in Figure 1(f) due to space constraints

[9]These routes are typically contained within the settled areas of a given a county and do not connect locations between counties. Because our analysis looks at trips between county centroids, they is unlikely to impact the resulting cost measures.

system over time. However, while this affects the cost of travelling on a given road segment in the network, it does not affect the existence or location of the segment itself. Instead, these qualitative improvements will be captured by the reference cost data used to calculate the cost of traversing each segment.

2.2 From reference costs to minimal transport costs

In addition to providing the topology of the network itself, the NHPN data provides two types of information for each road segment, which will be referred to as an *edge* for the purpose of running Dijkstra's algorithm: the distance of each edge d_e and the road type of the edge in a given year, $r_{e,t} \in \{1, 2, 3, 4\}$. This serves as the basis of the calculation of the dollar cost associated with each edge. Following Combes and Lafourcade (2005), we consider two types of reference costs: distance-related costs per mile travelled and time-related costs per hour spent travelling. The section below provides an overview of the items that enter the calculation of both time and distance related costs, as well as the data sources used, with more detail provided in Appendix A.

The time-based reference cost for an edge are the costs incurred by paying the truck drivers their wages, and are calculated as:

$$T_{a,t} = w_t \frac{d_e}{s_{r_{e,t},t}} \tag{1}$$

where w_t is the nominal average hourly earnings in trucking in year t. The time spent traversing edge e is given by the edge's distance d_e, in miles, divided by the driving speed on the edge in year t, $s_{r_{e,t},t}$, measured in miles per hour. The hourly wages were calculated using weekly earning in trucking, taken from the publications of the United States Department of Labor. We have digitized the data for the year 1955 from US Department of Labor Bulletin no 1195, and data for the years 1960-1990 from Bulletin of the United States Bureau of Labor Statistics, No. 2445. Data for 2000-2010 were taken from Occupational Employment Statistics Survey published by the Bureau of Labor Statistics.

The average driving speed data is a critical component of the analysis, as it encodes improvements in the quality of the road network, especially the specific contribution of the IHS, the technological capabilities of motor vehicles, and congestion effects in urban areas. We collected and manually digitized average driving speeds for the four types of roads we consider in each of seven benchmark years, and in each of forty-eight contiguous states. This results in 1,344 different speeds ($4 \times 7 \times 48$), providing detailed variation over time, geography, and the four types of roads. The main source was the Federal Highway Statistics supplemented with the US Historical Statistics, US Bureau of Transportation Statistics, and Department of Commerce.

The distance-based reference costs for each edge and year are calculated as the sum of fuel costs and vehicle operating costs:

$$D_{e,t} = (p_{e,t} \times gpm_{e,t} + vcpm_t) \times d_e \tag{2}$$

The fuel cost is the product of fuel price on the edge in a given year, $p_{e,t}$, the fuel consumption on the edge in gallons per mile $gpm_{e,t}$ multiplied by the edge's distance d_e. State-level fuel-prices were collected and manually digitized for the years 1955-1970 from the Bulletin of US Department of Labor No 1197, and US Department of Agriculture's 'Agricultural Prices: Annual Summary'. The prices for 1980-2010 were taken from the US Energy Information Administration's average price of motor gasoline series. Fuel consumption in each year and each of the forty eight contiguous states was calculated by dividing vehicle-miles travelled by total fuel consumption, using data from the Federal Highway Statistics 1950-2010. As is the case for driving speeds, the spatially disaggregated fuel consumption data capture qualitative improvements over time, specifically the overall improvement in fuel efficiency seen in the motor industry over the 1955-2010 period. The data also captures geographical constraints, such as the higher fuel consumptions recorded in mountainous areas, due to the higher grades of the roads. Finally, we also include US-wide vehicle operating costs per mile $vcpm_t$, in the form of the cost of tires, depreciation, and maintenance. This was collected and manually digitized data from Federal Highway Administration reports, Highway Research Board bulletins, and research by Winfrey (1969), Berwick and Dooley (1997), and Barnes and Langworthy (2004).

Once each edge in the road network has been allocated a cost for each year of the analysis, the cost in a given year of travelling on a route $R_{i,j}$, denoted $\tau_{i,j,t}$, between counties i and j is simply the sum of the costs associated with each edge in $R_{i,j}$.

$$\tau_{i,j,t} = \sum_{e \in R_{i,j,t}} (T_{e,t} + D_{e,t}) \tag{3}$$

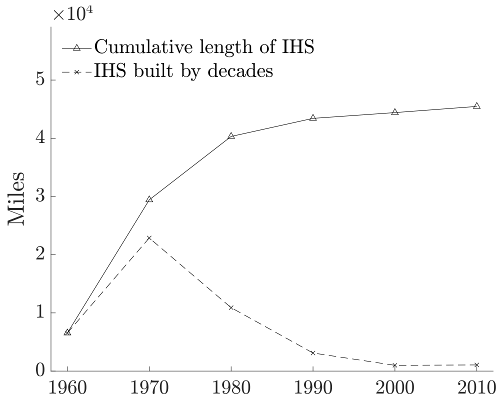
The minimal cost of travelling from county i to county j in year t, $\tau^*_{i,j,t}$, can be found using Dijkstra's algorithm. Specifically, Dijkstra's algorithm searches over the space of all possible routes $R_{i,j}$ and returns the route associated with the lowest cost.[10]

$$\tau^*_{i,j,t} = \min_{R_{i,j}} \tau_{i,j,t} \tag{4}$$

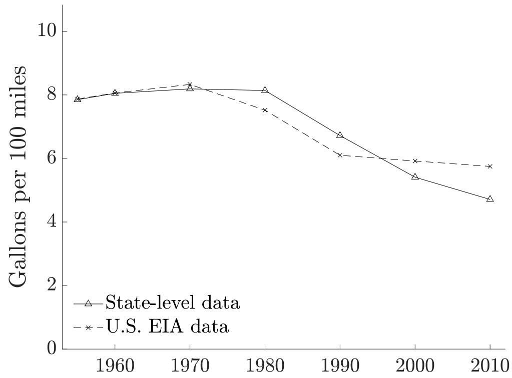
Before we proceed further, we need to make three comments. First, as previously mentioned, given the much larger geographical scope of the analysis compared to the French case in Combes and Lafourcade (2005), both types of the costs vary not only across years and the type of edges but also across US states, providing a high-level of spatial disaggregation. Second, due to the federal nature of the USA and to the fact that our analysis goes back to 1955, it has not been possible to gather data relating to insurance and accommodation costs that are included in Combes and Lafourcade (2005) for the French case. In this respect, we are in a similar situation to Jaworski and Kitchens (2019), who similarly report lack of data availability for these ancillary costs in the USA. Finally, given the large size of the NHPN dataset, the road network is simplified prior to running Dijkstra's algorithm, in order to keep the problem computationally tractable. Details of this procedure, which does not affect the optimality of the solution found by Dijkstra's algorithm, are provided in appendix B.

[10] It is important to point out that the transport costs calculated using this method correspond to the minimal marginal cost of a single trip between two county centroids, and do not reflect the overall total transport costs incurred on the US road network.

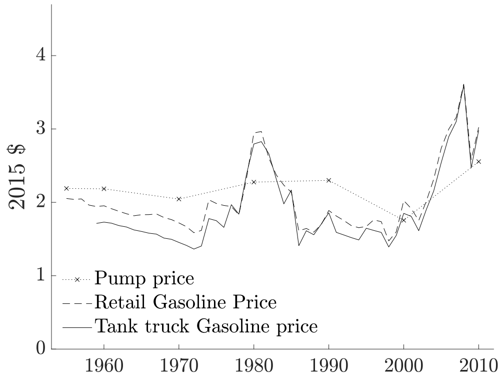
Figure 2: Determinants of distance costs



(a) Length of the IHS by decade



(b) Fuel efficiency



(c) Gasoline prices

3 Main determinants of transport costs components

Before presenting the county-pair transportation costs obtained using Dijkstra's algorithm, it is important to present and discuss the road network and reference costs that enter the analysis. Because these new and large datasets underpin the temporal and geographical variation of the minimal county-pair transport costs obtained with Dijkstra's algorithm, it is important that we check that on aggregate they are consistent with known stylised facts.

3.1 The time-evolution of the IHS

The five digitized interstate highway maps for the years 1960, 1970, 1980, 1990 and 2000, are presented in Figure 1. The digitized maps shows that the interstate highways were

Table 2: Mileage of the Interstate Highway System by Decades

	1956 - 1960	1961 - 1970	1971 - 1980	1981 - 1990	1991 - 2000	2001 - 2010	1956 - 2010
			IHS mileage built				*Total*
New England	464	933	348	103	3	12	1,863
Middle Atlantic	1,220	1,418	541	218	209	129	3,735
East North Central	1,225	3,440	1,477	314	297	17	6,770
West North Central	810	2,955	1,347	311	3	2	5,428
South Atlantic	320	3,091	2,133	774	336	212	6,866
East South Central	93	2,200	827	244	22	45	3,431
West South Central	952	2,773	1,393	389	66	0	5,573
Mountain	706	4,009	1,993	527	25	10	7,270
Pacific	755	2,045	835	225	31	1	3,892
US	*6,545*	*22,864*	*10,894*	*3,105*	*992*	*428*	*44,828*
			Share in IHS mileage built				*Final*
New England	7.1	4.1	3.2	3.3	0.3	2.9	4.2
Middle Atlantic	18.6	6.2	5.0	7.0	21.1	30.1	8.3
East North Central	18.7	15.0	13.6	10.1	29.9	4.0	15.1
West North Central	12.4	12.9	12.4	10.0	0.3	0.4	12.1
South Atlantic	4.9	13.5	19.6	24.9	33.9	49.5	15.3
East South Central	1.4	9.6	7.6	7.9	2.2	10.6	7.7
West South Central	14.5	12.1	12.8	12.5	6.7	0.1	12.4
Mountain	10.8	17.5	18.3	17.0	2.5	2.4	16.2
Pacific	11.5	8.9	7.7	7.2	3.1	0.2	8.7
US	*100.0*	*100.0*	*100.0*	*100.0*	*100.0*	*100.0*	*100.0*

Sources for 1956-2000: PR-511, Baum-Snow (2007).
2001: `https://www.fhwa.dot.gov/ohim/hs01/hm41.htm`
2010: `https://www.fhwa.dot.gov/policyinformation/statistics/2010/hm20.cfm`

often built as disjointed highway segments that were gradually linked together, which is consistent with the fact the creation of the IHS was mainly an improvement to selected roads from the existing road network. In order to ensure the accuracy of this time-evolution of the network, we specifically checked the sequence of maps against the data digitized by Baum-Snow (2007) on the total number of miles of interstate highways open to public in each year and each county.

