HYSTERESIS & URBAN RAIL

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ABSTRACT

Cities are endowed with and accumulate natural and constructed assets based on their unique histories, which in turn define the choice set of the present. But, common practice is that current behavior can be described without reference to past circumstances. This work departs from that practice by examining the effects of historical urban rail on current residential location and travel behavior, from the era of horsecars and streetcars to the present in Boston. It uses aggregate spatial data, with controls for possible endogeneity over these long time frames to explore the hysteretical effects of past access to rail—the extent to which the urban system retains the impacts of rail even when it no longer exists.

Current density and travel behavior are measurably influenced by past access to rail. These findings are robust to a series of alternate causal, functional, and spatial specifications. The built environment and demographic patterns are found to be the strongest mechanisms for these persistent effects. Past access to rail has shaped the city, and that shape has, in turn, affected travel behavior. For density and auto ownership there is an additional measurable effect of past access unexplained by the built environment or demographic patterns. This legacy is plausibly explained by cultural effects—mnemonics—due to personal history or behavioral norms.

This research shows that past rail access continues to reverberate in current residential location and travel behavior. These findings of quasi-irreversability add to an understanding of the long-term impacts of rail infrastructure, and imply a need to consider how policy decisions will influence the city's future choice set.

Keywords: Planning, history, urban rail, travel behavior, built environment

1 INTRODUCTION

> It is a fact not unobserved upon that the current state of cities can be traced back to their patterns when growing. —S. Marshall [2005]

Cities are composed of long-lived capital—buildings, roads, and rail among them—and multiple actors with many intentions [Altshuler, 1965]. Inertial forces based on the actual and desired conditions of the surrounding built environment (BE), and the socioeconomic characteristics of an area's residents and businesses, build up friction to change. The accretion of events—the intentions and accidents of history—determine the choice set of the present.

This work puts forth the hypothesis that urban change is hysteretic. It is not possible to understand the direction of the present without knowing the history of the system. Instead, urban systems have hysteretic properties similar to iron. When iron ore is brought into contact with a magnetic field it retains some of the magnetization after the magnetic field has been removed. The shape of the city—its density, its urban form, and way people move about it—retain the imprints of the historical processes that caused and continued to influence the evolution of the city form.

One such historical process is the evolution of urban rail from single cars pulled by horses, to those powered by electricity, and eventually multi-car trains running on elevated, surface, and underground tracks. To test whether urban futures are conditioned by past exposure to urban rail, this work examines the impacts of proximity to horsecars, streetcars, elevateds, and subways on residential density[i] and travel behavior in one city—Boston—over an extended time period—from 1865 to the present. The overarching hypothesis is that urban rail has permanent direct and indirect effects on the geography of density and behavior over exceptionally long time frames, and that these effects outlast the urban rail itself—they are persistent and hysteretic.

Transportation planning analysis falls mostly into two categories: (1) ahistorical quantitative work where the current (future) system state is determined by descriptors of the present (future), without knowledge of the past. (2) Historical qualitative inspiration and lessons extracted from the unique history of a place often used to motivate alternate visions of the future. This paper attempts to find a third way by demonstrating that responses to past urban rail are systematic—that there is a measurable effect of the history of urban rail on present circumstances.

The analysis in this paper is restricted to one city—Boston. In Boston, some routes have been in continuous operation from the time the cars were pulled by horses. Others have been replaced by subways, by elevateds, or by buses. Still others have been abandoned altogether.[ii] This distinctive pattern creates fertile ground for disentangling the effects of this infrastructure on present day patterns. While the specifics of Boston's history are unique, the pattern of gradual and selective replacement of urban rail was replicated in cities across the nation.

The remainder of this article is organized as follows: section 2 reviews the literature; section 3 discusses the plausible mechanisms for past rail's effect on current patterns; section 4 describes the methods and data used to arrive at the findings in section 5; and, finally, section 6 concludes with a summary, implications for planning, and extensions for future research.

2 LITERATURE

Past work on the quantitative historical impacts of transportation networks have focused on (a) the accumulation period of the network, rather than the deterioration, and/or (b) a single mode. The literature reviewed here is on rail networks, but the road network literature is broadly similar. For example, Lichter and Fuguitt [1980] find evidence in both directions in their study of growth and the US Interstate system between 1950 and 1975.

Examining the growth of intracity rail networks and density, Xie and Levinson [2010] use a Granger causal structure with a 5-year lag and a residential parcel data set to find that streetcar development preceded density within 800 meters of a streetcar line in Minneapolis. King [2011] uses a similar method for New York City, and finds that commercial density preceded subways, but that subways did not precede residential or commercial development. Levinson [2008a] finds that population growth has decoupled from station development over time in London. In a companion piece, Levinson [2008b] finds that rail and population density are mutually reinforcing outside the city center, but that rail density preceded population density within the city center. The mixed results above indicate that restricting study to one subset of a mode is likely to result in different findings in each metropolitan area studied, as a result of the historical uniqueness of development patterns and technology penetration.

