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Operating subsidies and transit efficiency: applying new metrics to old problems

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Abstract

This research revisits the perennial policy concern that operating subsidies hamper transit efficiency. We argue that the relationship between subsidies and efficiency can be better understood at the regional level and propose improved metrics related to transit efficiency. To begin, we focus on the impact of subsidies on transitsheds rather than transit operators to recast subsidy as a per resident metric, and we average vehicle load in the transitshed as our efficiency metric. Comparing these measures, we discover a surprising trend – transit efficiency is strongly and positively correlated with per resident operating subsidy. To explore this relationship further, we decompose per resident subsidy into federal and non-federal components and generate several new measures to improve modeling of transit efficiency at the transitshed level—subsidy revenue ratio, vehicle ratio, and guideway mile ratio (the latter two of which are scaled by "effective" population). We then apply a linear regression with these new measures on four years of data across the fifteen most populous transitsheds in the United States. Results suggest that operating subsidies promote transit efficiency (with federal subsidies being roughly three times as effective as non-federal subsidies) as long as the subsidies do not unduly outpace revenues. Results also suggest that the vehicle ratio is negatively associated with transit efficiency while the guideway mile ratio is positively associated. These findings offer support for operating subsidies that are reasonably offset by revenues and for targeting capital investments towards fixed guideway infrastructure rather than towards expanding fleet size.

Keywords Subsidy · Transit · Efficiency · Regression · Performance metrics

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Introduction

The common practice of subsidizing transit operations raises perennial concerns about the efficiency of public transportation provision in the absence of market discipline. The ample research literature on this topic is difficult to align (and therefore difficult to translate into policy) due to widely varying definitions of subsidies, efficiency, and transit provision. The current research seeks to clarify these concepts (and advance related policy discussions) by reframing them through a proposed set of consistent metrics tied to the same unit of analysis—the metropolitan region.

The typical focus of transit efficiency research is on a single operator rather than a single operating area. This traditional approach fails to reflect the user reality of a transit network supplied by multiple operators, emphasizes modes in isolation rather than in coordination, and divorces transit provision from the population that both enjoys and subsidizes it. Our research recasts the unit of analysis from individual operators to the regional transitshed. We aggregate all transit data to a shared geography and then scale those values by that geography's population. That scaling enables cross-regional comparison.

This approach leads naturally to our proposed metric for characterizing operating subsidies, namely the subsidy per regional resident. This metric clearly shows how much subsidy each resident receives/contributes while making it easy to compare those levels to other areas. The new metric for assessing transit efficiency is similarly grounded in the area-wide focus. The sum of all passenger-miles traveled (*PMT*) across operators in the transitshed is divided by the sum of all vehicle revenue miles (*VRM*) supplied in that same area. That *PMT*/*VRM* ratio is easily understood as the average vehicle load within that geography.

We define transitsheds using the census geography of urbanized areas (UZAs) which "represent densely developed territory, and encompass residential, commercial, and other non-residential urban land uses" (2022) and serve as the basis for the allocation of federal monies for transit (Office of Budget and Policy 2021). We examine the fifteen most populous UZAs based on the 2010 census, shown in Fig. 1. The UZAs are identified by their major city and abbreviated according to airport code (with the exception of Chicago and New York, for which we use the more intuitive codes CHI and NYC, respectively).

Figure 2 shows a scattergram of our scaled subsidy and transit efficiency metrics for these fifteen regions with the regression line superimposed. Surprisingly, given conventional wisdom that subsidies beget inefficiency, the relationship is linear and positive (Pearson's r = 0.87). More subsidy correlates with more efficiency. New York, which boasts the highest efficiency score of 27.4 passengers per vehicle, receives a subsidy of $445 per resident while Phoenix, the region with the lowest load factor of 8.7 passengers per vehicle, only receives a subsidy of $97 per resident. (Regions above the regression line are more efficient than average given their subsidy, while regions below the line, such as Phoenix, are less efficient.) These unexpected findings challenge the common perception that subsidies hamper efficiency.

This paper proposes additional metrics to explore this apparent paradox and better capture the drivers of transit efficiency. The goal of this work is to advance public discussion of transit policy.