The completed mileage of the IHS, presented in Figure 2(a) with a breakdown by regions in Table 2, shows substantial variation over time and space. The largest increase in mileage was in the 1960s, declined afterwards and eventually petered out in the 1990s and 2000s. Indeed, fifty percent of the total IHS mileage was built by 1970, in the first fourteen years of the system. Geographically, construction was concentrated initially in the West, Middle Atlantic and Midwest regions, before shifting significantly to the South Atlantic region. Upon its completion, the distribution of IHS across regions is skewed: five regions concentrate over 70% of the mileage, each with a similar share of 12-16%, with the remaining mileage shared over the other four regions.

3.2 Distance-based costs: fuel efficiency, fuel price, and vehicle operating costs

Table 3 presents the regional variation in distance-based costs and their determinants over the period of analysis. This reveals that US-wide distance-based costs declined from \$126.7 to \$35.8 per 100 miles between 1955 and 2010, a 72% drop in real terms, and that this pattern holds for all US regions.

As a robustness check we compare in Figure 2(b) the average of the 48 state-level fuel efficiencies calculated from the US Highway Statistics, used in our analysis, against the overall US fuel consumption as reported by the US Energy Information Administration. We see a good agreement between the series, with a similar pattern of a stable fuel efficiency until the 1970s, followed by a decline until 2010. Figure 2(c) similarly compares average of the state-level gasoline price data used in our analysis to the annual time series of retail and tank-trunk prices, all expressed in 2015 \$US, and again we see that the decadal state-level averages follow the same pattern as the aggregate data.

Table 3 provides the regional breakdown for the various components of the distance-based reference costs. Most regions experienced a slight worsening of fuel efficiency until 1970, with significant regional variations reflecting differing geographical features, such as higher fuel consumption in the Mountain region. By the 1980s, fuel efficiencies were improving in all US regions. Regarding fuel prices, Table 3 shows again considerable spatial variation in addition to the well-known time trends. For instance, the Mountain region experienced the smallest increase between 1955 and 2010, due to starting off with the highest fuel costs, probably reflecting difficulty of supply stemming from geographical remoteness and relatively poor infrastructure in 1955. Similarly, in the 1970s – the decade of the oil shocks – the Western and Southern oil-producing regions saw the smallest in-

Table 3: Distance-based reference costs

	1955	1960	1970	1980	1990	2000	2010	1955-2010
	Fuel efficiency (Gallons per 100 miles)							
New England	7.84	7.89	7.94	7.63	6.35	5.41	5.00	-36%
Middle Atlantic	7.70	7.34	7.99	7.94	6.64	5.50	4.88	-37%
East North Central	7.75	8.00	8.09	8.17	6.77	5.42	4.67	-40%
West North Central	7.84	8.52	8.43	8.61	7.16	5.65	4.75	-39%
South Atlantic	7.86	7.95	8.04	7.77	6.64	5.37	4.58	-42%
East South Central	8.24	8.55	8.50	8.04	7.09	5.30	4.40	-47%
West South Central	8.31	8.66	8.90	8.94	6.98	5.54	4.93	-41%
Mountain	8.05	8.33	8.37	8.32	6.84	5.43	4.52	-44%
Pacific	7.58	8.11	7.88	8.00	6.27	5.24	4.76	-37%
US	*7.85*	*8.05*	*8.19*	*8.14*	*6.72*	*5.41*	*4.71*	*-40%*
	Pump price of gasoline (2015 US$ per gallon)							
New England	2.06	2.05	2.00	2.31	2.39	1.89	2.63	28%
Middle Atlantic	2.04	2.02	1.99	2.32	2.26	1.76	2.55	25%
East North Central	2.25	2.20	2.08	2.29	2.30	1.71	2.55	13%
West North Central	2.23	2.21	2.02	2.28	2.32	1.71	2.53	14%
South Atlantic	2.17	2.13	2.01	2.25	2.32	1.69	2.50	15%
East South Central	2.23	2.21	2.07	2.27	2.28	1.65	2.46	11%
West South Central	2.09	2.09	1.94	2.18	2.24	1.68	2.44	17%
Mountain	2.41	2.37	2.14	2.27	2.32	1.80	2.61	8%
Pacific	2.24	2.39	2.15	2.31	2.27	1.89	2.73	22%
US	*2.21*	*2.19*	*2.03*	*2.28*	*2.30*	*1.68*	*2.53*	*15%*
	Vehicle operating costs, US average (2015 US$ per 100 miles)							
Tires	17.51	16.03	12.66	8.05	3.88	5.51	3.80	-78%
Maintenance	48.14	44.08	34.48	28.47	21.95	13.76	11.41	-76%
Depreciation	43.77	40.07	11.67	10.87	14.92	11.37	8.70	-80%
	Distance reference costs (2015 US$ per 100 miles)							
New England	125.55	116.36	74.69	65.03	55.93	40.84	37.04	-70%
Middle Atlantic	125.09	114.98	74.71	65.83	55.75	40.34	36.36	-71%
East North Central	126.82	117.80	75.62	66.08	56.32	39.89	35.82	-72%
West North Central	126.90	119.00	75.85	67.02	57.34	40.31	35.95	-72%
South Atlantic	126.49	117.11	74.99	64.89	56.19	39.73	35.35	-72%
East South Central	127.76	119.04	76.40	65.62	56.94	39.40	34.74	-73%
West South Central	126.75	118.25	76.07	66.91	56.39	39.95	35.96	-72%
Mountain	128.80	119.96	76.74	66.31	56.59	40.44	35.70	-72%
Pacific	126.39	119.52	75.71	65.84	55.02	40.56	36.92	-71%
US	*126.74*	*117.80*	*75.42*	*65.91*	*56.18*	*39.72*	*35.84*	*-72%*

Source: Detailed description of sources is in Appendix A.2 and A.5.
Note: Distance-based reference costs are calculated by multiplying fuel consumption by gasoline price and adding tire, maintenance, and depreciation costs.

creases in gasoline prices, whilst the North-East saw the largest. Finally, vehicle operating costs – which sum tire costs, maintenance costs and depreciation – declined dramatically between 1955 and 2010: from $109 to $24 (in 2015 $US) which is a 78% decline.

Table 4: Average speed by type of road, 1955-2010

	1955	1960	1970	1980	1990	2000	2010
				Urban			
(1) Interstate	-	50.04	56.94	56.54	58.64	57.82	56.66
(2) Other	46.42	48.22	54.87	54.48	56.41	55.00	53.90
				Rural			
(3) Interstate	-	51.74	58.88	58.53	61.16	61.72	61.95
(4) Other	48.45	49.98	56.87	56.53	56.74	57.20	57.42
				All roads			
	47.43	49.99	56.89	56.52	58.24	57.94	57.48

Source: Detailed description of sources is in Appendix A.4.
Notes: Speeds in miles per hour. 1960: average of 1958 and 1959; 1970: average of 1967 and 1969; 1980: average of 1977 and 1979; 1990: average of 1987 and 1989.

In summary, it is clear that overall distance-based reference costs experiences a large and quantitatively similar decline in all regions over the 1955-2010 period. However, the pace of this decline showed significant spatial variation across regions, due to state-level variation in the individual components, all of which are likely to affect the choice of cost-minimising routes when applying the Dijkstra algorithm.

3.3 Driving speeds and time-based costs

The state-level driving speed data we have collected forms a central part of the analysis, as it allows us to quantify the qualitative improvement brought on by the IHS relative to other types of roads. As discussed in section 2, we have collected data on average driving speeds on four types of roads, for all forty-eight contiguous border US states, over the benchmark years of 1955, 1960, 1970, 1980, 1990, 2000, and 2010, resulting in 1,344 data points. Table 4 and 5 summarise this driving speed data by type of road, and by region respectively. They confirm that driving speeds are higher on average for interstate highways relative to non-interstate roads, and higher in rural than urban areas. Average speeds increased by about 21% between 1955 and 2010 and, as was the case for the time-reference costs, exhibit a considerable variation over time and geographical regions.

Regarding the time variation, Table 4 shows that average speeds increased between

Table 5: Time-based Reference Costs

	1955	1960	1970	1980	1990	2000	2010	1955-2010
	Average driving speed (miles per hour)							
New England	43.65	50.31	57.25	56.76	58.35	56.96	56.43	29.3%
Middle Atlantic	45.22	48.68	55.40	55.71	58.35	57.98	57.20	26.5%
East North Central	47.73	51.28	58.36	57.51	59.07	58.88	58.86	23.3%
West North Central	47.50	50.62	57.60	56.58	58.41	57.63	57.52	21.1%
South Atlantic	46.98	50.04	56.94	56.56	57.75	58.06	58.11	23.7%
East South Central	49.16	49.04	55.81	55.92	58.05	58.16	57.86	17.7%
West South Central	47.73	50.44	57.40	57.26	58.55	59.52	59.17	24.0%
Mountain	50.34	49.75	56.61	56.05	57.30	57.98	58.18	15.6%
Pacific	48.58	49.77	56.63	56.32	58.31	56.24	54.00	11.2%
US	*47.43*	*49.99*	*56.89*	*56.52*	*58.24*	*57.94*	*57.48*	*21.2%*
	Hourly earnings of truck drivers (2015 US$)							
US	18.03	19.89	23.03	27.70	23.75	20.39	19.77	9.7%
	Time-based reference costs (2015 US$ per 100 miles)							
New England	41.3	39.5	40.2	48.8	40.7	35.8	35.0	-15.2%
Middle Atlantic	39.9	40.9	41.6	49.7	40.7	35.2	34.6	-13.3%
East North Central	37.8	38.8	39.5	48.2	40.2	34.6	33.6	-11.1%
West North Central	38.0	39.3	40.0	49.0	40.7	35.4	34.4	-9.4%
South Atlantic	38.4	39.8	40.5	49.0	41.1	35.1	34.0	-11.3%
East South Central	36.7	40.6	41.3	49.5	40.9	35.1	34.2	-6.8%
West South Central	37.8	39.4	40.1	48.4	40.6	34.3	33.4	-11.5%
Mountain	35.8	40.0	40.7	49.4	41.4	35.2	34.0	-5.1%
Pacific	37.1	40.0	40.7	49.2	40.7	36.3	36.6	-1.4%
US	*38.0*	*39.8*	*40.5*	*49.0*	*40.8*	*35.2*	*34.4*	*-9.5%*

Source: Detailed description of sources is in Appendix A.2 and A.3.
Notes: Speed: 1960: average of 1958 and 1959; 1970: average of 1967 and 1969; 1980: average of 1977 and 1979; 1990: average of 1987 and 1989, Wages: except for 1955 and 1960, hourly earning are decadal averages, e.g. 1970 earnings are the average of 1961-1970.
Earnings in 1960 are the average of 1958-1960.
Time reference costs = (earning of truckers/speed)×100

1960 and 1970, and then again between 1980 and 1990, but remained stable between 1970 and 1980, and declined slightly after 1990. The stability of average speeds in the 1970s decade conceals the fact that they dropped quite dramatically in the early 1970s, following the oil shocks, and took the rest of the decade to return to the levels seen in 1970 (Highway Statistics 1979). The decline after 1990 was instead driven by lower speeds in urban areas, both on the interstates and other roads, reflecting increasing congestion.