Baum-Snow and Kahn [2000, 2005] and Glaeser et al. [2008] examine the influence of transit system expansion on adjacent areas in the United States from 1970 to 2000 using a census tract based model with fixed tract effects and demographic controls. Notably, they find that (a) places that received transit between 1970 and 2000 are between the density of those that do not receive new transit, and those that already had it [Baum-Snow and Kahn, 2005]. (b) Moving from 3km to 1km from transit increases transit usage by 1.42 percentage points [Baum-Snow and Kahn, 2005]. (c) New transit lines reduced the decline in transit mode share near the CBD, and increased ridership versus a decline farther than 10km from the city [Baum-Snow and Kahn, 2005]. Within Boston, Baum-Snow and Kahn find that new rail affects mode share outside 10km of the CBD in aggregate, but not within 10km.

The explicit assumption in much of this work is that there is not a lag adjustment to rail. Baum-Snow and Kahn [2005] test and find that there is not a temporal lag of more than a decade in adjustment of transit mode share to new rail construction in the US from 1970 to 2000, with a very few exceptions (including Boston). But, in all of the cases studied, the focus has been on areas where rail did not exist previously, and now does. In this situation the treatment continues, and the control is all those places that neither formerly had rail, nor received new rail. This is only a subset of the places whose rail access has changed since the development of streetcars.

The evolutionary economic geography [e.g. Boschma and Frenken, 2011] and path dependence [e.g. David, 2005] literatures hypothesize that the quasi-irreversability of the BE strongly impacts future paths for neighborhoods and cities [Martin and Sunley, 2006, Bertolini, 2007]. Because of the probabilistic paths that it foments, deleterious policy cannot be erased instantaneously, if at all—its accumulated effects persist. “Once a city places a road or enacts a set of zoning rules that destroy a small neighborhood retail base, tearing up the road or removing the zoning rules will not lure the business back." [Woodlief, 1998] Empirical evidence either for or against this notion is scant.

The co-development of rail and land use in the past clearly shaped cities and the current transportation network, but the degree to which the past continues to influence travel behavior is unexamined. The remainder of this paper attempts to begin filling this gap—the quantitative effects of rail networks on population density and travel behavior—using the insight that lags in adjustment, whether temporary or permanent, are likely to exist.

3 MECHANISMS

In the typical model, the present is assumed to be at equilibrium based on the assets that now exist—transportation, employment, retail, housing location, etc. The past created the conditions for the present, but has no direct effect on present behavior. This paper hypothesizes that there are legacies from past to present that are not explained solely by a description of current conditions. In Figure 1[iii], past rail influences current density, auto ownership and mode share through (A) the placement of current rail, (B and C) the road network and housing characteristics of the past, and that which persists to the present, and (D) preferences and constraints imposed by economic circumstances and lifecycle as embodied in demographic patterns. Past access to rail can also (E) affect current behavior via culture—heuristics that simplify complex decision making [Nunn, 2012]. Exogenous factors may also influence both the mechanisms and the effects.