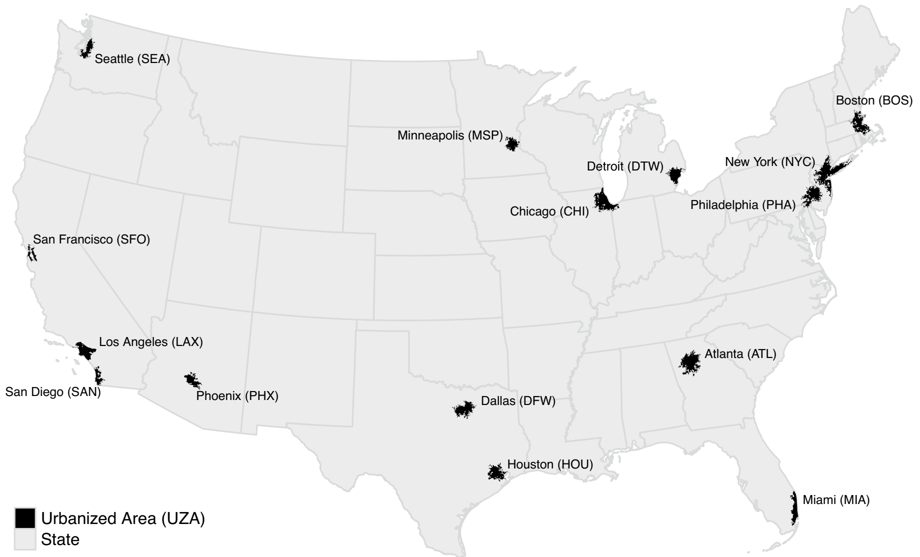

Fig. 1 Map of Studied Urbanized Areas

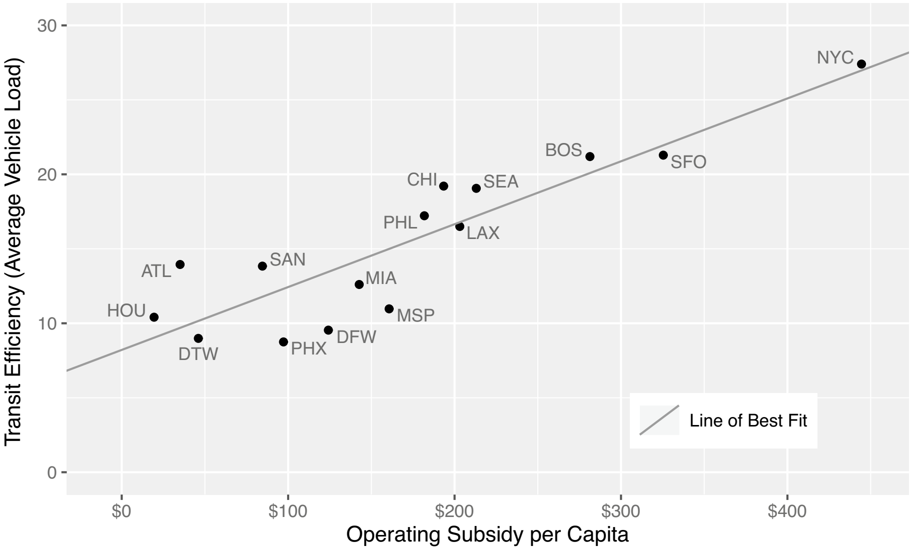

Fig. 2 Scattergram of Operating Subsidy to Transit Efficiency (2016–2019 Average)

Literature review

The Urban Mass Transportation Act of 1964 allocated federal monies to local transit services for the first time in the United States (Smerk 1965). This shift culminated the piecemeal transition of transit agencies across the country from privately run enterprises to publicly subsidized entities. This transition elevated questions regarding operating subsidy and service allocation to the national level. A core concern was whether operational support would reduce transit efficiency.

Efficiency represents the amount of output for a given level of input, often measured as costs per vehicle-mile or hour (Dajani and Gilbert 1978; Fielding et al. 1978; Anderson 1983; Cervero 1984; Karlaftis and McCarthy 1998) or per passenger (Cervero 1984). Several researchers have used non-fiscal measures such as vehicle-miles per employee or per vehicle (Dajani and Gilbert 1978; Fielding et al. 1978; Cervero 1984; Karlaftis and McCarthy 1998) which can be compared without concern about purchasing power differences. Sulek and Lind (2000) use a particularly complicated measure that is the weighted sum of outputs (revenue miles, passenger boardings, miles between collisions) divided by the weighted sum of inputs (labor costs, fuel/material costs, fleet size).

Commonly researchers present output measures unscaled by inputs. These are technically measures of effectiveness not efficiency, such as number of trips (Holmgren 2013), passengers, vehicle-miles (Anderson 1983; Nolan 1996; Sakano et al. 1997; Roy and Yvrande-Billon 2007; Cowie 2009; Obeng 2011; Obeng et al. 2016; Lee and Yeh 2019; Sujakhu and Li 2020; Obeng and Sakano 2020), passenger-miles (Cantos et al. 1999), and revenues (Kang and Kim 2017).

Several studies of subsidies focus on these effectiveness measures rather than efficiency ones. A common finding is that operational subsidies result in more service coverage (Obeng 2011; Obeng et al. 2016) but lower service frequencies (Anderson 1983; Sakano et al. 1997), which can have counteracting impacts on ridership (van Reeven and Karamychev 2016). Subsidies often lead to lower fares (Anderson 1983) which can encourage ridership (Fitzová et al. 2018), but subsidies as a share of revenues are associated with reduced ridership (Cantos et al. 1999; Fitzová et al. 2018). Brons (2005) found that studies using service outputs had lower effectiveness impacts than those that measured revenues.

The few studies that focus on efficiency measures find a negative relation to subsidy. Increased operating subsidies are associated with increased costs and reduced labor productivity (Cervero 1984; Pickrell 1985; Karlaftis and McCarthy 1997) while reduced operating subsidies are associated with the reduced costs and increased labor productivity (Cowie 2009). Obeng and Azam (1995) calculated the cost elasticity of transit subsidies as 1.7 suggesting costs are quite sensitive to subsidy.

Several authors note that the governmental source of subsidy has differential impacts on efficiency. A study of seventeen transit properties in California, accounting for 98% of all transit trips made in the state in 1980, found that both local and federal subsidies (measured as the share of operating funds) reduced labor efficiency (measured as vehicle miles per employee) with the effect of local subsidies being about twice as large as that from federal subsidies (Cervero 1984). A study of medium-sized bus transit agencies across the United States found that the share of operating funds from state subsidies reduced effectiveness, measured as vehicle miles, while the share that came from federal subsidies increased it (Nolan 1996). A study of eighteen transit systems of different sizes in Indiana found slightly differing results. There local subsidies had a positive relationship with efficiency for large systems (while the impacts of federal and state subsidies were not statistically significant) but federal and state subsidies had a positive relationship with efficiency for small systems (while the impacts of local subsidies were not statistically significant). The authors concluded that "there does not appear to be a general relationship between operating subsidies and public transit performance" (Karlaftis and McCarthy 1998).

These studies focus on transit agencies as the unit of analysis using a wide array of measures of efficiency (many of which are actually measures of effectiveness). Furthermore, many of the efficiency measures are limited in their cross-sectional and longitudinal relevance as they are presented in nominal rather than real dollar values.

Our research builds on these efforts while introducing several innovations. First, we reframe the unit of analysis to the regional transitshed rather than a single agency. Second, we select a true efficiency measure (i.e., one that scales outputs by inputs) that is divorced from local currency but tied to a core policy concern (i.e., average vehicle load) to facilitate comparison. Third, we propose other metrics tied to regional population and population concentration to further understand efficiency. Finally, when we do employ monetary values (always important for public policy decisions) in our metrics, we ensure that they are converted into real and not nominal terms. This adjustment ensures that dollars mentioned can be compared consistently over time but does not account for regional differences in purchasing power with those dollars.

Methodology

This study uses publicly available data from the National Transit Database (NTD) and the U.S. Census Bureau to generate advanced metrics for understanding transit efficiency (for both rail and bus services) across an urbanized area. This research is particularly interested in the role of operating subsidies on average vehicle loads (our metric of transit efficiency). This research is also focused on developing better measures for characterizing urban environments supportive of transit. A linear regression model is estimated using four years of data from the fifteen most populous urbanized areas in the United States to quantify the influence of these policy variables on transit efficiency.