Two facts stand out from the spatial breakdown of average driving speeds in Table 5: first, the increase in speeds between 1955 and 2010 was unequal across regions, with the Pacific and Mountain regions experiencing the lowest increases relative to other regions, probably due to the more mountainous terrain. Second, the decrease in average speeds between 2000 and 2010 was confined mostly to the states New England, the Middle Atlantic and Pacific regions. Given that these regions contain the New York City/Boston urban area, Los Angeles, and San Francisco, i.e. some of the most urbanized metropolitan areas of the country, this is consistent with the fact, presented in Table 4, that the decrease in US-wide average speeds over the period was due to lower speeds in urban areas.

The real earnings of truck drivers, which is the other major component entering the time-based reference costs (1), exhibit an inverted U-shape pattern peaking in 1980. The increase between 1955 and 1980 was due to the strong labor unions, and the subsequent drop is attributed mainly to the deregulation of the motor carrier's industry and the rise of non-union trucking providers (Rose, 1987; Hirsch, 1988; Hirsch et al., 1998; Belman and Monaco, 2001). We should note that whilst real earnings of truck drivers had been declining since 1980, they were still 10% larger in 2010 than in 1955.

The final panel of Table 5 presents the regional breakdown of the overall time-based reference by region and decade, revealing again an inverse U-shape pattern, driven mostly by the real wages of truckers. In fact, the large increase observed in the 1970s is due to the 20% increase in the real earnings of truckers being compounded by the stable driving speed over that decade. However, as was the case for the distance-based costs, that aggregate picture hides significant spatial variation. In this case, this is entirely driven by the regional variation in driving speeds, with the effect of geographical terrain explaining the relatively small reduction in time-based costs in the Mountain region and the declining urban driving speeds in the first decade of the new millennium explaining the similar effect in the Pacific region.

3.4 Total transport reference costs

The total reference transport costs were calculated by summing the time-based (1) and distance-based (2) costs for forty-eight contiguous states, four types of roads, and all benchmark years. Tables 6 and 7 present the breakdown by type of road and by US region respectively. Table 6 shows a 56% decrease between 1955 and 2010, from $165 to $73 per

Table 6: Total Transport Reference Costs per 100 miles, 2015 US$

	1955	1960	1970	1980	1990	2000	2010
				Urban			
(1) Interstate	-	158.81	117.66	113.37	92.86	77.45	73.12
(2) Other	165.59	160.36	119.25	115.16	94.31	79.39	75.03
				Rural			
(3) Interstate	-	157.46	116.27	111.75	91.35	75.07	69.94
(4) Other	163.96	158.86	117.72	113.38	94.09	77.87	72.62
				All roads			
	164.77	158.87	117.73	113.41	93.15	77.44	72.68

Source: Detailed description of sources is in Appendix A.2 to A.5.

Table 7: Total Transport Reference Costs per 100 miles by Regions, 2015 US$

	1955	1960	1970	1980	1990	2000	2010	1955-2010
New England	166.87	157.16	116.70	112.30	92.81	79.20	74.53	-55%
Middle Atlantic	164.99	157.18	118.17	114.03	92.66	78.05	73.41	-56%
East North Central	164.62	157.82	116.83	112.74	92.76	76.98	71.76	-56%
West North Central	164.88	159.56	117.62	114.47	94.23	78.24	72.79	-56%
South Atlantic	164.89	158.16	117.26	112.37	93.48	77.39	71.81	-56%
East South Central	164.44	161.02	119.63	113.76	94.09	77.05	71.40	-57%
West South Central	164.54	158.96	117.99	113.78	93.17	76.69	71.74	-56%
Mountain	164.64	161.27	119.28	114.25	94.14	78.11	72.08	-56%
Pacific	163.53	160.77	118.20	113.51	91.97	79.43	76.10	-53%
US	*164.77*	*158.87*	*117.73*	*113.41*	*93.15*	*77.44*	*72.68*	*-56%*

Source: Detailed description of sources is in Appendix A.2 to A.4.

100 miles. The breakdown by the type of roads confirms that it was cheaper to drive on rural roads than in urban areas, and on the interstates compared to non-interstates, which is explained by the distribution of driving speeds. The overall decrease in transport costs slowed down considerably in the 1970s, reflecting the fact that increasing gasoline prices, stagnant driving speeds and high labour costs were offsetting the continuing decrease in the vehicle operating costs. The costs decline then resumed its pace from the 1980s, driven by significant improvements in fuel efficiency and the fall in labour costs. As was the case for both the distance-based and time-based costs, the regional breakdown in Table 7 shows that this aggregate picture hides some spatial variation that will likely affect the choice of optimal routes when attempting to minimise the cost of travelling from county to county.

4 US County-pair minimal transports costs, 1955-2010

With 3015 counties taken from the 48 contiguous US states, the output of the Dijkstra analysis is a set of 4,818,960 (3105 × 3104 × 1/2) distinct county-pair optimal routes $R^*_{i,j}$.[11] Since the output for each origin/destination pair records the entire route, we can also obtain the mileage travelled by type of roads in addition to the value of the minimal transport costs. The composition of the route is especially important because it allows us to calculate the share of distance travelled on the IHS and thus investigate the relationship between the distance of a given county-pair route and share of it travelled on the IHS, which is carried out in section 4.3.

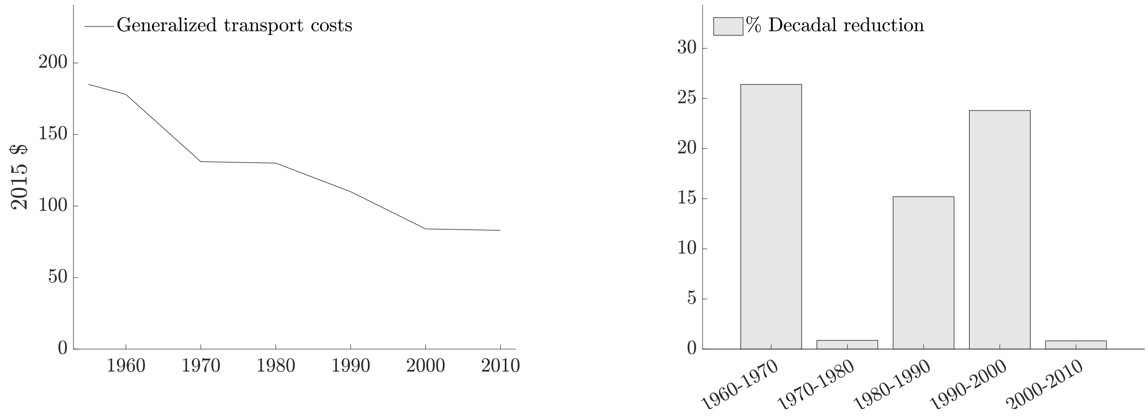
4.1 The spatial and time evolution of pairwise minimal transport costs

In order to illustrate the temporal and spatial evolution of the pairwise county minimal transport costs $\tau^*_{i,j,t}$, in each of the 3015 counties i we calculate a weighted average over all destination counties j for all the benchmark years, $\bar{\tau}^*_{i,t} \propto \sum_j w_{i,j}\tau^*_{i,j,t}$ and then compute the percentage change between the benchmark years.[12] Figure 3(a) presents the aggregate change over time of the average county-pair minimal transport costs, and Figure 3(b) breaks this down by decade. Overall, the time evolution of the minimal costs is entirely consistent with that of the total reference costs discussed in section 2.2. They have declined from 185 2015 $US per 100 miles in 1955 to 83 $ per 100 miles in 2010, in phases that reflect what was previously observed: an initial and substantial decline of 26% between 1960 and 1970, a stagnation during the 1970-1980 decade as fuel and labour costs counteracted technological improvements, followed by two decades of significant decline

[11] Since a route is simply a set of connected edges in the network between two vertices, we have $R^*_{i,j,t} = R^*_{j,i,t}$, and $\tau^*_{i,j,t} = \tau^*_{j,i,t}$. Also, because counties are represented by a centroid, we also have $\tau_{i,i,t} = 0$.

[12] The $w_{i,j}$ weights follow a simple gravity model and are calculated as a ratio of the average population in the destination county j (average over the period 1955-2010) to the square of distance between the origin and destination county, while the distance is the great circle distance.

Figure 3: Time evolution of minimal transport costs



(a) Average minimal transport costs

(b) Decadal changes

between 1980 and 2000 (42% in total) as labour costs fell and fuel efficiency improved, and finally a second period of stagnation between 2000 and 2010 caused by the slowdown in IHS development, rising fuel costs and falling driving speeds.

The spatial distribution of changes in the average county-pair transport cost over 1955-2010 is presented in Figures 4 and 5. In both cases, the panels on the left hand-side present the results obtained using the state-level reference costs detailed in section 3. The panels on the right present equivalent results obtained with a benchmark analysis using US-wide averages instead of the state-level data for the fuel efficiency, fuel costs and speeds. The purpose of this benchmark is twofold. First it establishes the consistency of the overall methodology against the existing literature, especially Herzog (2021) and Jaworski and Kitchens (2019), who similarly rely on the Dijkstra algorithm to find the cheapest routes between locations, but based on US-average data. Second, the comparison between the state-level and benchmark analysis helps to identify the contribution of the spatially disaggregated reference costs to the overall cost-accounting exercise.

Two key features stand out from a comparison of the two approaches: first, while the average level cost reductions is similar in both cases, the variation in the percent change in transport costs is much narrower when using aggregate data compared to the state-level data.[13] This is not a surprise in itself, as using spatially disaggregated reference costs

[13]Note that while the colormap used in the columns of Figures 4 and 5 is the same, the range it applies to is much narrower in the right hand side columns (US-level costs) than on the left (State-level costs). As an illustration, Figure 9 in appendix C, which presents the evolution of US-level costs using the same

injects more sources of variation into the analysis, however this suggests that relying on aggregate determinants is bound to underestimate the historical dispersion in transport costs. The second important feature is that when using aggregate determinants, the spatial variation in the county averages is tied very closely to the road network, to the point that the IHS network can be made out in the right-hand side panels of Figure 4. The disaggregated analysis shows instead much smoother spatial variation, allowing the identification of much stronger regional effects.