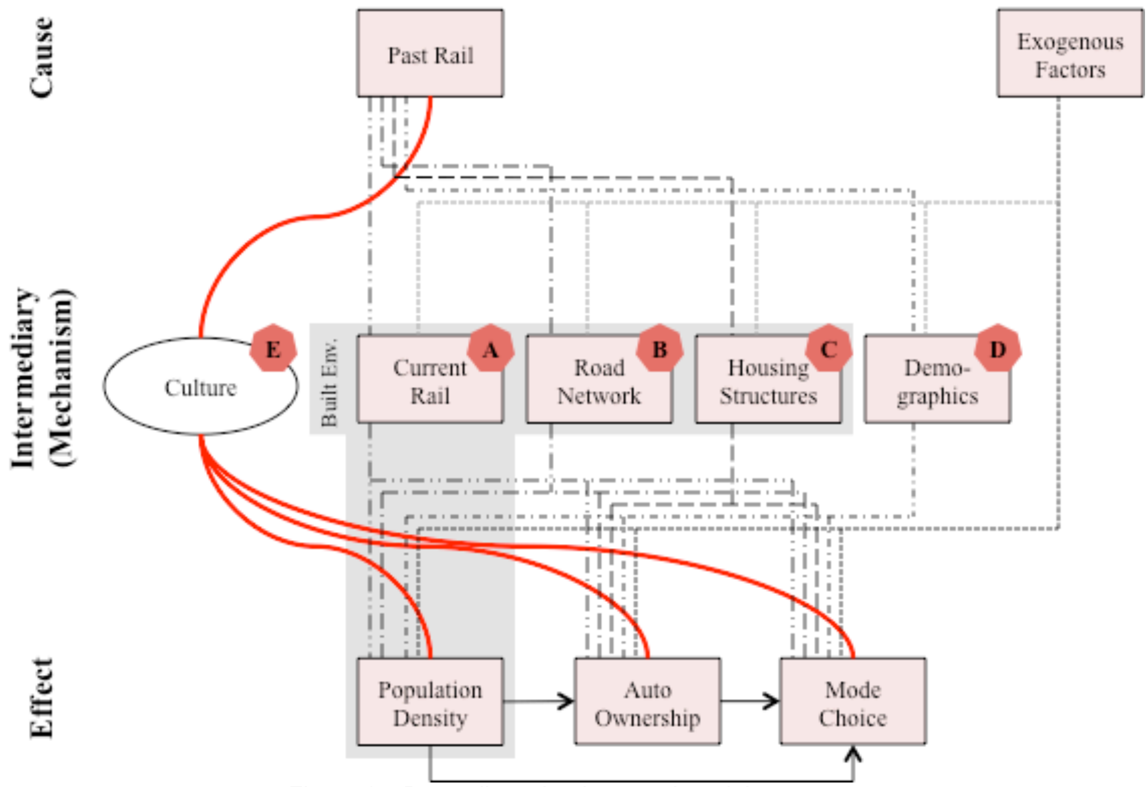

Figure 1 – Past rail mechanisms and model structure

The mechanism behind (A) is that cumulative causation (positive feedback cycles), direct and indirect cost savings, and inertial forces mean that it is easier to replicate network design as new transportation technologies emerge than it is to create networks anew. The private investment—long-lived residential, industrial, and commercial buildings—around transportation infrastructure is an order of magnitude greater than the infrastructure itself [Kothari, 2007]. Structures are rebuilt (in theory, at least) when the increase in value for the developer exceeds the costs of new construction [Wheaton, 1982]. As neighborhoods age, buildings grow more diverse through infill, and there is systematic variation between and among land uses in capitalizing the value of access [Landis et al., 1995]. Waves of reconstruction are therefore increasingly unlikely. The diversity of use, size, and design means that there are always some buildings whose use value precludes redevelopment. The coordination and compensation problem between landowners and government is similarly steep.

On (B and C), past rail plausibly influences current behavior because it uniquely shapes the network and housing characteristics of the BE, or because it puts in place forces which determine those portions of the BE that persist into the present. Zoning and neighborhood pressure mean that newly constructed elements of the BE more closely resemble the past BE. The effect of the BE on behavior is partially physical—it changes attributes of the choice—and may also be partially cultural—it changes weighting of the attributes. For example, a denser street grid might make walking more pleasurable or less costly because of more, and more direct, walking routes to a given point. Living near other people who walk might also change one's attitudes toward walking. A walk with the same attributes is seen as more pleasurable.

Under this mechanism, the portions of the BE that influence the utility or the cultural attributes of the choice environment bear more resemblance to the BE associated with the past. For example, a BE shaped during the streetcar era may have shorter blocks, less room for parking, narrower streets, more integrated storefronts, and so on associated with residential location and travel behavior of the past. The signals of the BE both change current behavior so that it more closely resembles the walking and transit city at initial construction, and attract people who have a preference for a lifestyle associated with that behavior.

The self-selection described above—where the characteristics of the BE determine residential choice, and travel behavior is pre-determined—is plausibly a product of past rail's influence on demographic patterns (D). Demographics, as proxies for roles and responsibilities associated with lifecycle stages [Chapin, 1974], as well as partial proxies for preferences, can influence travel behavior patterns because of the desires and constraints imposed by roles and preferences. If past rail is associated with unique demographic patterns—for example, poorer people who can less afford automobiles or rich people who act coherent with environmental values—it may similarly influence travel behavior via the demographic mechanism as a contextual effect [Goetzke and Weinberger, 2012].

On (E), cultural effects may be the result of historical travel behavior choices in places once proximate to rail. Above and beyond the travel-utility-modifying characteristics of the BE, culture can affect behavior because the built environment acts as a mnemonic device that reminds people of their own, or their family's past choices [Rapoport, 1982, 1994]. The built environment unique to—or highly correlated with—past access to rail may be a signal that recalls preferences based on past experiences with the BE and travel, or observations of people who had similar roles and their behavior. Exposure to the patterns of the historical BE concurrent to its use influence perceptions and attitudes toward the portion of the BE that persists into the present. In this way, travel behavior may be, to some degree, habitual across generations—the entire choice set is not examined by each generation, except in relationship to past choices by prior generations.

Culture can also be the product of perceptions of behavior control that affect the weights of existing attributes of the travel behavior choice [e.g. Karash et al., 2008, Ajzen, 1991]. If people are influenced in mode choice or auto ownership by their neighbors, because out-migration takes place gradually, places with higher transit usage in the past will continue to have higher transit usage long after the adjacent urban rail no longer exists. This is an example of what Goetzke and Weinberger [2012] term endogenous effects.

4 METHODS

This section provides an overview of the structure of the analysis. Data is collected from disparate historical sources, and analyzed at the census tract level. Residential density, auto ownership, and auto mode share are modeled as a function of past and present rail access, characteristics of the BE including road network structure and housing, and demographic patterns as in Figure 1. The measures used for these are described, the formal structure of the models presented, and methods for reducing the influence of spatial autocorrelation, alternate causal paths, and omitted variables discussed

4.1 Data

Analysis of how past rail access affects current location and travel behavior requires knitting together sparse historical sources on infrastructure location and relatively disaggregate population data with current socioeconomic data. Four periods of analysis have been selected, corresponding to landmarks in infrastructure development and data availability: 1865 and horsecars, 1925 and streetcars, 1960 and the modern rail system, and the most recent year for which detailed data at the tract level is available, 2000.