Data collection

The National Transit Database (NTD) is a public resource managed by the U.S. Department of Transportation that consolidates required reporting information from transit agencies receiving federal funds. While the specific NTD reporting requirements vary depending on the categorization of the transit agency as full, reduced, or rural reporters, the resulting data are available by agency, mode, and time period to "provide insight into the effectiveness and productivity of a transit agency" (Office of Budget and Policy 2021).

This research relies on annual data beginning in 2016, when the NTD developed a new format for reporting operating subsidies, through 2019, the last full year collected prior to the ridership shock of the coronavirus pandemic that began in 2020. Data are collected from every full reporting transit agency that identifies one of the fifteen most populous UZAs, based on the 2010 Decennial Census (U.S. Department of Transportation 2022), as its primary service area (Barrett 2022). Agencies are considered full reporters once they operate thirty buses or maintain either fixed guideway or high-intensity busway services (Office of Budget and Policy 2021). Transit service data collected for all fixed-route bus or rail modes (with the associated NTD abbreviations) include the number of transit vehicles available for maximum service (*VAMS*), vehicle-revenue miles (*VRM*), and passenger-miles traveled (*PMT*). Income data at the agency level are collected for operating subsidy (broken down by source as federal, state, or local) and directly generated revenue, such as fares, advertising, and rents (Office of Budget and Policy 2017). To facilitate comparison, these financial data are adjusted to 2019 dollars following the procedure recommended by the U.S. Department of Transportation (2021) for benefit–cost analyses. All of these agency-level data are aggregated to the UZA level. Finally, the NTD provides some data points at the UZA level directly. This research collects such information for population, area in square miles, and fixed-guideway directional route miles (*FGDRM*). *FGDRM* can refer to busways as well as rail.

Table 1 presents these aggregated data by UZA, ordered from most to least populous. A third of the UZAs span multiple states and a fifth span three or more states as denoted by their U.S. Census Bureau naming convention. The number of primary transit agencies range widely from 72 in Los Angeles and 44 in New York to 5 in Detroit and 3 in San Diego; however, the range of full reporters is substantially narrower with all but Los Angeles and New York having fewer than 10. Similarly, the UZAs are home to rather different numbers of residents with 18 million in New York and 12 million in Los Angeles to less than 3 million in both San Diego and Minneapolis. The New York UZA is exceptionally large at 3,450 square miles. The next largest UZAs, Atlanta (2,645 sq mi) and Chicago (2,443 sq mi), are roughly a thousand square miles smaller. With the exception of the smallest two UZAs, San Diego (732 sq mi) and San Francisco (524 sq mi), all the remaining UZAs cover between one and two thousand square miles. This variation in size and population results in a range of gross densities from a high of 6,999 residents/square mile in Los Angeles to a low of 1,707 in Atlanta.

The last three columns in Table 1 average values from 2016 through 2019 to provide insight on the transit systems that operate within each UZA collectively. Transit agencies in New York operate roughly four times the number of vehicles (20,145) and twice the length of the fixed guideway network (2,577 miles) as Chicago, the next largest system (5,417 vehicles and 1,284 fixed guideway miles). All the remaining systems have less than one thousand miles of fixed guideway, with several systems, namely Atlanta (99 miles), Houston (43 miles), and Detroit (6 miles), operating fewer than one hundred miles of guideway. Finally, total operating subsidies range from more than \$8 billion in New York to less than \$100 million in Houston.

Metric development

A major contribution of this research is the development of new metrics to better describe both transit service and the environment that supports transit. A goal of this effort is to build on the measures collected by the NTD the same way that the sabermetric movement built on the statistics traditionally gathered by Major League Baseball (MLB) – i.e., to more accurately represent what matters. Sabermetrics guides decisions to win more games; our “subwaymetrics” guide decisions to improve transit efficiency. We can loosely categorize our new metrics as pertaining to efficiency, funding, or infrastructure. The formulas for the new metrics are presented in Table 2 while their values for the selected UZAs are presented in Table 3.

Efficiency

The transit efficiency measure (E), described earlier, uses the ratio of passenger-miles traveled (PMT) to vehicle-revenue miles (VRM) supplied to represent the average load of transit vehicles across the full reporting primary transit agencies in a given urbanized area. We use the definitions provided by the NTD with PMT the cumulative “sum of the

Table 1 Aggregate data on urbanized areas (UZAs) population and transit

Urbanized area	Code	Primary transit agencies		Population (in 2010)	Area	Density	Vehicles	Guideway miles	Operating subsidy
UZA		Total	Full reporters		Sq Mi	Pop / Sq Mi	*VAMS*	*FGDRM*	
New York-Newark, NY-NJ-CT	NYC	44	33	18,351,295	3,450	5,319	20,145	2,577	$8,157,779,785
Los Angeles-Long Beach-Anaheim, CA	LAX	72	17	12,150,996	1,736	6,999	5,081	646	$2,468,680,373
Chicago, IL-IN	CHI	14	8	8,608,208	2,443	3,524	5,417	1,284	$1,664,974,361
Miami, FL	MIA	23	5	5,502,379	1,239	4,442	1,654	241	$785,100,604
Philadelphia, PA-NJ-DE-MD	PHL	9	4	5,441,567	1,981	2,746	2,812	831	$989,421,150
Dallas-Fort Worth-Arlington, TX	DFW	11	5	5,121,892	1,779	2,879	1,055	273	$635,983,197
Houston, TX	HOU	8	2	4,944,332	1,660	2,979	1,427	43	$96,297,596
Atlanta, GA	ATL	12	6	4,515,419	2,645	1,707	1,140	99	$158,274,497
Boston, MA-NH-RI	BOS	16	6	4,181,019	1,873	2,232	2,431	917	$1,176,323,531
Detroit, MI	DTW	5	4	3,734,090	1,337	2,793	573	6	$635,983,197
Phoenix-Mesa, AZ	PHX	6	5	3,629,114	1,147	3,165	936	49	$352,818,844
San Francisco-Oakland, CA	SFO	10	9	3,281,212	524	6,266	3,315	721	$1,067,816,161
Seattle, WA	SEA	9	8	3,059,393	1,010	3,028	2,508	471	$651,863,794
San Diego, CA	SAN	3	2	2,956,746	732	4,037	974	269	$249,912,877
Minneapolis-St. Paul, MN-WI	MSP	8	7	2,650,890	1,022	2,594	1,409	133	$425,953,321