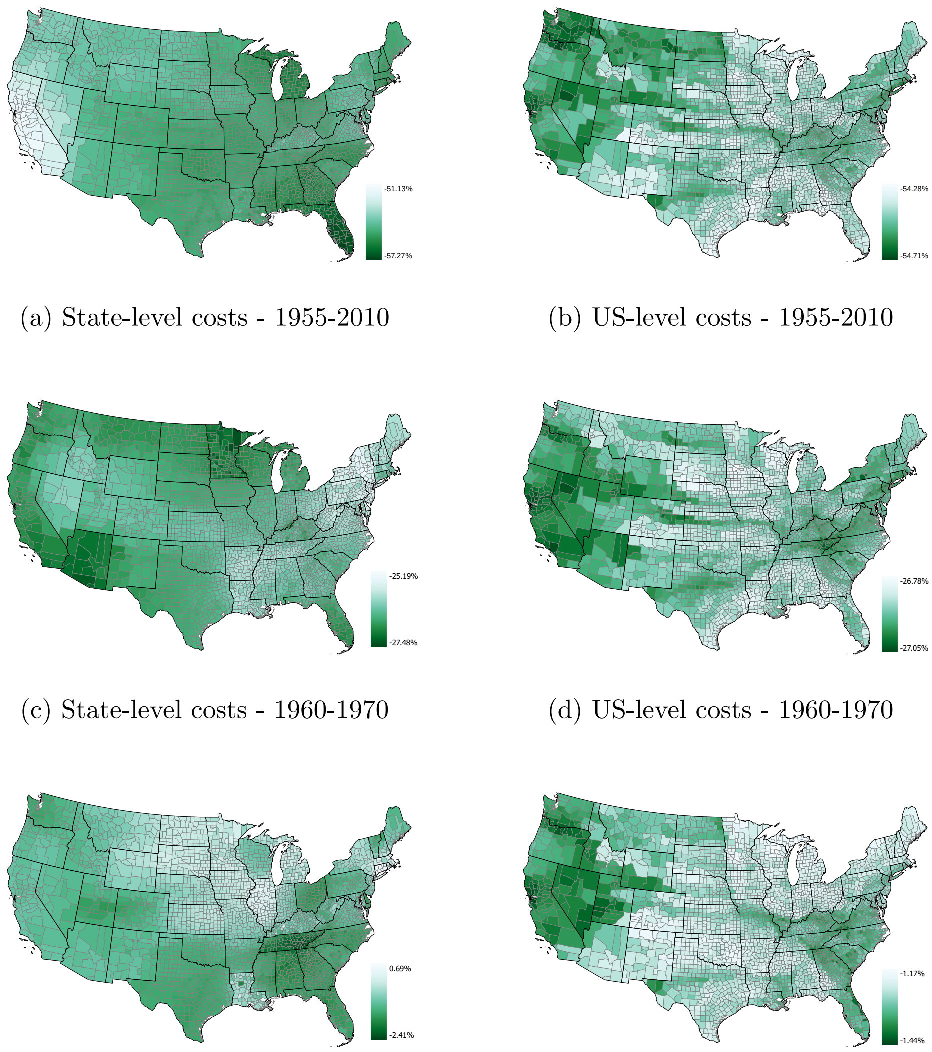
Figures 4(a) and 4(b) present the long-run change between 1955 and 2010, with the other panels presenting the changes decade by decade. Two facts stand out from Figure 4(a). First, the range of the decline of the transportation costs across all US counties is between 51% and 57%. Second, we can distinguish three broad parts of the US: (i) a part with the lowest decline in the transportation costs that includes Pacific coast, northern regions along Canadian border and Atlantic coast from New York City to the Chesapeake Bay (ii) a part with a medium decline of transportation costs which includes middle regions of the US from Minnesota to Texas, and most of the South, (iii) and a part with the highest decline of the transportation costs which includes Michigan, Florida, Atlanta metropolitan area, and eastern parts of New England. It is interesting to observe that the two areas that see the largest reductions are not spatially joined.

The decade-by-decade evolution of the county-level average minimal transport costs are presented in the following panels. For 1960-1970, shown in Figure 4(c) it is important to first note that the difference between the largest and the lowest decline is only one percentage point (25.9 to 26.9 %) and therefore the spatial variation visible in the map suggests was not that large. The Western and Northern parts of the US seemed to have benefited the most, however, one can also see evidence of larger cost reductions along certain recently developed interstates, such as the Midwest sections of I-80.

As previously stated, the 1970s saw a substantial slowdown in the pace of transport cost reductions. Figure 4(e) reveals that the largest decreases, around 1.5 %, were concentrated in the Southern states. This is not surprising as they experienced the lowest

range as the state-level analysis, suggests an extremely homogenous spatial evolution of transport costs when using US-level aggregates.

Figure 4: Spatial distribution of pairwise average costs - Part I



(a) State-level costs - 1955-2010

(b) US-level costs - 1955-2010

(c) State-level costs - 1960-1970

(d) US-level costs - 1960-1970

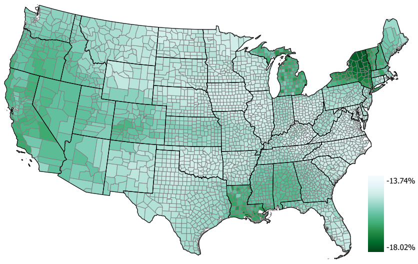
(e) State-level costs - 1970-1980

(f) US-level costs - 1970-1980

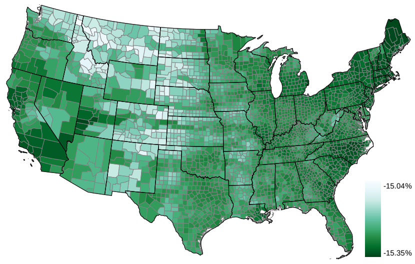
increases in fuel prices during the two oil shocks. The only areas to benefit, such as counties in Nevada and California and sections of Florida and Georgia, correspond to locations that saw the greatest increase in IHS connectivity over the period 1970-1980, visible in figure 1(b)-(c).

The larger declines of the transport costs in the 1980s, presented in Figure 5(a), saw the largest reductions occur in relatively peripheral regions, such as New England, Michigan, northern California, Oregon, Nevada, Utah, Colorado, and the southern states of Louisiana, Mississippi, and Alabama. This reduction was driven by a roll-back of the high fuel costs seen during the 1970s, the decline of the real earning of truckers, and finally

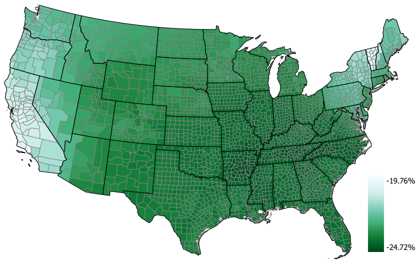
Figure 5: Spatial distribution of pairwise average costs - Part II



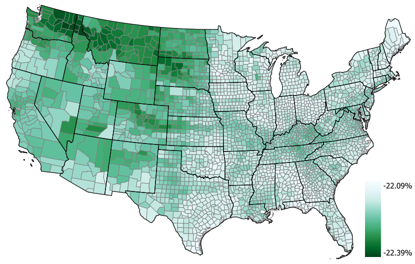
(a) State-level costs - 1980-1990



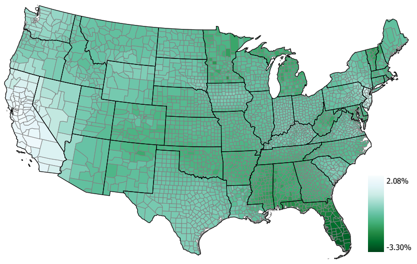
(b) US-level costs - 1980-1990



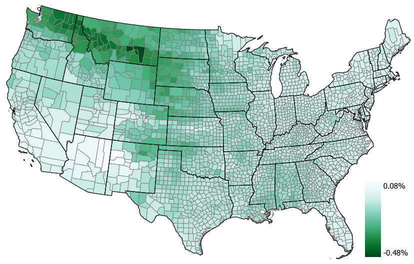
(c) State-level costs - 1990-2000



(d) US-level costs - 1990-2000



(e) State-level costs - 2000-2010



(f) US-level costs - 2000-2010

by the near completion of the interstate highways, offering higher driving speeds across the continent.

This reduction in transport costs continued in the 1990s, as shown in Figure 5(c), with a further reduction of 22-24%. The regional pattern shows that the further reduction was concentrated in the Southern states. Finally, Figure 5(e) shows the changes in county-level average minimal transportation costs in the first decade of the new millennium. Here we see that the while some regions, such as the southern states still saw transport cost reductions, albeit at a smaller scale than previously, for other areas,for instance California, the costs stagnated or even even increased. This is consistent with the distance-reference

Table 8: Shift-Share Analysis of the Sources of Transportation Costs 1955-2010.

	Panel A: Percentage in total transportation costs						
Costs	*1955*	*1960*	*1970*	*1980*	*1990*	*2000*	*2010*
Fuel cons. (1)	10.6	11.1	14.2	16.0	15.7	11.9	16.6
Op. costs (2)	66.9	63.2	50.4	40.9	41.5	40.2	33.4
Labour (3)	22.5	25.6	35.4	43.1	42.8	47.9	50.0
	Panel B: Percentage change in average costs						
	1955 - 1960	*1960 - 1970*	*1970 - 1980*	*1980 - 1990*	*1990 - 2000*	*2000 - 2010*	*1955 - 2010*
Fuel cons. (4)	1.70	-5.65	11.40	-16.63	-41.08	31.44	-30.99
Op. costs (5)	-8.44	-41.30	-19.41	-13.94	-24.72	-21.94	-78.09
Labour (6)	10.02	1.70	21.16	-15.89	-13.14	-1.66	-2.60
Total (7)	-3.21	-26.31	-0.67	-15.21	-22.33	-5.87	-56.08
	Panel C: Contribution to the changes in transportation costs (%)						
	1955 - 1960	*1960 - 1970*	*1970 - 1980*	*1980 - 1990*	*1990 - 2000*	*2000 - 2010*	*1955 - 2010*
Fuel cons. (8)	0.18	-0.63	1.62	-2.66	-6.45	3.75	-3.28
Op. costs (9)	-5.65	-26.12	-9.78	-5.70	-10.26	-8.82	-52.22
Labour (10)	2.26	0.44	7.49	-6.86	-5.62	-0.80	-0.59
Total (11)	-3.21	-26.31	-0.67	-15.21	-22.33	-5.87	-56.08

Source: Detailed description of sources is in Appendix A.2 to A.5.
'Fuel cons.' refers to fuel consumption costs and 'Op. costs' referes to vehicle oerating costs.

costs increasing slightly due to fuel prices and time-reference costs increasing following the fall in average driving speeds in urban areas, as seen in Tables 3 and 5.

4.2 Relative importance of distance and time-based costs: a shift-share analysis

In this section, we provide a decomposition of the relative contributions of the distance-based and time-based costs to the minimal transportation costs. As our overall cost methodology follows Combes and Lafourcade (2005), we also use their shift-share approach to analyse these impacts. The results of the analysis are provided in Table 8, where fuel consumption costs include the contributions of fuel efficiency and gasoline prices, vehicle operating costs include tire costs, maintenance costs and depreciation, while labor costs combine the contributions of trucker wages and driving speeds.