The vector files describing infrastructure location are drawn from the Chase Map of 1865 [Chase, 2006], and for the streetcar era from the Mather Boston Elevated Railway map of 1925 [Mather, 1925]. These digital maps are georeferenced using ArcGIS 10 to provide a background on which to trace the rail vectors. Because these maps were often more figurative than literal, additional map and textual sources—in addition to common sense and the current rail alignment—are used to recreate the paths of past rail. Rail infrastructure for 2000 is reconstructed from year 2010 files provided by the Central Transportation Planning Staff [Massachusetts Office of Geographic Information and Central Transportation Planning Staff, 2007]. Similarly, the rail system from 1960 is recreated by subtraction of routes that no longer run, and addition of past alignments by reference to past figurative system maps, and assorted textual records.[iv] US census data provides reliable population data from 1960 onwards at the tract level [GeoLytics, Inc., 2009, GeoLytics, Inc. et al., 2003], with data on auto ownership restricted to 1980 and later. Information on historic places are geocoded from Massachusetts Cultural Resources Information System [Massachusetts Historical Commission, 2011] and on municipal location in 1860 traced from maps of the era.

4.2 Measures

A simple measure of urban rail access—proximity within ½ mile—eliminates possible problems with endogeneity of opportunities that more sophisticated measures use. This matches well with the specificity of tract level data. Findings are robust to the specification of threshold distance at ¼ and 1 mile.

Including indicators of network structure controls for the hypothesis that the effect of past access to urban rail on current density is due to the portion of the built environment that is independent from the housing built concurrent to that rail. The indicators used are connectivity (streets per intersection), and local and non-local street density (streets per square mile). The first two are associated with smaller blocks, while the latter is associated with increased regional accessibility, but also invasive road architecture, and disamenity from noise and pollution.

Housing characteristics control for the size and quality of housing component of the BE. More rooms per housing unit, all else equal, is expected to be higher quality housing. On the other hand, the proportion of rental units under $300 per month indicates lower quality. Finally, the proportion of 1-family and 2-family homes is a proxy for parking availability. If the descriptors of the BE are imperfect, past rail access may also be a proxy for the omitted characteristics of the BE unique to past rail that influence behavior—for example, parking availability.

Indicators of lifecycle and socioeconomic status are used as demographic indicators. This paper uses both the average income in the tract, and the proportion of the population below the poverty line, which implies a kink in the effect of income. The proportion of the population that is white uses race as an indicator of pre-existing preferences for automobility. Lastly, the proportion of the population over the age of 65 is indicative of differential need for and use of the auto.

4.3 Model

In this work, mechanisms A, B, C, and D are explicitly proxied, as are exogenous measures, as shown in Equations 1, 2, and 3. The grouped cultural (legacy) effects are embodied in the parameter estimates of past rail's effect on current behavior. They are the patterned remainder associated with past rail access, rather than directly measured. If the effect of past rail placement on current placement is the main mechanism, then there will be no systematic relationship between past rail access and current behavior. Inclusion of demographic and BE controls circumscribes the legacy effects.

$$(1)\quad D^{i}_{2000} \quad f\left[N^{i}_{2000}, E^{i}, R^{i}_{2000}, R^{i}_{1960}, R^{i}_{1925}, R^{i}_{1965}\right] + \varepsilon$$

$$(2)\quad A^{i}_{2000} \quad f\left[N^{i}_{2000}, H^{i}_{1980}, D^{i}_{1980}, P^{i}_{1990}, E^{i}, R^{i}_{2000}, R^{i}_{1960}, R^{i}_{1925}, R^{i}_{1965}\right] + \varepsilon$$

$$(3)\quad M^{i}_{2000} \quad f\left[N^{i}_{2000}, H^{i}_{1980}, D^{i}_{1980}, P^{i}_{1990}, A^{i}_{1990}, E^{i}, R^{i}_{2000}, R^{i}_{1960}, R^{i}_{1925}, R^{i}_{1965}\right] + \varepsilon$$

D: Density; ***A:*** Auto Ownership; ***M:*** Mode Choice; ***N:*** Network structure of BE; ***H:*** Housing characteristics of BE; ***R:*** Urban rail access; ***P:*** Demographic characteristics; ***E:*** Exogenous forces

The remainder of this section focuses on 5 methodological challenges: (1) endogeneity based on temporal simultaneity, (2) spatial auto-correlation, (3) alternate causal paths, (4) omitted causal variables, and (5) residential self-selection.