For ease of reference, we use airport codes as UZA abbreviations with the exceptions of New York-Newark, NY-NJ-CT and Chicago, IL-IN where we use NYC and CHI, respectively. The values for vehicles, guideway mileage, and operating subsidy are averaged across 2016–2019. Dollars were converted to 2019 values prior to averaging

Table 2 Base statistics and proposed transit metrics

	Base statistics	Abbreviation	Description	Formula
Unweighted	Population	P	Residents of UZA	
	Population (Tract)	T	Residents of Census Tract	
	Tract Weight	w	Census Tract Share of UZA Population	
	Subsidy (Total)	S	Operating Subsidy of Primary Agencies in UZA	
	Area	A	Square Miles in UZA	
	Density (Unweighted)	D	Gross Population Density	P/A
	Passenger-Miles Traveled	PMT	Passenger-Miles Traveled on Full Reporters in UZA	
	Vehicle Revenue Miles	VRM	Vehicle Revenue Miles on Full Reporters in UZA	
	Vehicles	$VAMS$	Transit Vehicles Available for Maximum Service	
	Guideway Miles	$FGDRM$	Fixed-Guideway Directional Route Miles in UZA	
Weighted	Density (Weighted)	D'	Population-Weighted Density	$\sum(w * T)$
	"Effective" Population	P'	Population-Weighted Density Applied to UZA Area	$D' * A$
Theme	Proposed Metrics	Abbreviation	Description	Formula
Efficiency	Transit Efficiency	E	Average Vehicle Load in UZA	PMT/VRM
Funding	Subsidy (Per Capita)	S'	Operating Subsidy per UZA Resident	S/P
	Revenue (Per Capita)	R'	Directly Generated Revenue per UZA Resident	R/P
	Subsidy Revenue Ratio	SRR	Subsidy Divided by Revenue	S/R
Infrastructure	Vehicle Ratio	$VAMS'10$	Vehicles Per 10,000 Effective Population	$10,000 * VAMS/P'$
	Guideway Miles Ratio	$FGDRM'100$	Guideway Miles per 100,000 Effective Population	$100,000 * FGDRM/P'$

PMT, *VRM*, *VAMS*, and *FGDRM* are existing abbreviations defined within the National Transit Database. This research, as a convention, denotes as "prime" those values which have been scaled by either area or effective population

Table 3 Values of proposed transit metrics by UZA

UZA	Efficiency	Subsidy per capita	Revenue per capita	Subsidy revenue ratio	Density (weighted)	Effective population	Vehicle ratio	Guideway miles ratio
	E	S'	R'	SRR	D'	P'	$VAMS'10$	$FGDRM'100$
NYC	27.4	$444.50	$565.60	0.8	30,158	104,047,304	1.9	2.5
SFO	21.2	$325.40	$354.40	0.9	13,878	7,272,325	4.6	9.9
BOS	21.1	$281.30	$203.10	1.4	7,737	14,492,701	1.7	6.3
CHI	19.2	$193.40	$135.80	1.4	9,168	22,398,144	2.4	5.7
SEA	19.0	$213.10	$260.40	0.8	4,705	4,752,515	5.3	9.9
PHL	17.2	$181.80	$112.90	1.6	7,864	15,578,989	1.8	5.3
LAX	16.5	$203.20	$55.90	3.6	12,523	21,740,124	2.3	3.0
ATL	13.9	$35.10	$53.60	0.7	2,250	5,953,889	1.9	1.7
SAN	13.8	$84.50	$44.20	1.9	6,920	5,065,762	1.9	5.3
MIA	12.6	$142.70	$35.10	4.1	6,872	8,514,520	1.9	2.8
MSP	10.9	$160.70	$57.60	2.8	3,737	3,819,353	3.7	3.5
HOU	10.4	$19.50	$16.30	1.2	4,427	7,349,139	1.9	0.6
DFW	9.5	$124.20	$26.90	4.6	4,233	7,530,757	1.4	3.6
DTW	8.9	$46.10	$19.00	2.4	4,189	5,601,324	1.0	0.1
PHX	8.7	$97.20	$20.00	4.9	4,803	5,509,717	1.7	0.9

Population drawn from 2010 Decennial Census. Subsidy, revenue, vehicle, and guideway mile data presented are 2016–2019 means. Dollars are all converted to 2019 values before averaging. Regions sorted by declining efficiency (E)

distances ridden by each passenger" and *VRM* the total miles that "vehicles are scheduled to or actually travel while in revenue service" which excludes miles traveled to change routes or to access storage facilities (Office of Budget and Policy 2017).

This efficiency measure considers all fixed-route vehicles from the shortest bus to the largest rail car in the region. The highest scoring networks, namely those in New York, San Francisco, and Boston (with $E > 20$), are characterized by highly patronized rail and articulated bus services while the lowest scoring networks, namely Dallas, Detroit, and Phoenix (with $E < 10$), despite all having rail networks, are characterized as sprawling car-oriented places.

Funding

Rather than using raw values, we measure subsidy and revenue measures per capita within the UZA. Our scaled subsidy metric (S') directly reflects the benefits to each resident and more closely aligns with federal formulas for allocating such funds. Our subsidy calculation adjusts the annual subsidy amounts reported by the NTD to equal real 2019 dollars as recommended by the U.S. Department of Transportation (2021). This adjustment addresses inflation over time, but not purchasing power parity among the different regions (a possible future extension of the metric). Additionally, using revenue per capita (R') rather than total revenue allows for direct comparisons between subsidies and revenues. All further mention of subsidies in this paper refers to these scaled values.