Panel A shows the share of fuel consumption, vehicle operating, and labor costs respectively in the minimal transport costs. These shares are calculated by averaging the distance travelled and time spent along routes and multiplying these averages by the corresponding reference costs: fuel consumption and vehicle operating costs from Table 3 and labor costs (expressed in hourly wages) from Table 5. We can see that the vehicle operating costs constituted the largest percentage of the generalized transport costs until 1980, after which the labor costs dominated, followed by fuel consumption.

The share of vehicle operating costs in the minimal transport costs experienced a substantial decline between 1955 and 2010: from 66.9% to 33.4%, reflecting technological progress in the production of trucks. Indeed, the annual percentage technological change in trucks and truck equipment was 3.3% per cent between 1948 and 2000 with even larger magnitude of 4.5% and 4% per cent in 1960-1969 and 1990-2000 respectively (Cummins and Violante, 2002, Table II). Relative to other modes of transportation, technological change in trucks was the second fastest right after aircraft with the rates of 7.9% in 1948-2000, but faster than automobiles with the rates of technological change of 2.5% over the same period. In comparison with other industries producing industrial equipment, technological progress in the production of trucks was faster than any other industrial equipment and machinery-producing industries (Cummins and Violante, 2002, Table II). This technological progress in the construction of trucks resulted in declining prices for truck components, tires, and improved quality which led to declining costs of truck maintenance, and truck depreciation (Winfrey, 1969; Paxson, 1981).

The share of fuel consumption increased between 1955 and 2010, with an initial peak in 1980, a decline for two decades and a second increase between 2000 and 2010. This pattern is driven solely by the prices of petrol, offset to some extent by improved fuel efficiency which was, as shown in Table 3. As previously explained, the share of labor costs increased at a fast pace until 1980, a result of strong teamsters' union. This growth stopped in the 1980s when the industry was deregulated and the real wages declined, as seen in Table 3. However, this was offset by the gradual decline in driving speeds due to congestion. As a result, the share of overall labor costs in the minimal transport costs increased overall reaching 50 per cent by 2010 and becoming the most important cost component.

Panel B shows the percentage change in all cost components over the benchmark years. These are then multiplied by the shares in Panel A to obtain the contribution of all cost components to the changes in the minimal transportation costs, as presented in Panel C. When we consider the entire period 1955-2010, minimal transport costs declined by about 56%, driven by the decline of vehicle operating costs. However, the decadal estimates reveal an interesting pattern. The decade of the 1960s saw a substantial decrease of the vehicle operating costs which was translated into a significant decline of the generalized transport costs – 26.3%. In the 1970s, however, the transport costs declined by less than one per cent despite the continuing improvement in the vehicle operating costs. This was because any cost advantage gained by lowering the costs of maintaining a truck were counterbalanced by the increase in the fuel consumption due to the global petrol price shock, and a steep rise in the labor costs. The decades between 1980 and 2000 saw a renewed reduction in minimal transport costs which, cumulatively, outpaced those of 1960s. This was due to the lower labor costs after the trucking industry was deregulated, continuing advancement in the technology of building and maintaining trucks, and declining fuel consumption costs. All this has slowed down considerably in the first decade of the 21st century in which declining vehicle operating costs were outweighed by the rising fuel consumption and only a very small decline in labor costs.

We can summarize the findings of the minimal transport cost decomposition as follows. First, there are two broad periods: before 1980, and after 1980. In the former, vehicle operating costs was almost exclusively the sole contributor to the minimal transport cost decline (except for 1960-1970 when fuel consumption lowered the costs as well, but their contribution was less than one per cent). Post-1980 decades witnessed a further reduction of the generalized transport costs driven by all three components except for 2000-2010 when the rising fuel consumption costs and an anaemic decline of labor costs countervailed the further decline in vehicle operating costs.

4.3 County-pair route distance and IHS share

As we mentioned at the beginning, the construction of the interstate highways was one of the most significant investments into road infrastructure in the post-World War II decades. It would be interesting to examine how the provision of this infrastructure affects the decision problem of finding the cheapest route between counties. Therefore, we investigate (i) a relationship between the distance along the cost-minimizing route travelled from county i to j and the share of such route carried out on the interstate highways. Here, we take advantage of the fact that the Dijkstra algorithm returns the entire cost-minimizing route $R^*_{i,j}$ between two counties i and j, enabling us to calculate the percentage of that route taken on the US interstates.

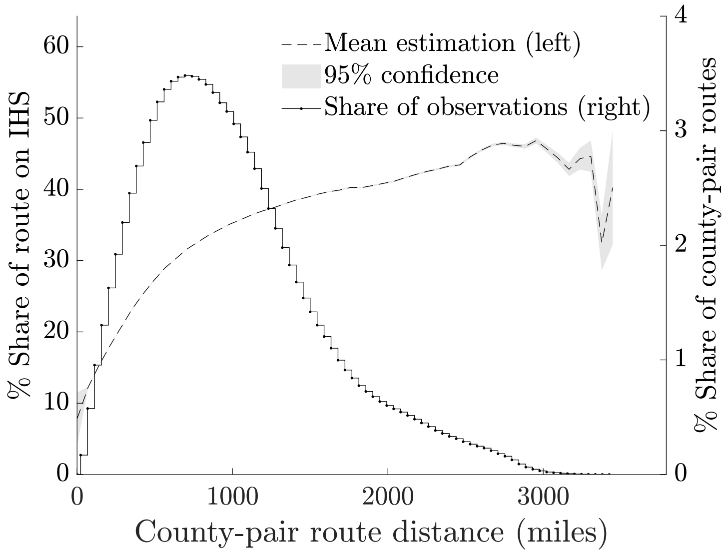
The IHS was built not only to facilitate high speed travel but also to facilitate travel on long-distance, cross-continental journeys. Therefore, we expect a positive relationship between the county-pair distance and the share of the route US taken on the US interstates. This is investigated by estimating the following non-parametric regression:

$$IHS_{i,j,t} = f(d_{i,j,t}) + \epsilon_{i,j,t} \tag{5}$$

where $d_{i,j,t}$ is the distance in miles of the cost-minimising route between county i and j in each year t, and $IHS_{i,j,t}$ is the share of that distance travelled on the US interstates. We use a local polynomial regression of degree one with an Epanechnikov kernel, using cross-validation to estimate the optimal bandwidth. Figure 6 presents the result, and shows that the share of routes taken on the US interstates indeed increases with distance, but the rate is not uniform. The mean share of a trip taken on the IHS initially increases quite rapidly as journey distance increases to about 1000 miles, then grows more slowly from that point onwards before increasing in volatility for trips between 3000 and 3500 miles. The latter behaviour can be explained by the vanishingly small share of county pairs that require a trip of that length, also shown in Figure 6, which results in a volatile estimate of the mean interstate share.

At the lower end of the trip distance distribution, this confirms that despite the IHS

Figure 6: Share of trip on IHS vs. trip length, local polynomial regression



representing only 10% of the overall mileage of the US road network, using it for a significant portion of a journey very rapidly becomes a valid cost-minimising strategy. At the higher end of the distance spectrum, as trips start spanning the width of the continent, this suggests that the IHS is indeed fulfilling its design requirements of facilitating long distance travel, as it forms a large share of the cost-minimising route.

5 Conclusion

The purpose of the paper is to provide accurate measurements of point-to-point marginal costs of transport on the post-World War II US road network. In doing so we take into account not only the evolution of the road network itself, most notably the construction of the IHS, but also the evolution of fuel prices, fuel efficiency, truck driver wages and driving speeds for urban/rural and interstate/non-interstate roads. As a first result, the resulting decadal sets of minimal pairwise county transport costs allow us to shed light on key factors behind the evolution of transport costs in the post-World War II age of highways. Overall, minimal transport costs, driven by a combination of higher driving speeds, improved fuel efficiencies, lower running costs and lower wages of truck drivers, fell significantly between 1955 and 2010. Crucially, the spatially disaggregated nature of the analysis enables us to document how this reduction was not only uneven across time, but also over the span of the 48 contiguous US states.

More importantly, the greater objective of the paper is to provide a detailed transport cost dataset that can facilitate future research on the long-impact of transport cost changes on the US economy. As highlighted throughout, when calculating average transport costs in one location we purposefully assume away the distribution of traffic over destinations, relying only on gravity weights as a proxy. Similarly, we only consider the evolution of transport costs themselves, not the impact of the resulting reductions on GDP or welfare. This is not because we believe that such factors are unimportant, but instead because the scope of such research exceeds that of this paper. However, given the central role that transport costs play in regional science for building measures of market access or explaining the spatial distribution of activity, the level of detail provided by this new dataset will help improve the understanding of the spatial dynamics of the US economy in the latter half of the 20th century.

CRediT author statement:

Barde: Conceptualization, Methodology, Software (Python, QGIS), Formal analysis (Network analysis / Dijkstra), Data Curation, Writing - Original Draft, Review & Editing, Visualization (maps, tables, plots, network). **Klein:** Conceptualization, Methodology, Software (arcGIS, Stata), Formal analysis (Econometric analysis), Data Curation, Writing - Original Draft, Review & Editing, Visualization (maps, tables, plots).

References

Barber, Richard J (1964) "Technological Change in American Transportation: The Role of Government Action," *Virginia Law Review*, pp. 824–895.

Barnes, Gary and Peter Langworthy (2004) "Per mile costs of operating automobiles and trucks," *Transportation Research Record*, Vol. 1864, pp. 71–77.

Baum-Snow, Nathaniel (2007) "Did highways cause suburbanization?" *The quarterly journal of economics*, Vol. 122, pp. 775–805.

Belman, Dale L and Kristen A Monaco (2001) "The effects of deregulation, de-unionization, technology, and human capital on the work and work lives of truck drivers," *ILR Review*, Vol. 54, pp. 502–524.

Berwick, Mark D and Frank Dooley (1997) "Truck costs for owner/operators,"Technical report, Upper Great Plains Transportation Institute, North Dakota State University.

Brinkman, Jeffrey and Jeffrey Lin (2019) "Freeway Revolts!," *Federal Reserve Bank of Philadelphia Working Papers*.

Chandra, Amitabh and Eric Thompson (2000) "Does public infrastructure affect economic activity?: Evidence from the rural interstate highway system," *Regional Science and Urban Economics*, Vol. 30, pp. 457–490.

Combes, Pierre-Philippe and Miren Lafourcade (2005) "Transport costs: measures, determinants, and regional policy implications for France," *Journal of economic geography*, Vol. 5, pp. 319–349.

Condeço-Melhorado, Ana, Javier Gutiérrez, and Juan Carlos García-Palomares (2011) "Spatial impacts of road pricing: Accessibility, regional spillovers and territorial cohesion," *Transportation Research Part A: Policy and Practice*, Vol. 45, pp. 185–203.

Cummins, Jason G and Giovanni L Violante (2002) "Investment-specific technical change in the United States (1947–2000): Measurement and macroeconomic consequences," *Review of Economic dynamics*, Vol. 5, pp. 243–284.

Duranton, Gilles and Matthew A Turner (2012) "Urban growth and transportation," *Review of Economic Studies*, Vol. 79, pp. 1407–1440.