Endogeneity based on codetermination of travel behavior and demographic or BE patterns is a concern, as are measurement issues based on an omitted force that determines population density in coordination with demographic and housing characteristics. To address the former, built environment and demographic indicators are measured with a lag where possible. To address the latter, the model of density (Equation 1) omits controls for demographics and structures [e.g. Brueckner and Rosenthal, 2009]. While this risks omitting relevant changes in these indicators over those two decades, findings are relatively robust to this specification.[v] Data in space may violate the assumption of Ordinary Least Squares regression (OLS) that error terms are uncorrelated. A spatial weight matrix describing this correlation can be used to reduce both the bias and inefficiency that results from this OLS violation [Anselin and Bera, 1998]. This paper uses a spatial error model to correct for spatial auto-correlation due to improper description of facets of the area—for example, the boundaries used are not good correlates for the homogeneity of the dependent variable. In keeping with the choice of spatial error and localized effects, an adjacency weight matrix is specified. Robustness checks for alternate spatial specifications are also performed.

There are also concerns that omitted exogenous factors cause both the past rail and the subsequent behavior. The primary alternate causal paths are that (a) rail connected primal places, and it is this primacy, not the rail that is the causal path and (b) places built at the turn of the 20th century, regardless of whether streetcars ran there, are denser and have different behavioral patterns. To address the former, this paper uses two indicators of primacy. The first is whether the area was part of a municipality in 1860, and thus presumably more important. The second is the number of historical places pre-1860 in the tract. The second measure may also indicate historic preservation, which would have confounding effects, but would still provide an appropriate control for differentiating the effects of primacy from that of subsequent rail. To address alternate path b, the proportion of housing that was built prior to 1940 is used, lagged to 1960 values to eliminate the confounding effect of urban renewal. In combination, these are the exogenous factors referenced in Figure 1 and in Equations 1, 2, and 3.

There are likely to be omitted variables over time that effect the density or travel behavior of an area, but are not included with the controls above. Inasmuch as these are due to characteristics of the town, the use of municipal fixed effects [e.g. Sieg et al., 2002, Ihlanfeldt, 2007, Glaeser and Ward, 2009, Zabel and Dalton, 2011, for zoning and density] will reduce the impact of this omission. Municipal fixed effects can control for overall levels of permitted density due to zoning, natural resource desirability, and other relatively stable endowments, including the mix of city services, amenities and tax rates.

Additionally, because individual residential choice is not modelled explicitly within the models of auto ownership and mode choice, the degree to which self-selection is the causal influence is unknown. The inclusion of demographic indicators helps reduce, but does not eliminate, the hypothetical impact of self-selection [Brownstone and Golob, 2009, Cao et al., 2006, Mokhtarian and Cao, 2008, Boarnet, 2011].

5 FINDINGS

This section presents selected findings for population density, auto ownership, and mode choice. Additional robustness checks have been run throughout for alternate causal explanations, functional definitions, spatial specifications, and interaction effects, but are not presented here. Given the building boom concurrent to the age of ubiquitous streetcars, it is expected that access to rail during the streetcar era—proxied here as the urban rail network in 1925—will have the strongest effect of all past rail networks on current density, auto ownership, and auto mode share.

5.1 Density

The series of models in Table 1 support the finding that past access to rail has a significant effect on subsequent density. They point to the built environment as the strongest mechanism, but find a legacy effect beyond the BE.

The monocentric model implies a specific functional form—negative exponential—that results from regressing the natural logarithm of density on distance from the CBD. Access to rail in each period is an additional binary regressor. If the coefficient on rail proximity in past periods is significant and positive, the associated density gradient is taller.

Table I – Comparison of density gradient model controls

	(1)	(2)	(3)	(4)	(5)
Intercept	8.84 ***	7.87 ***	8.27 ***	7.73 ***	5.38 ***
Dist. To CBD	-0.08 ***	-0.05 *	-0.04 .	-0.03 .	0.01
Rail 1865	0.28 **	0.24 **	0.22 **	0.20 *	0.16 **
Rail 1925	0.86 ***	0.87 ***	0.83 ***	0.73 ***	0.36 **
Rail 1960	0.19	0.25 *	0.23 .	0.26 *	0.18 *
Rail 2000	0.13	0.10	0.10	0.05	0.08
Bus 2010	0.47 ***	0.44 ***	0.46 ***	0.43 ***	0.24 ***
PRIMACY					
Historic places			-0.06 ***	-0.08 ***	-0.06 ***
Not in city, 1860			-0.39 **	-0.38 ***	-0.04
Pre-1940 HU				0.98 ***	0.49 ***
NETWORK STRUCTURE					
Connectivity					0.79 ***
Local streets					0.05 ***
Non-local streets					-0.02 *
λ	0.65 ***	0.54 ***	0.57 ***	0.46 ***	0.33 ***
Municipal FE	N	Y	Y	Y	Y
AIC	1032.0	1039.0	1022.9	990.2	636.2
adj. r^2 (OLS)	.668	.744	.749	.775	.881

n=590 tracts, dependent: log population density 2000. Spatial error (λ) model includes municipal fixed effects. Pre-1940 housing units lagged to 1960. Rail access is based on a binary indicator of whether the tract centroid is within .5 miles of the network. Bus controls only for the current bus network, and is limited to areas where streetcars did not run. Local and non-local streets measured in road length miles per square mile. Historic places truncated at 4.
'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

In Model 1, past proximity to the horsecar and streetcar are both significant, but streetcar access has a much stronger effect, as expected. Bus access beyond the streetcar extent—which is likely a proxy for prior era's bus access as well—has a stronger effect on density than horsecar access. The inclusion of municipal fixed effects in Model 2 also indicate some role for rail in 1960, but no role for current rail. Municipal fixed effects imply that the amenities of an area strongly influence the residential location decision. In model 3, past urban rail's effects on modern density are not significantly changed by the inclusion of indicators of primal, historic, preserved places—they are independent.