Figure 3 presents the subsidy by government level (i.e., federal, state, and local) in declining total subsidy per capita. These data illustrate that the formula-allocated federal subsidies provide a relatively consistent, albeit small, amount of financial support to regions; by contrast, state and local governments provide widely varying amounts that, in combination, account for the vast majority of total subsidy (outside of Atlanta and

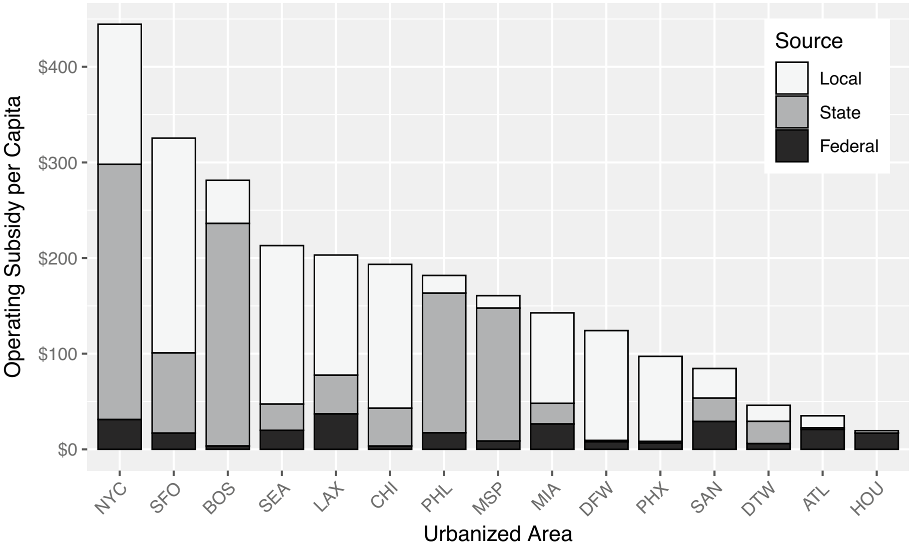

Fig. 3 Subsidy by Source (2016–2019 Averages in 2019 Dollars)

Houston). Since the relationship between state and local subsidies are themselves also so variable—for example, Philadelphia enjoys strong state support but relatively limited local support while Dallas enjoys strong local support but limited state support—we decompose the total subsidy (S') into federal (S'_{Fed}) and non-federal ($S'_{S\&L}$) components; the latter of which combines state and local support into a single value.

We assess the relationship between subsidies and revenue in Fig. 4. The line of equivalence represents the points when per capita subsidies and revenues are equal. UZAs below the line have more revenues than subsidy while UZAs above the line have more subsidy than revenues. Subsidies and revenues are highly correlated (Pearson's r = 0.89), although some low revenue systems, such as Los Angeles, have comparatively high subsidies.

To measure the relationship between subsidies and revenue, we propose the subsidy revenue ratio (*SRR*) shown in Table 3. This formulation is structured so that values between zero and one refer to funding situations in which revenues exceed or equal subsidies (i.e. on or below the line of equivalence in Fig. 4) while values greater than one (i.e. above the line of equivalence in Fig. 4) refer to situations in which subsidies exceed revenues. This formulation has two key advantages over the more traditional cost recovery ratio that measures the share of operating costs that is covered by revenues (and is typically presented as a percentage). First, the subsidy revenue ratio reflects the reality that public transit relies on public support and that the best performing systems typically achieve a cost recovery ratio of only 50%. The subsidy revenue ratio sets that level as the basic threshold instead of the unrealistic number of 100% cost recovery. Systems whose *SRR* is less than one have exceeded the basic threshold of 50% cost recovery. Second, the subsidy revenue ratio is structured to highlight the variation among the vast majority of transit systems that do not meet this threshold. While this variation is compressed between 0 and 50% for the cost recovery ratio, it is extended from one indefinitely for the subsidy revenue ratio – enabling a better understanding of financial tiers.

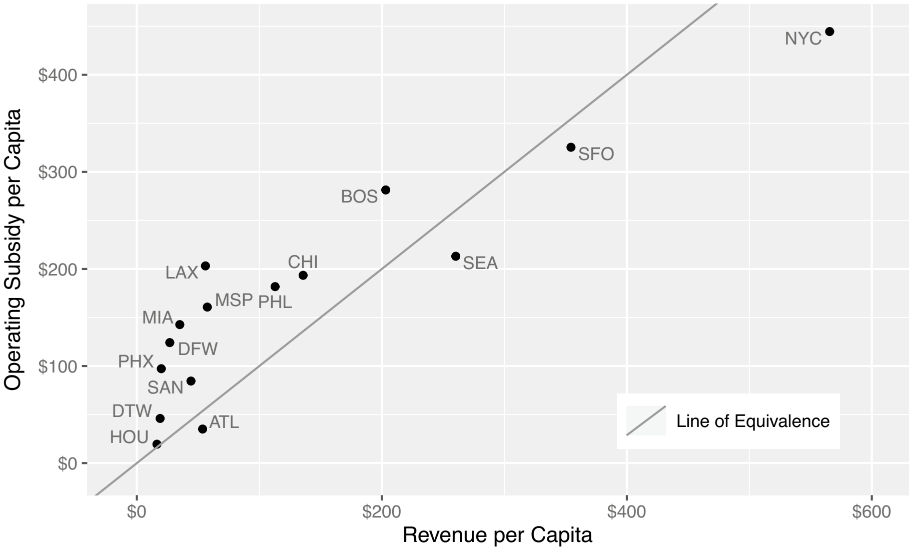

Fig. 4 Comparing Subsidies to Revenues (2016–2019 Averages in 2019 Dollars)

Among the major regions included in this study, the subsidy revenue ratio ranged from a low of 0.7 in Atlanta to a high of 4.9 in Phoenix. Hierarchical clustering grouped the systems into five *SRR* bins, shown in Fig. 5, with breakpoints roughly aligned with integer values. While these breakpoints are based on only a small sample of UZAs, they do identify peer systems. For example, Dallas (DFW) and Houston (HOU), both located in Texas, are the fourth and fifth largest metropolitan areas, respectively, in the United States based on population and report similar transit efficiency scores, weighted population densities, and per capita revenues, as shown in Table 3. Despite the reasonable expectation that the two cities would land in the same *SRR* tier, Houston is in the second and Dallas is in the fifth – because Dallas's per capita operating subsidy is six times that of Houston resulting in very distinct *SRR* scores.