Frye, Dustin (2021) "Transportation networks and the geographic concentration of employment," *Working Paper*.

Herzog, Ian (2021) "National transportation networks, market access, and regional economic growth," *Journal of Urban Economics*, Vol. 122, p. 103316.

Hirsch, Barry T (1988) "Trucking regulation, unionization, and labor earnings: 1973-85," *Journal of Human Resources*, pp. 296–319.

Hirsch, Barry T, David A Macpherson, and Marcus Alexis (1998) "Earnings and employment in trucking: Deregulating a naturally competitive industry," in *Regulatory reform and labor markets*: Springer, pp. 61–124.

Jaworski, Taylor, Carl Kitchens, and Sergey Nigai (2020) "Highways and Globalization,"Technical report, National Bureau of Economic Research.

Jaworski, Taylor and Carl T Kitchens (2019) "National policy for regional development: Historical evidence from Appalachian highways," *Review of Economics and Statistics*, Vol. 101, pp. 777–790.

Koopmans, Carl, Wim Groot, Pim Warffemius, Jan Anne Annema, and Sascha Hoogendoorn-Lanser (2013) "Measuring generalised transport costs as an indicator of accessibility changes over time," *Transport Policy*, Vol. 29, pp. 154–159.

Nall, Clayton (2015) "The political consequences of spatial policies: How interstate highways facilitated geographic polarization," *The Journal of Politics*, Vol. 77, pp. 394–406.

Paxson, David S (1981) "Changes in intercity trcukload costs & service 1950-1980," in *Proceedings – Twenty-second Annual Meeting of Transportation research Forum*, pp. 508–515.

Rose, Nancy L (1987) "Labor rent sharing and regulation: Evidence from the trucking industry," *Journal of Political Economy*, Vol. 95, pp. 1146–1178.

Smith, Vernon L (1957) "Engineering data and statistical techniques in the analysis of production and technological change: fuel requirements of the trucking industry," *Econometrica: Journal of the Econometric Society*, pp. 281–301.

Winfrey, Robley (1969) "Economic analysis for highways,"Technical report.

A Data: Sources and preparation

A.1 NHPN IHS build data and urban/rural classification

The process of generating the map of the extant IHS in 1960, 1970, 1980, 1990, 2000, and 2010 respectively was as follows. For each signed interstate (I-2 to I-99) we used the 'Interstate Density Maps' to identify which interstate highways sections were built by county and decade respectively and created the corresponding indicators in the NHPN shape file. Since the NHPN shape file splits each numbered highway into very fine-grained segments, this enabled us to determine not only whether an interstate highway was built in a county by the end of each decade, but also the length completed. This enabled us to verify that the total length was correct against the Baum-Snow (2007) digitized PR-511 data, and correct any discrepancies to closely match that data. Most counties, especially rural ones, are traversed at most by a single interstate highway, making it straightforward to determine the length built by the end of each decade. For counties with more than one interstate highway, it is also straightforward to determine the extant network if all interstate highways were open to public by the end of a given decade. For the remaining counties, in which different interstate highway segments was finished in different decades, we referred to Interstate-Guide to determine which portion of which interstate highway was opened to public by the end of each decade. Again, since the NHPN shape file splits each highway into very detailed segments on the scale of hundred meters, we were able to determine very accurately which portion of which highway and in which county was open to the public by the end of each decade. The resulting six digitized interstate highway maps for the years 1960, 1970, 1980, 1990, 2000, and 2010 are presented in Figure 1.

The NHPN data contains a rural/urban classification code for the road segments, however this only applies to the vintage of the NHPN data (2014), and does not provide historical information. In order to track the evolution of urbanisation over time, we use the rural-urban continuum codes provided by the US Department of Agriculture. This encodes the level of urbanisation for each county with a range that goes from 1 (Counties in metro areas of 1 million population or more) to 9 (Completely rural or less than 2,500 urban population, not adjacent to a metro area). Because our distinction is a binary one, we treat codes 1-7 as urban and 8-9 as rural.

A.2 Fuel: prices and consumption

The sources used and how the raw data were cleaned up are detailed below. The crucial aspect that needs to be clarified is the fact that we have used data on gasoline prices and consumption in the analysis, despite the fact that most US road transport vehicles have run on diesel since at least the mid 1950s. The main obstacle to using diesel prices and consumption is the difficulty in acquiring reliable data for the pre 1975 period. The US Energy Information Administration does not provide price data prior to 1975, and the only source for state-level historical prices are the USDA agricultural price statistics. Examination of the diesel prices in those publications revealed abnormally low values relative to gasoline prices, including after 1975 where the USDA can be directly compared to the USEIA data. Because the USDA data collects prices paid by farmers, it is very likely that these diesel prices include tax-exempt off-road diesel (also known as 'red diesel'), which is heavily used in the agricultural sector for running farm machinery and other off-road equipment. Because using these tax-exempt prices as determinants for on-road costs would introduce distortions, it was decided to rely on gasoline data instead. This decision was further justified by the fact that the US aggregate gasoline and diesel monthly price series reported by the USEIA track very closely, as visible in figure 7.

The raw data sources for gasoline prices were as follows:

- **1955**: US Department of Labor, Bulletin No. 1197, Bureau of Labor Statistics 1956, Table 3
- **1959-1974**: US Department of Agriculture, Crop Reporting Board, Economics and Statistics Service, Agricultural Prices. Annual Summary, edition 1959-1974
- **1975-2010**: US Energy Information Administration, State Energy Data System

State-level gasoline prices for the period 1975-2000 were taken from US Energy Information Administration, series MGTCD (average price of motor gasoline), which was

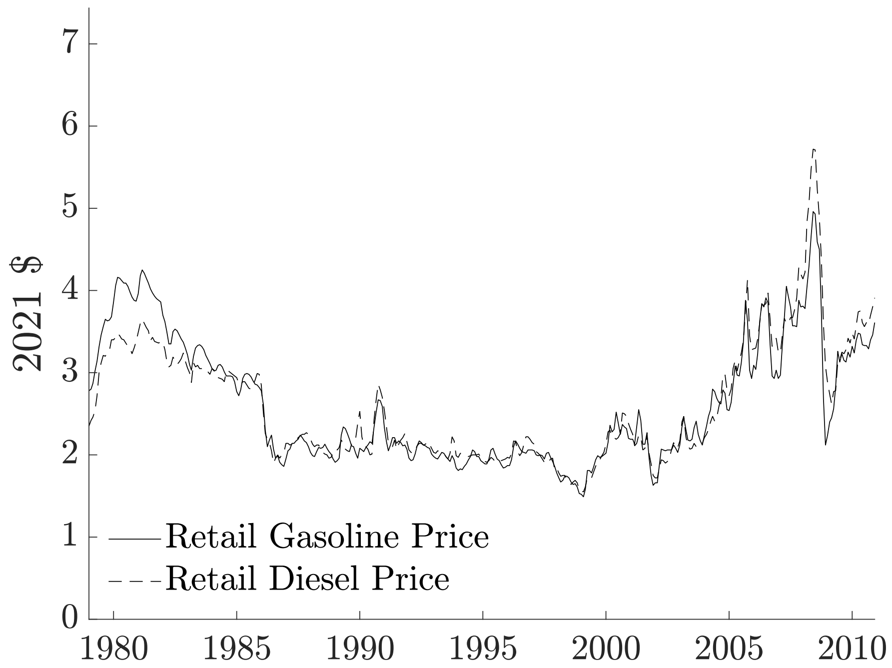


Figure 7: US monthly fuel prices 1979-2010, US Energy Information Administration

straightforward. Similarly, prices from 1959-1974 were obtained from scanned copies of paper publications produced by USDA. While this required a large digitisation effort to convert the scanned documents to tabular format, the data collection itself was also straightforward.

Obtaining state-level gasoline prices for 1955, before the inception of the Interstate Highway System, required more work. We used retail prices of gasoline in fifteen cities in fifteen U.S states for 1955 from the Bulletin of US Department of Labour. To calculate the prices in the remaining states, we assumed that the ratio of state to U.S average gasoline price is stable between 1955 and 1959 and used U.S average retail gasoline price prices in 1955 and state gasoline prices in 1959. Since the prices for the years 1959-2010 are tank-trunk prices, we scaled down 1955 retails prices using the state ratios of retail to tank trunk prices in 1959.

For fuel consumption, the sources were as follows:

- **State-level gasoline consumption data**: Federal Highway Statistics 1950-2010
- **US average gasoline consumption**: US Energy Information Administration,

https://www.eia.gov/totalenergy/data/browser/?tbl=T01.08#

The state-level fuel consumption data is what was used as an input to the analysis, with the US average data serving as a validation check.

A.3 Earnings of truck drivers

Several sources were used for the earnings of truck drivers:

- **1955**: Union Wages and Hours, United States Department of Labor, Bulletin No. 1195, 1955, Table 7
- **1960-1990**: 'Employment, Hours, and Earnings, United States, 1909-94 : Bulletin of the United States Bureau of Labor Statistics, No. 2445'. We used nominal wages of non-supervisory workers in SIC421 'Trucking and courier services except for air' for the period 1964 to 1994. For the period 1958-1964, no data for trucking are available and so we used nominal average weekly earnings only for SIC 42 'Motor freight transportation and warehousing'.
- **2000-2010**: Occupational Employment Statistics Survey, Bureau of Labor Statistics, Department of Labor, average wages of two occupation categories: (i) truck drivers, heavy and tractor-trailer, (ii) truck drivers-light, include delivery/route workers.[14]

A.4 Driving Speeds

The state-level driving speeds used in the analysis were obtained as follows:

- **1955**: Speed data for urban, and rural roads are from 1957 Federal Highway Statistics (page 22), and 1964 US Department of Commerce report 'Accidents on Main Rural Highways Related to Speed, Driver, and Vehicle' (page 6, Table 3) respectively. The Department of Commerce report provides information on speed in eleven states; speed in the remaining states was imputed by assuming that the speed in

[14] https://www.bls.gov/oes/tables.htm, accessed August 3, 2020

the states located in the same U.S Census region is the same. Urban speed is calculated using US average speed from the Federal Highway Statistics and assuming that the ratio of state to US average speed is the same in rural and urban areas. Since there was no Interstate Highway System, there are only two types of roads: urban non-interstate, and rural non-interstate.

- **1958-1970**: US-wide average speeds are from U.S Historical Statistics, Series Q188. To calculate state-level speed data, we used a ratio of state to US average speed. Specifically, we assume that the ratio of state speed to US average speed is the same as in the second half of the 1970s. Using second half of the 1970s is justifiable as the average speed at that time was similar to the levels of 1960s after a decline in the early 1970s. The stability of state speed to US average speed ratio over time was examined using data from 1955, and 1976-1991 for which Federal Highway Statistics provides detailed state-level breakdown. The calculated ratios are remarkably stable over time and regression analysis showed no statistically significant time trend. This confirmed that whilst average US speed was generally increasing over time, as shown in Table 4, the state-level average speed relative to US average speed showed no discernible time trend.