Model 4 adds a control for density following the age of the BE. This reduces the impact of past proximity to horsecars and streetcars. Model 5 adds network controls as well, which reduce the magnitude and strength of the parameter estimates on past access to rail significantly, but also reduce other parameter estimates as well. Notably, places farther from the CBD and/or outside city boundaries in 1860 are no longer significant. Because the parameter estimate on rail in 1925 is reduced in magnitude this model suggests that the street network is the main mechanism of past rail's effect on subsequent density. The significance of I in all of the models suggests that the spatial model is useful in reducing the impact of spatial autocorrelation, and the high r^2 indicates that omission is less likely to be problematic.

While multicollinearity is a concern, the full set of controls has a VIF below 4. Streetcar proximity has a VIF of 6.97, which is indicative of multicollinearity that is neither trivial nor severe. However, regression coefficients are stable excluding this indicator. Thus, the apparent degree of multicollinearity should not influence inference for Boston, but may do so for cities that do not share this same data pattern.

5.2 Auto ownership

In the models in Table 2, past access to urban rail is associated with lower levels of auto ownership. The high r^2 suggests that the models are relatively complete in explaining the variability in current levels of auto ownership. Of the time periods tested, only access to 1925-era rail has a significant effect on auto ownership, with an effect size approximately equal to current rail. Access to streetcars captures a different mechanism than current rail access. This effect persists after controlling for demographic variation, current access, and characteristics of the built environment. The inclusion of these additional indicators does not significantly reduce the measured effect of access to current rail on auto ownership.

Table II – Comparison of auto ownership model controls

	(1)	(2)	(3)	(4)
Demographic Controls	N	Y	Y	Y
Density Control	N	N	Y	Y
Other BE Controls	N	N	N	Y
Dist. to CBD	0.04 ***	0.02 ***	0.02 ***	0.01 ***
Rail 1865	-0.05	-0.01	-0.01	0.01
Rail 1925	-0.19 ***	-0.12 ***	-0.11 **	-0.08 **
Rail 1960	-0.05	-0.01	-0.01	0.03
Rail 2000	-0.11 **	-0.12 ***	-0.12 ***	-0.07 ***
Bus 2010	-0.12 ***	-0.07 **	-0.07 **	-0.04 *

	(1)	(2)	(3)	(4)
Demographic Controls	N	Y	Y	Y
Density Control	N	N	Y	Y
Other BE Controls	N	N	N	Y
Density			-0.03 ***	-0.01 *
λ	0.77 ***	0.68 ***	0.65 ***	0.36 ***
AIC	-201.3	-528.6	-537.2	-877.9
adj. r^2 (OLS)	0.661	0.847	0.859	0.936

n=590 tracts, dependent: vehicles per household, 2000. Spatial error (λ) model. Rail access is based on a binary indicator of whether the tract centroid is within .5 miles of the network. Bus controls only for the current bus network, and is limited to areas where streetcars did not run. Demographic controls are average income in the tract, the proportion of the population below the poverty line, the proportion of the population that is white, and the proportion of the population over the age of 65. Density is population in 10,000s per square mile, lagged to 1980 value. Other BE controls are connectivity (streets per intersection), local and non-local street density (streets per square mile), rooms per housing unit, the proportion of rental units under $300 per month, and the proportion of 1-family and 2-family homes.
'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

The addition of demographic controls in Model 2 in Table 2 reduces the strength of the influence of past access to streetcars, and improves overall model fit. The inference is therefore that approximately ⅓ of the influence of past access to streetcars on current auto ownership levels is plausibly the result of its effect on residential sorting.

Model 3 in Table 2 adds a single built environment indicator of BE—density. As expected, density is negatively related to auto ownership. Adding density to the model reduces the effect of streetcar access by 10%, and has no effect on current rail access. Thus, density is neither a substitute for the effect of current rail access on auto ownership, nor is it a strong mechanism for the effect of past access to streetcars on current auto ownership.

The BE descriptors beyond density in Model 4 in Table 2 improve model specification, and reduce the impact of both rail access in 1925 and density. The attributes of the BE collectively used in Model 4 substitute for the direct effects of density on auto ownership.[vi] Given these other indicators of the BE, density has a smaller parameter estimate. Thus, density's effect on auto ownership are for the most part a function of parking availability, street connectivity, regional accessibility, and housing quality.