Infrastructure

Both of our infrastructure measures are scaled by "effective" population (P') which we define as the product of the population-weighted density of the region and the size of the region. This value represents the theoretical population necessary for the gross density (the quotient of population and area) of the region to equal the actual weighted density. In other words, it extends the experienced population density of residential areas to the entire region.

The distinction between gross density and population-weighted density is particularly relevant for transit. Gross density is a blunt measure of regional transit suitability as it does not account for the distribution of the population within a region. The Los Angeles urbanized area (often the poster child of sprawl) has a higher gross density than the New York urbanized area (often the Platonic form of dense urban form), but a lower population-weighted density. Los Angeles's population is evenly spread across the region while New York's population is highly concentrated in some areas, such as Manhattan, and highly

Fig. 5 Subsidy Revenue Ratio Clusters (2016–2019 Averages)

dispersed in others, such as the leafy suburbs of New Jersey and Connecticut. A way to capture this concentration mathematically is to calculate a density that is weighted by population. We generate such a population-weighted density (D') by subdividing the UZAs by their component census tracts (a smallish, consistently defined geographical unit with between 1,200 and 8,000 residents), calculating the gross density for each tract, and then calculating a weighted sum of those tract-level densities with the weights for each tract equal to the proportion of the total UZA population residing in each tract. The 2010 census counts of tract populations were used for this calculation.

Figure 6 presents the unweighted (i.e. gross) density of each region with the population-weighted density both in residents per square mile (≈2.6 km^2). This chart demonstrates how such weighting reflects the intuition about the difference between the transit friendliness of the New York and Los Angeles UZAs as the weighted density of the former is more than twice that of the latter. This weighted density represents the typical density experienced at residential locations.

Scaling by the actual population is appropriate for measures that relate to the entire population of a region without consideration of urban form. For example, all residents of an urbanized area benefit from and also subsidize their transit network, whether or not they actually use it. For this reason, we consider subsidy per capita. By contrast, scaling by the effective population is preferred for metrics that relate to the built environment, such as transit. Clustered development facilitates transit and results in large effective populations. Applying this theoretical value as the denominator for comparing infrastructure across urbanized areas serves as a coarse proxy for residential concentration and thus the "transit-supportiveness" of the urban form.

The effective population can be used as a scaling variable to generate comparable metrics of transit provision. Specifically, we propose a measure of transit vehicle provision as the ratio of *VAMS* for every 10,000 residents of effective population ($VAMS'10$) and a measure of transit rail (and busway) provision as the ratio of *FGDRM* for every

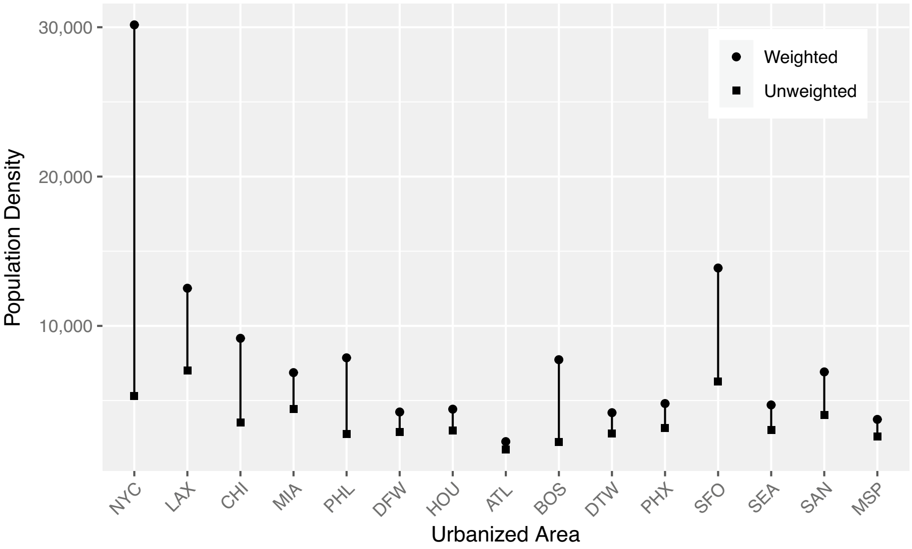

Fig. 6 Population Density (Person per Square Mile) by Urbanized Area (2010)

100,000 residents of effective population ($FGDRM'100$). Table 3 presents both metrics for each of the UZAs and Fig. 7 graphs them as density plots. These metrics offer new ways to characterize transit provision across a region. Collapsing all of the service variation and land use nuance into a single number is both reductive and intentional. This approach yields metrics that, while imperfect, are comparable across regions and thus can inform policy.

For example, Fig. 7 shows the distribution of the vehicle ratio ($VAMS'10$) is highly clustered and therefore leptokurtic (kurtosis = 3.9) with a primary peak for vehicle ratios between 1.25 and 2.5 and a small secondary peak at 5.0. That secondary peak is comprised solely of San Francisco and Seattle, two polycentric West Coast regions whose dense population centers are scattered across seismically shaped bays possibly well served by transit. Between the peaks of the distribution lies Minneapolis ($VAMS'10 = 3.7$) whose vehicle ratio is far higher than its midwestern peers, possibly an indicator that its region has too many buses.

Figure 7 also shows the distribution of guideway mile ratios ($FGDRM'100$) is rather dispersed and therefore platykurtic (kurtosis = 2.6) with a relatively even spread from roughly zero through six. This smoother distribution likely reflects the collapsing of very diverse offerings of fixed guideway services from longer mileage, lower ridership commuter rail networks to shorter mileage, higher ridership heavy rail systems. Yet even with this distribution it is possible to see patterns for peer comparison. For example, the higher side of the main curve represents most legacy rail systems outside New York, namely Philadelphia (5.3), Chicago (5.7), and Boston (6.3), but also a relative rail newcomer, San Diego (5.3), which might aspire to be closer to its similarly land-constrained Pacific peers, namely San Francisco (9.9) and Seattle (9.9). More dispersed regions with retrofitted rail networks, such as Miami (2.8), Los Angeles (3.0), Minneapolis (3.5), and Dallas (3.6), fall in the middle of the main fixed guideway curve; however, Atlanta (1.7) is conspicuously lower, possibly suggesting room for guideway expansion.