- **1971-1991**: : Speed data are from the Federal Highway Statistics 1981-1991, tables VS-1. These provide near-complete data for all types of road, with only a few missing observations imputed as the average speed of the U.S Census region in which the state with the missing data is located. Unfortunately, the reporting of speed data in the Federal Highway Statistics was discontinued after 1991.

- **2000-2010**: Data in 2010 are proxied using 2012 data on average speed in selected metropolitan areas published in 'Freight Facts and Figures 2017, US Department of Transportation' (Table 4-1), and speed data US interstates published in 'Top 25 Commodity Corridor Performance Measures' provided by the Federal Highway Administration. This data enables us to cover thirty states. The remaining data is imputed by again assuming that the ratio of state-level speed to US average speed is the same as in 1991. We have tested this assumption by comparing the imputed speed to the observed data for the 30 states for which we have speed data. This comparison revealed a very close match, indicating again that the imputation works well. An exception is Connecticut, Oregon, and Washington where the speed would be about ten percent higher, hence the transport costs for the routes through those states are upper bounds. As there is no speed data available for 2000, we take the average of 1991 and 2010.

A.5 Vehicle operating costs

Vehicle operating costs include tire costs, maintenance costs, and depreciation rate. The sources are:

- **1955, 1960**: 'Line-Haul Trucking Cost in Relation to Vehicle Weight', Highway Research Bulletin 303, 1961, Figure 25, 26. The data are for a truck type 2-S2 (Figure 25). A comparison with a truck type 2-S3 (Figure 26) reveals that the running costs are very similar.

- **1970**: Winfrey, R. (1969): Economic Analysis for Highways, Table A-2, A-4, A-5.

- **1980**: 'Vehicle Operating Costs, Fuel Consumption, Pavement Type and Condition Factors', Federal Highway Administration, 1982; maintenance costs are taken from Table 2, tire costs from Figure 10, depreciation is calculated using data from Table 2, Table 19, Table B.33. The data for a truck type 2-S2.

- **1990**: All three components were calculated using truck-to-passenger car cost ratios (truck 2-S2 type) since data for truck operating costs in 1990 are missing. We have calculated the average of truck-to-passenger car ratios for each component of operating costs over 1970, 1980, and 2010 and applied it to the 1990 passenger car operating costs to obtain the truck operating cots. Data for passenger car tire costs, maintenance costs and depreciation come from 'Costs of Owning and Operating Automobiles and Vans', Federal Highway Administration, 1984, Table 4.

- **2000**: Berwick, Mark and Frank Dooley (1997): Truck Costs for Owner/Operators. Upper Great Plains Transportation Institute, North Dakota State University, Table 4.2, the data for year 1996.
- **2010**: Barnes, Gary and Peter Langworthy (2004): The Per-Mile Costs of Operating Automobiles and Trucks, Transportation Research Record: Journal of the Transportation Research Board, No. 1864, TRB, National Research Council, Washington, D.C., 2004, pp. 71–77. Table 2, data is for 'commercial truck'.

B Network simplification and analysis

The US road network is modelled as a graph $\Gamma = (V, E)$, with vertices V representing the intersections in the road network, and edges E representing the road segments themselves. Given two vertices v and u, (v, u) represents an edge $e \in E$ connecting v and u. n_v is the degree of vertex v, i.e. the number of edges that connect to v. Indices i and j will be used to index vertices that are also county centroids, and these will form a set $C \subset V$. Finally $R_{i,j}$, which will be referred to as a route, is a path on Γ connecting centroids i and j. $R^*_{i,j}$ will be used specifically to denote the optimal route between i and j.

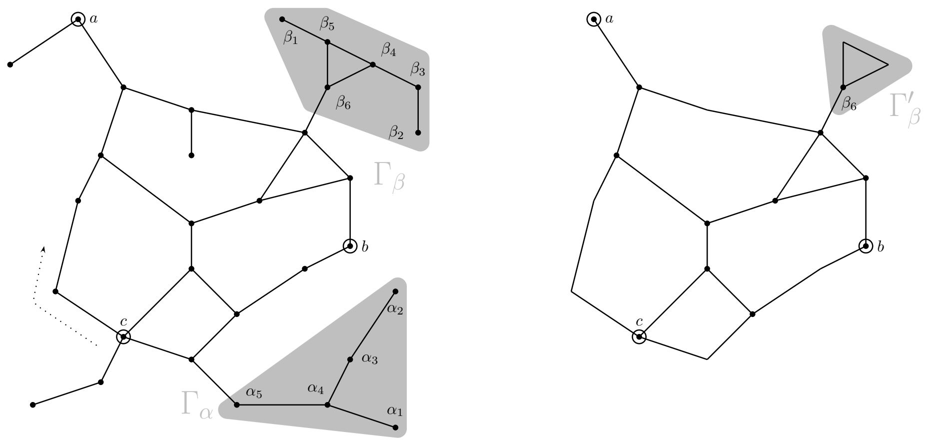
B.1 GIS stage: Network generation

The raw NHPN GIS data only contains road segments, with related information such as the county/state FIPS code, the length of the segment and the signage of the road. This gives us the edges E of the network, but not the vertices. In order to generate a proper graph Γ, we first generate the two endpoints of each road segment. Whenever two road segments are connected, this will result in two vertices being added at the location of this connection, one for each of the two corresponding edges. As a second step, therefore, all duplicate vertices are deleted, resulting in a set of unique vertices V. Crucially, the number of duplicates in the same location directly provides the degree of each vertex, n_v, which will play a central role in the simplification strategy presented below.

Before carrying out the simplification, two additional tasks are carried out. The first of these is the calculation of the transport costs on each edge in E in a given year, τ_e. This is done with (1) and (2), using the spatially disaggregated reference cost data for driving speeds, wages, fuel prices and fuel consumption described in Appendix A, combined with the distance and state FIPS code of each edge provided by the NHPN data. The NHPN data also provides the signage of the road segment corresponding to each edge, allowing the identification of interstates, although this is modified as explained above to reflect the construction of the IHS. The resulting transport costs for each year of analysis are stored in a set of symmetric $|V| \times |V|$ matrices τ_t.

The second task is the identification of the county centroids, which will form the start and end points of the routes in Dijkstra's algorithm. The strategy used for determining the coordinates for the centroid of each county is to average the coordinates of all the vertices in that county. Because the density of the road network is directly correlated to the density of the population, this allows us to obtain centroids that very closely track the largest population centre in each county without requiring very disaggregated population data. Rather than adding a new set of vertices to Γ, which would then also requires a new set of edges to connect them to the rest of the graph, we simply locate the closest existing vertex to the average and flag it as the centroid. The average distance between the average of vertex locations and the vertex selected as a centroid is small, 1.77 miles, with a standard deviation of 2.03 miles. The largest errors are located in the low population density Western states, with Nye County, Nevada seeing a maximal error of 29.94 miles. These relatively small deviations relative to the scale of the contiguous USA validates this choice of approach. Those vertices of Γ that are flagged as centroids form a subset $C \in V$.

At the end of this process, we have a full graph $\Gamma = (V, E)$ representing the US road network: a set of edges E representing the roads, a set of vertices V representing the intersections, with information about costs associated with edges, the degree of the vertices, and a set of identifiers C indicating which vertices represent a county centroid. Because of the high fidelity of the NHPN data, this graph is very large, with $|V| = 592,828$ vertices and $|E| = 625,610$ edges.



(a) Before simplification (b) After simplification

Figure 8: Network simplification

B.2 Simplification stage 1: Removal of degree 1 vertices

Before running Dijkstra's algorithm for pairs of US county centroids, we first simplify the graph Γ obtained in the GIS step. This is because the algorithm needs to be run $3105 \times 7 = 21,735$ times, once for every origin county and every benchmark year, and the time-complexity of Dijkstra's algorithm increases quadratically with $|V|$. Given the size of the raw graph, in order to keep the problem tractable, we need to first simplify the graph to reduce the number of edges and vertices. We do this by removing those road intersections that do not enter the decision problem of finding the cheapest route between two vertices in C, in order to ensure that the optimal solution found by Dijkstra's algorithm is not affected by the simplification process. Figure 8 is provided to help illustrate the simplification process, via a toy example where a, b and c represent centroids that will be the origin or destinations of our routes.

The first step is to iteratively eliminate all vertices of degree 1, as well as the edges that lead to them. These vertices represent the termination point of a dead-end road, or a cul-de-sac, and such locations can only be visited by a cheapest route if they happen to be either the destination or the origin of that route. The proof of this is trivial, and intuitively experienced by any driver who accidentally turns onto a dead-end road! Suppose that a route $R_{i,j}$ visits a degree 1 vertex v that is not its origin or destination: because $n_v = 1$, it is connected to a single edge (v, u), and the route will traverse (v, u)

twice: once on the way to v, and once on the way back. Therefore, there also exist at least one vertex that is visited twice, u. A cheaper route can be obtained by removing (u, v) and (v, u) from $R_{i,j}$, and visiting u only once.

Algorithm 1 Removal of degree 1 vertices

Require: V: Vertices of Γ
Require: n: vector, degree of each vertex
Require: E: Edges of Γ
Require: C: Set of vertices in V that are centroids

while $\exists\, v \in V : n_v = 1 \ \wedge \ v \notin C$ **do**
  $v \leftarrow \text{find}(v \in V : n_v = 1 \ \wedge \ v \notin C)$ ▷ find degree 1 vertex
  $u \leftarrow \text{find}(u \in V : (v, u) \in E)$ ▷ find find connected vertex
  $V \leftarrow V \setminus v$ ▷ remove v from vertices
  $n \leftarrow n \setminus n_v$
  $E \leftarrow E \setminus (v, u)$ ▷ remove (v, u) from edges
  $n_u \leftarrow n_u - 1$ ▷ Reduce degree of u by 1
end while

return V, E, n

In fact, a much more general statement can be made: suppose that Γ contains a subgraph that is connected to the rest Γ by a single edge, and additionally suppose that this subgraph does not contain any centroids. Then, using the same logic as above, the cheapest route between any pair of centroids will never visit this subgraph. Figure 8(a) shows two such subgraphs, labelled Γ_α and Γ_β, which will never be visited by the optimal routes between a, b and c. [15] In theory, such subgraphs can therefore be removed from the original graph without affecting the choice of optimal route.

The removal of degree 1 vertices is carried out iteratively, using algorithm 1. This very simple and fast implementation will remove single branches, such as the road to the lower left of centroid c, as well as single-edge connected subgraphs, as long as the subgraph is a tree. This is the case for subgraph Γ_α, which is entirely removed by the procedure: in the first round, the algorithm will remove α_1 and α_2, and reduce the degree of α_3 to 1 and α_4 to 2. Subsequent rounds will sequentially remove α_3, then α_4 and α_5.