5.3 Auto mode share

With and without controls in Table 3—for the demographic makeup of the tract, the local built environment, and auto ownership levels—the finding remains the same: while current rail network access decreases auto mode share, current proximity to buses and past proximity to streetcars do not significantly affect journey-to-work mode choice in 2000. Because Rail 1865 is not robust to spatial specification, it is in line with this pattern.

Table III – Comparison of mode share model controls

	(1)	(2)	(3)	(4)
Demographic	No	Yes	Yes	Yes
Built Environ.	No	No	Yes	Yes
Auto owner.	No	No	No	Yes
Rail 1865	-0.031 **	-0.031 **	-0.027 **	-0.024 **
Rail 1925	-0.003	-0.014	0.001	-0.003
Rail 1960	-0.037 *	-0.026 *	-0.019	-0.013
Rail 2000	-0.045 ***	-0.045 ***	-0.044 ***	-0.046 ***
Bus 2010	0.002	-0.004	0.012	0.01
% No cars				-0.337 ***
λ	.819 ***	.783 ***	.670 ***	.590 ***
AIC	-1415.6	-1609.2	-1692.5	-1742.3
adj. r^2 (OLS)	0.769	0.867	0.903	0.915

n=590 tracts, dependent: auto mode share of journey-to-work trips, 2000. Spatial error (λ) model. Rail access is based on a binary indicator of whether the tract centroid is within .5 miles of the network. Bus controls only for the current bus network, and is limited to areas where streetcars did not run. Demographic controls are average income in the tract, the proportion of the population below the poverty line, the proportion of the population that is white, and the proportion of the population over the age of 65. BE controls are density, connectivity (streets per intersection), local and non-local street density (streets per square mile), rooms per housing unit, the proportion of rental units under $300 per month, and the proportion of 1-family and 2-family homes.
'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Model 4 in Table 3 demonstrates that controlling for auto ownership has little impact on parameter estimates of transport's effect on auto commute mode share. Auto ownership is proxied by the proportion of zero-vehicle households. In sum, there are no effects due to past proximity to rail after basic controls for subsequent rail access.

5.4 Summary

There are three main findings from the models presented above and summarized in Table 4, and the additional robustness checks performed but not presented. (1) Past access to rail has a stronger effect on current density than on auto ownership (larger elasticity estimates in Table 4), but both are significant. The daily choice of modes is not found to be significantly influenced by past access to rail after controlling for current access. (2) Demographic and built environment controls, as well as controls for additional causal mechanisms reduce the measured effect, but do not eliminate it. Even if demographics and the BE are exogenous from past rail (which is unlikely to be the case), past rail measurably influenced subsequent levels of density and auto ownership. (3) The effect of past rail on density and auto ownership are larger than the commensurate effects of the current rail system, but smaller than the current rail system for mode share. Places that were oriented to transit when first developed maintain the signals associated with that orientation over time, just as places built around auto usage put up impediments to retrofitting to transit usage [e.g. Dunham-Jones and Williamson, 2009].

Table IV – Elasticity estimates

	Demo. controls	No	Yes	Yes
	BE controls	No	No	Yes
Density	Prior streetcars	0.355 ***	n/a	0.152 ***
	Current rail	0.025	n/a	0.021
Auto ownership	Prior streetcars	-0.058 ***	-0.040 ***	-0.024 ***
	Current rail	-0.019 ***	-0.021 ***	-0.013 ***
Auto mode share	Prior streetcars	0	-0.01	0
	Current rail	-0.015 ***	-0.015 ***	-0.015 ***

Elasticity estimates based on an arc elasticity of 100% of access at the tract level.
'***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

6 CONCLUSIONS

This research provides quantitative evidence of the effect of infrastructure on residential location and travel behavior over long time periods, and plausible mechanisms to support these empirical findings. The assumption in the literature on travel behavior is that behavior is a function of the current attributes of the person and the environment. The past existence of rail is an indicator both of some omitted characteristic(s) of the BE unique to those places that once had rail and a cultural inheritance, but the mixture of the two is unknown. The identification of a unique effect of past access to rail on density and auto ownership, and the lack of effect on current mode share, provide baseline comparisons. The findings are robust to spatial specification, and to tests for alternate causal hypotheses, including that rail followed primacy, rather than the other way around.

6.1 Implications

The impact of proximity to old streetcar and horsecar routes on current behavior is a curious subject. Historical access, growth patterns, and transportation alternatives cannot be reconstructed. The models in this paper are predicated on the unique historical circumstances of Boston's growth. They are not predictive. The policy implications are indirect. Past urban rail cannot be built anew. So, why does it matter?

Patience. The history of planning practice is a machine that produces lessons—both as visions to repeat and mistakes to avoid. History is also used on its own—it is ennobled and preserved. It is used as the progenitor of existing conditions—from housing to transportation, and urban design. This research suggests that history continues to be reflected in the present, instead of being simply the necessary time that accretes so that we may stand on its shoulders. As such, efforts must be made to understand how the history and present of a place may influence its future, for time frames beyond those on which a typical benefit-cost analysis or urban design charette focuses.