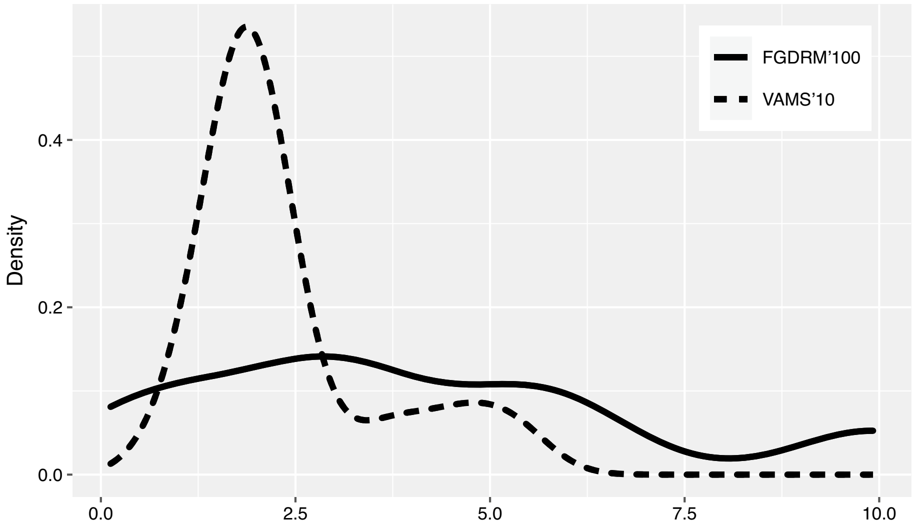

Fig. 7 Vehicle ($VAMS'10$) and Guideway Mile ($FGDRM'100$) Ratio Densities (2016–2019 Averages)

Regression model

To understand the role of operating subsidy on regional transit efficiency, we estimated a series of linear regression models using four years of data (2016–2019 inclusive) from the fifteen UZAs. Transit efficiency was the response variable and predictors included the metrics discussed above. The final model estimates are shown in Table 4. These results are robust to alternative model specifications, for example, those that include population density and year as predictors. The model also demonstrates strong goodness-of-fit as it explains 93% of the variation in transit efficiency across the four years and fifteen systems.

The parameter estimates in Table 4 show that, *ceteris paribus*, transit efficiency increases with both federal and non-federal operating subsidies—notably the impact associated with each federal dollar is thrice that of state and local subsidies. This distinction on the source of the subsidy is similar to findings elsewhere (Cervero 1984; Nolan 1996). The negative sign on the subsidy revenue ratio adds a countervailing impact to these relationships—an impact that can be rather substantial as subsidies outpace revenues. For example, in Seattle and Los Angeles, two regions with similar rates of subsidy ($213 and $203 per capita, respectively), the expected efficiency impact of the subsidy revenue ratio parameter would be 1.2 fewer passengers per vehicle in Seattle (where $SRR = 0.8$) but 5.3 fewer passengers per vehicle in Los Angeles (where $SRR = 3.6$).

The parameter estimates also consider the two metrics of transit provision as control variables. The vehicle ratio ($VAMS'10$) is negatively related to transit efficiency while the guideway mile ratio ($FGDRM'100$) is positively related. Interestingly, increased population density (weighted) improves efficiency regarding vehicles but reduces it regarding fixed guideway mileage.

Discussion

The model parameters suggest several key insights for policy.

First and foremost, they challenge commonly held assumptions that operating subsidies, on their own, result in less transit efficiency. Our findings suggest that per UZA resident, each $100 of federal subsidy increases average vehicles loads by nine riders while each $100 of non-federal subsidy increases average vehicle loads by three riders. This disparity

Table 4 Model parameter estimates

Coefficient	Abbreviation	Estimate	SE	t-value	*p*-value	Sig
(Intercept)		12.31	0.670	18.37	0.000	***
Federal Subsidy per Capita	S'_{Fed}	0.09	0.017	5.69	0.000	***
Non-Federal Subsidy per Capita	$S'_{S\&L}$	0.03	0.002	15.22	0.000	***
Subsidy Revenue Ratio	SRR	– 1.48	0.140	– 10.55	0.000	***
Vehicles Per 10,000 P'	$VAMS'10$	– 0.30	0.101	– 2.94	0.004	***
Guideway Miles Per 100,000 P'	$FGDRM'100$	0.24	0.101	2.43	0.018	*

Dependent Variable: Transit Efficiency (E) representing the average vehicle load across the UZA

Residual Standard Error = 1.429; df = 54; Adjusted R-Squared = 0.930

Significance Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

in efficiency impact further suggests state and local governments might adopt policies modeled on the more rigorous federal criteria for allocating support.

The model parameters qualify the first finding by suggesting that while operating subsidies do support efficiency, that support can be undermined to the extent that subsidies outpace directly generated revenues. In other words, subsidies per se are not a problem for transit efficiency (on the contrary they are a positive), but they generally only provide this nourishing role when they are a complement to and not a substitute for directly generated revenues. This finding suggests that directly generated revenues still send important market signals to transit properties regarding demand. Too much subsidy compared to revenue obscures those signals (and degrades efficiency).

Retrieving these lost signals might be achieved by restructuring subsidies to be responsive to revenues. Instead of funding formulas tied to population levels or local tax proceeds (both of which are divorced from transit performance), subsidy formulas might reflect directly generated revenues. For example, a region might determine a set subsidy revenue ratio (e.g., $SRR = 2$) and simply match revenues to achieve that level. Such incentives would encourage regions to be more entrepreneurial in demonstrating value to riders and in pricing transit fees to better capture that value. Such incentives may also offer justification for cutting poorly patronized lines and improving service along corridors of high demand. These changes would harm geographic equity (where political jurisdictions seek to ensure coverage to areas that subsidize the network regardless of need) but would likely improve social equity by redirecting service to where it is most desired.