[15]Such topologies are common on real-life road networks, as many residential neighbourhoods are designed in this manner. There is a single collector road connecting the area to the main road network, precisely to avoid excess traffic being routed through the neighbourhood.

Algorithm 1, however, cannot cope with subgraphs that contain a cycle, such as Γ_β, where the cycle formed by vertices β_4, β_5 and β_6 will not be removed. This is because after the elimination of the single branches containing β_1, β_2 and β_3, the vertices in the cycle will all have a degree of at least 2, and will therefore be ignored by the algorithm. This leaves a remainder subgraph, labelled Γ'_β in Figure 8(b). Unfortunately the problem of identifying, and then removing single-edge connected subgraphs that do not contain centroids, such as Γ_α and Γ_β is computationally complex and time-demanding. Because the purpose of the network simplification is to reduce the overall computation time required, and because the remainder subgraphs left by Algorithm 1 will never be visited by an optimal route in any case, it was decided that this simpler and faster simplification, albeit slightly sub-optimal, was sufficient. This process removes 16,984 vertices and 16,976 edges from Γ.

B.3 Simplification stage 2: Removal of degree 2 vertices

Once all non-centroid degree 1 vertices are removed the next step is to remove degree 2 vertices. Unlike the degree 1 vertices, which are cannot be part of an optimal route unless they are a centroid, these can be visited by an optimal route. Despite this, they are irrelevant to the decision problem of Dijkstra's algorithm, because they do not represent a decision point where any real choice is available to a driver. Such a vertex has one edge leading to it, one edge leading away from it, and is therefore not a true intersection.[16]. Using Figure 8(a) as an illustration, suppose a driver travelling from c to a decides to follow the route indicated by the dotted arrow: when the driver arrives at the next vertex, which has degree 2, there is no choice but to continue along the route. The only alternative is to return to c, which as established in the previous section, means the route cannot be the cheapest. Thus, for the purposes of finding optimal routes in Γ, any two edges connected by a vertex of degree 2 can essentially be treated as a single edge. This insight forms the basis of the second simplification algorithm.

[16]The overwhelming majority of degree 2 vertices in the NHPN data represent administrative boundaries in the data, where the same signed road is broken up according to county boundaries, minor changes in road signage, or maintenance identifiers, etc.

Algorithm 2 Removal of degree 2 vertices

Require: V: Vertices of Γ
Require: E: Edges of Γ
Require: W: Edge weights (cost, distance, time, etc.)
Require: C: Set of vertices in V that are centroids

$V' \leftarrow \{v \in V : n_v > 2 \ \vee \ v \in C\}$ ▷ get critical vertices
$E', W', M \leftarrow \varnothing$ ▷ initialise empty return variables
$L_{(v,u)} \leftarrow 0 \quad \forall (v,u) \in E$ ▷ label all edges as unvisited

for all $s \in V'$ **do** ▷ for all critical vertices
    $V_s \leftarrow \{u \in V : (s,u) \in E\}$ ▷ find vertices connected to s
    for all $u \in V_s$ **do**
        $v \leftarrow s$
        if $L_{(v,u)} = 0$ **then** ▷ only run on unvisited paths
            $P \leftarrow \varnothing$
            $W_P, \mathit{stop} \leftarrow 0$
            while $\mathit{stop} = 0$ **do**
                $P \leftarrow P \cup \{(v,u)\}$ ▷ add edge to path
                $L_{(v,u)} \leftarrow 1$ ▷ flag edge as visited
                $W_P \leftarrow W_P + W_{v,u}$ ▷ increment path weight
                if $u \in V'$ **then** ▷ if u is a critical vertex, we are done
                    $E' \leftarrow (s,u)$ ▷ add new single edge (s,u)
                    $M \leftarrow ((s,u), P)$
                    $W'_{s,u} \leftarrow W_P$
                    $\mathit{stop} \leftarrow 1$
                else ▷ else, move to next edge on the path
                    $v' \leftarrow v' \in V : (u,v') \in E \ \wedge \ v' \neq v$
                    $v \leftarrow u$
                    $u \leftarrow v'$
                end if
            end while
        end if
    end for
end for

return V', E', W', M

Algorithm 2 constructs a new graph $\Gamma' = (V', E')$ and an edge mapping M, allowing to reconstruct in the original graph Γ any route $R_{i,j}$ found in Γ'. The new set of vertices V' consists of all the vertices in V that either have a degree greater than 2, or that represent a centroid location.[17] In other words, V' is the subset of the critical vertices of

[17] The vertices a and b in Figure 8(b) respectively have degree 1 and 2 yet because they represent centroids, they are not removed as part of the overall simplification.

Γ, representing origins and destinations of routes, as well as those vertices in the graph that represent true decision points for a route. Let v, u be two such critical vertices, appearing both in V and V', and assume that they are connected in Γ by a path $v - u$ made up entirely of degree 2 vertices. Let P be the subset of E containing the edges in the $v - u$ path. Then in Γ' v and u are directly connected by a single edge $(v, u) \in E'$, where the weight of the edge (be it a travel cost, a distance, or a time) associated with (v, u) are simply the sum over the edges in the disaggregated path P, i.e. $W_{(v,u)} = \sum_e W_e \quad \forall e \in P$.

Figure 8(b) illustrates the result of this process. The simplified graph Γ' preserves the core topology of the full graph Γ, as well as the edge cost or distance information required to run Dijkstra's algorithm, while greatly reducing the number of vertices and edges. In our case, the reduction in the graph size is dramatic, with only $|V'| = 51,602$ vertices and $|E'| = 84,403$ remaining in the simplified graph Γ'. This represents an order-of-magnitude reduction in the number of vertices, which given the $\mathcal{O}(|V|^2)$ time-complexity of Dijkstra's algorithm represents roughly a two order-of magnitude improvement in the runtime of our analysis.

B.4 Dijkstra's algorithm and route reconstruction.

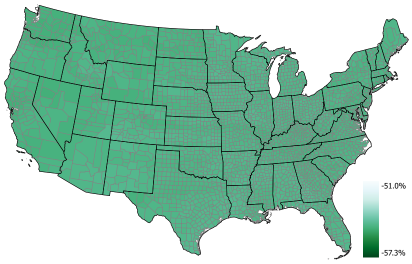
As previously stated, the optimal routes $R^*_{i,j}$ on the simplified graph Γ' between centroids $i, j \in C$ are found using Dijkstra's algorithm. In our implementation, each individual run of the algorithm involves picking a starting point $i \in C$ and a set of target destinations $\{j, k, \dots\} \in C$, and results in a corresponding set of optimal routes to the targets $R^*_{i,j}, R^*_{i,k}, \dots$ as well as a vector of minimal transport costs from i to the set of targets $\tau^*_{i,j}$. Building a full matrix of transport costs in a given year thus requires $|C| = 3105$ runs, one for each origin county. This needs to be repeated for each of the 7 years in the analysis.

The network simplification carried out above reduces the computation time of a single run, from 1 origin county to 3104 destinations (producing 3105 optimal routes), to an average of 241 seconds, which is an extremely significant gain. Nevertheless, given the number of runs required, further optimisation of our implementation was required. First, the implementation takes into account the symmetry of the transport cost matrix, i.e. $R^*_{i,j} = R^*_{j,i}$ and $\tau^*_{i,j} = \tau^*_{j,i}$, to shrink the target set as runs proceed and reduce the overall computation required by a factor of 2. For the very first run, using centroid i as the origin, the target set is $C \setminus \{i\}$. For the second run, starting in j, the target set is smaller, $C \setminus \{i, j\}$, given that $R^*_{i,j}$ was already produced as part of the first run. The target set for the next iteration, starting in k will be $C \setminus \{i, j, k\}$, and so on and so forth. As a second step we took advantage of the trivially parallel nature of the problem, as all runs are independent from each other, differing only in their starting point and target sets. The analysis was therefore run in parallel, using 72 threads on a 36-core cluster, which enabled the 3105 runs required to obtain optimal costs for a given year to be processed in just under 3 hours, thus making the overall analysis tractable.

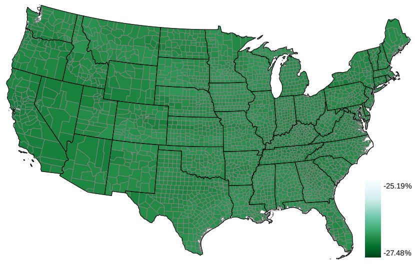
Finally, while Dijkstra's algorithm is run on a simplified network Γ' compared to the full network Γ, because the simplification only removes vertices that are not relevant to the decision process of finding a cost-minimising route, the minimal cost of reaching j from i will be the same in both graphs. Similarly, an optimal route $R^*_{i,j}$ on Γ' is also optimal on Γ, once the single edges between critical vertices in $R^*_{i,j}$ are replaced by the corresponding sequence of edges containing degree 2 vertices. This is done using the edge mapping M produced by Algorithm 2, which gives us the ability to 'undo' the simplification if required, and recover information that is lost in the simplification process: the signage of a road segment, it's rural/urban nature etc. In particular, this is what enables us, for example, to calculate the share of an optimal route's distance travelled on the IHS.

C Supplementary figure

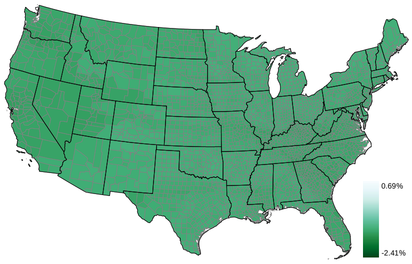
Figure 9: Spatial distribution of pairwise average costs, US-level costs with state-level cost range



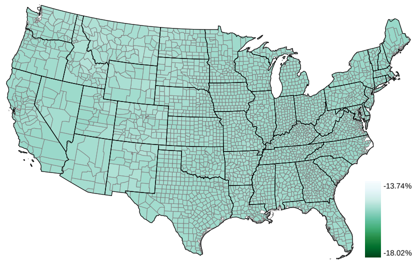
(a) US-level costs - 1955-2010



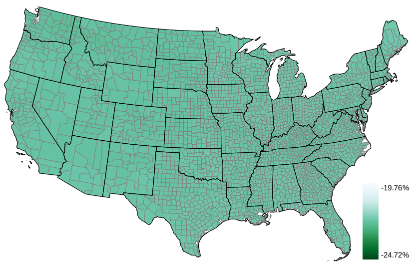
(b) US-level costs - 1960-1970



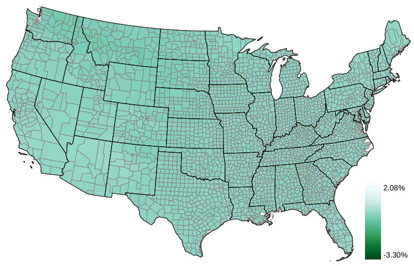
(c) US-level costs - 1970-1980



(d) US-level costs - 1980-1990



(e) US-level costs - 1990-2000



(f) US-level costs - 2000-2010