Locating growth. Because new rail infrastructure is a relatively expensive capital project, the debate over whether those dollars should be dedicated to current residents or used to shape future places is well worn. The findings of persistent effects of infrastructure, if true beyond Boston, imply that opportunities to shape the future BE lie in those areas that are not yet built in a relatively irreversible fashion—where density does not yet exist, or where the embodied costs of redevelopment are not too high. Areas nearer central cities that were once, or are currently, industrial centers are one such example that are more likely to have lower costs of redevelopment but be near enough to the center of the city to capitalize on existing agglomerations. Increasing allowable density in these areas is a necessary complement to directing the market to these places when rail is built. In order to ensure that development signals and public investment signals are coherent. It allows market forces to decide when the timing for such changes is appropriate, rather than precluding such changes through regulation. The Hong Kong model [e.g. Zhao et al., 2012] is one such example of an aggressive approach to coherent signals in public and private development

Culture as policy. Culture implies an alternate set of policy interventions beyond infrastructure. Policy can be aimed at influencing culture directly, or as an expected side effect of a physical intervention—for example through street programming, a host of small interventions in the BE through zoning modifications, enforcement, or paint can change behavior, the surrounding BE, and perceptions of the desirability of that behavior. These plausibly produce a positive feedback cycle based on neighbors' reactions that are transmitted over time through culture. Policies can also influence travel behavior through culture incidentally, for example, bicycle and car sharing can modify how people value modes. If travel preferences are a product of exposure, in the long run changes in personal history may be a cultural artifact that changes perceptions of the value offered by the auto, and thus travel behavior and residential location.

6.2 Limitations

Access to past rail as measured is not a perfect proxy for the actual effect of streetcars, neglecting frequency of service, capacity, route access, and ease of transfers among other qualities. To the extent that the proximity measure for rail is not fully descriptive of the value of past rail, it will increase Type I errors. While non-residential developments are clearly an important part of the urban change wrought by rail, they are omitted from study because of issues with data consistency over long time frames, and the differing theoretical basis for firm decisions.

This work focuses on the average treatment effect—the expected value over the population of moving from an area far from to an area proximate to past rail [Mokhtarian and Cao, 2008, Heckman, 2008]. Average treatment over the population is a combination of the treatment effect on the treated and the untreated. If cultural effects exist, then the expected value over the population is not merely the sum of individual effects. But, construction of an alternate population counterfactual is implausible. Thus, the degree to which the effect being measured is actually average treatment on the treated is unknown.

Findings may be subject to selection bias if communities that expect to benefit from the expansion or contraction of rail advocate for their desired outcome and are successful. The degree to which the effects of past proximity to rail on current behavior are in fact caused by that rail is attenuated by the extent to which (a) political power in influencing the decisions to build or destroy that rail was effective and (b) there was foresight as to the effects of the build/destroy decision.

6.3 Future research

Future research can address some of the limitations of this work. Models that treat past development endogenously rather than exogenously would allow examination of feedback effects across eras. Structural models with endogenous residential location could more directly examine the interactions between travel behavior in the past and residential location in the present, which this work can only speculate on. More information on neighborhood characteristics—from retail stores to attractiveness—would allow better models connecting past rail to the BE, and could reduce the influence of omitted characteristics of the BE on findings. Using additional access measures, such as predicted accessibility, may better capture the value of past and present access. A more complete understanding of the effects of past rail would likely result from examination of the interaction between past access to urban rail, firm, and residential location.

Examining other cities would allow examination of growth during different eras, with varied institutional and technological arrangements of their transportation networks. How large a role does growth play? What is the differential effect in timing of streetcars? To what extent do city size, employment centrality, and the accompanying road infrastructure interact with rail to produce persistent effects? Data on urban rail networks over multiple eras and cities would allow a combination of tract and city level effects.
While this paper only scratches the surface of work to be done in this research vein, it is our hope that it establishes the possibilities for demonstrating a systematic relationship between past infrastructure and present behavior.

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[i] Density is used throughout this paper to refer to the aggregate of individual residential location choices.

[ii] For example, the A (Watertown) branch of the Green Line was abandoned and the Orange Line in Charlestown and the South End relocated.

[iii] Not an exhaustive list of factors influencing population density, auto ownership, and mode choice.

[iv] The ne.transportation, misc.transport.urban-transit, and rec.railroad groups are a particularly fruitful source.

[v] In theory, these models cascade, so that predicted density influences auto ownership, which in turn influences mode choice, and thus each predicted value should be used as an instrument for the actual value. This was tested, and actual auto ownership levels have a small effect on mode share using the modeled form (vehicles per worker). The use of temporally lagged behavior to prevent endogeneity presents data availability issues for using this instrument consistently, and thus it is omitted. To the extent that these cascading effects actually exist, their omission in these models will result in finding weaker effects of past rail access on subsequent auto ownership and mode choice than actually exist.

[vi] See Bhat and Guo [2007] for similar findings.