Retrieving these lost demand signals might also (and perhaps more effectively) be achieved by restructuring subsidies to be responsive to efficiency. Instead of using the SRR to set the upper boundary of operating subsidies, subsidy policy might establish a minimum efficiency level (e.g., $E = 10$) as the lower boundary for receiving operating subsidies. Alternatively, subsidies might simply reflect efficiency with more efficient systems being rewarded with more subsidies. (Los Angeles is a possible example of this approach with both relatively high efficiency and SRR scores.) These efficiency- based subsidy approaches would incentivize regions to capture ridership and lead to many of the same entrepreneurial outcomes discussed in the previous paragraph. Furthermore, focusing on ridership over revenue may even yield more equitable outcomes. For example, this approach would be compatible with a fareless system (or the emergency support provided transit during the Covid-19 pandemic) while the revenue-oriented one would not.

The model parameters also provide some guidance on how to improve efficiency through capital investments. The findings favor expanding mileage of dedicated transit rights-of-way over expanding fleets. Such fixed guideway mileage does not necessarily mean expensive rail infrastructure but includes far less costly busways that improve service for the existing fleets. For systems that exceed a certain SRR cap or fail to meet a certain E threshold, operating subsidies might be re-allocated fund fixed guideway mileage.

It is important to recall that all of these findings are predicated on two core assumptions: first, the primary objective of transit efficiency (measured as average vehicle load), and, second, the focus on the regional transit network rather than the individual transit providers. In terms of the former, we are explicitly prioritizing efficiency above other typical transit goals such as coverage or geographic equity. That prioritization allows for market signals to better drive transit provision decisions and to better justify the allocation of limited public resources. In terms of the latter, we are arguing that transit systems should be seen from the perspective of the consumer and taxpayer and not the agency itself. It is not analytically appropriate for a commuter rail agency to tout their high efficiency but ignore the many local feeder services that make that efficiency possible. Transit is a regional good (whose benefits spillover among local political jurisdictions) and should be planned, assessed, and subsidized on that basis. We hope that this presentation of metrics will support such an integrated consideration and encourage metropolitan planning organizations and other regional actors to adopt this position. The use of region-level metrics and subsidy policies should incentivize greater coordination among operations across a region.

Limitations

This research is constrained by several limitations that warrant mention.

First, the metric development, while intended to be broadly applicable, is grounded in the reality of transit organization and associated data reporting in the United States. The structure of the National Transit Database determines the metrics' measurement basis in the imperial rather than the International System (SI) of units, their geographic extent through the U.S. Census Bureau definition of an urbanized area, and their consideration of transit through the availability of NTD reporting variables. The accuracy of these metrics is also reliant on the quality of the underlying data within the NTD. We limited our sample to the fifteen largest regions, in part, to minimize the chance of errors within the NTD data as these regions have the largest professional staff devoted to transit administration and planning. While relying on the NTD is a strength within the U.S. context that leverages the federal investment in collecting transit data, it is also a limitation as the proposed metrics will need to be tweaked to be applied in other countries.

Second, these metrics explicitly characterize transit provision by the fixed-route services that carry the overwhelming share of passengers in larger regions. The proposed metrics do not account for demand-response services, such as required paratransit and emerging dynamic shared-use options (e.g., Via partnering with agencies). Future work might productively add nuance to the proposed metrics by extending them beyond fixed-route services.

Third, the core efficiency metric only accounts for miles when the transit vehicle is in service. We have chosen to exclude deadheading. This decision reflects both the political reality that transit is assessed based on ridership (which is not possible during non-revenue service) and the spatial reality that the location of shops and garages in relation to the network varies substantially across transit agencies complicating a fair comparison across systems. (While the current focus on passenger usage excludes consideration of non-revenue miles, we certainly recognize the need for new efficiency metrics in this aspect of transit provision. We would recommend a simple ratio of non-revenue to revenue vehicle miles.)

Finally, this work is entirely based on transit operations and use prior to the disruption of the Covid-19 pandemic. While the general approach ports perfectly to a post-pandemic world, the specific values identified within this research may not reflect the new normal of transit ridership that emerges once the full impacts of the pandemic on work travel are known. Policy makers should be cautious in applying the values presented here and sensitive to evolving conditions on the ground. Calculation of these metrics using post-pandemic data might recalibrate reported relationships.

Conclusion

Debates over the appropriate role of operating subsidy in supporting public transportation continue to rage. This research attempts to shift the terms of that debate in ways more productive for policy. Fundamentally, we argue for recasting the unit of analysis from a single transit operator to a single regional transitshed, prioritizing transit efficiency (defined as average vehicle load) as the goal of service design, and adopting the subsidy revenue ratio as the key metric of fiscal performance.

Our emphasis on efficiency, on how much "bang for the bus" a community receives for its investment in transit, raises a number of important questions for future research. The most pressing concern is whether an efficiency-oriented service design would improve or degrade accessibility for transit dependent riders. We suspect that such an approach would yield better service for the patrons who need transit the most at the expense of broad regional coverage—a tradeoff we support—but recognize the need for testing this hypothesis and the difficult politics of its ramifications for geographic equity. Another issue is whether efficiency-oriented service design would also yield strong greenhouse gas emission reductions across a region (and, if so, might those exceed the benefits from investing in lower emitting buses). We are certainly not against cleaning the transit fleet; we just want to prioritize getting people onto transit (and not driving themselves) as the key calculus for mitigating climate change.

We propose a new way to consider operating deficits through the subsidy revenue ratio and present clusters of systems at different tiers. We would like to see systems strive for transit efficiency while also seeking to reduce their subsidy revenue ratios. Figuring out how systems can jump to better and better tiers of fiscal balance will require more research (from fare policy to urban form to resource management). For example, how might Dallas maintain its Houston leve1 of transit efficiency while approaching Houston's much lower level of subsidy? Conversely, what is Los Angeles doing to achieve high transit efficiency despite its relatively high subsidy revenue ratio? Could Atlanta learn from Los Angeles and introduce a bit more subsidy but gain a lot more riders? There is room for a renewed interest in the role of operating subsidies in transit efficiency and in exploring more nuanced incentive structures to leverage the power of these public funds to optimize transit provision.

Finally, this research is also a call for greater use of the National Transit Database for research and policy making. Maintaining the NTD is a huge task for the federal government and for the participant agencies. Extracting more value from this investment, possibly through better metrics, is a win for everyone—particularly if it leads to enhanced transit service at less cost to society.

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Declarations

Competing interests The authors declare no competing interests.

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