FINDING A FAIR FARE: ESTIMATING THE EQUITY OF EXISTING AND ALTERNATIVE TRANSIT FARE STRUCTURES

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ABSTRACT

Transit agencies seeking to understand the distributional effects of their fare policy and the aspects of fare structure driving those effects face a dearth in rider demographics and a challenge in connecting trip characteristics to rider characteristics. This paper presents a novel method of integrating stated demographics (from regional travel survey and registered farecard datasets) and revealed travel behavior (using origin, destination, and transfer inference (ODX) models) to understand fare equity within the Washington Metropolitan Area Transit Authority's Metrorail system as experienced across rider segments defined by race and income. The distribution of transit costs and benefits currently experienced by riders is further contextualized through the development and evaluation of revenue-neutral alternate fare structures to identify features of fare policy that lead to socially progressive outcomes in the context of Washington, D.C. Results indicate that peak-pricing differentiation benefits both low-income riders and riders of color. We further find that the current fare structure's inclusion of network distance penalizes the more circuitous trips disproportionately taken by the same rider groups. Our results suggest that a distance-based fare with a crow-flies distance basis between origin and destination stations would benefit the same riders while more closely aligning the benefit of travel from origin to destination with the monetary cost required.

Keywords: Transit; fare policy; equity; passenger demographics; origin-destination data

INTRODUCTION

Using fare policy, transit agencies pursue often-divergent goals such as ridership, revenue, and the equitable distribution of the costs and benefits of transit among riders. The Washington Metropolitan Area Transit Authority (WMATA), which is explored in this paper, uses a distance-based fare with peak-pricing differentiation for its Metrorail service. WMATA's Metrorail system is uncommon among US subway systems in that it utilizes both peak period differentiation and distance-based fares.

Transit agencies seeking to understand the distributional effects of their fare policy, and the fare structure aspects driving those effects, face a dearth of rider demographic information and a challenge in connecting trip characteristics to rider characteristics. This paper presents an innovative method of combining datasets containing stated demographics and revealed travel behavior of transit riders. We apply this method to Metrorail in order to examine the equity of its fare structure. We analyze how the fare burden is borne by rider segments across race and income. We further contextualize current fare equity by developing and introducing a suite of alternate fare structures that incorporate trip distance, time of travel, and journey characteristics to differing extents. Comparison between race- and income-based rider segments help illustrate how residential locations, travel patterns, and fare structure mediate the equity of the fare system as experienced by historically-disadvantaged riders. This exercise provides insight on trip characteristics that can be employed to improve equitable outcomes across fare regimes.

LITERATURE REVIEW

Determining the cost to ride

In considering how to price their services, transit agencies weigh different high-level goals. Chief among them is providing convenient and affordable transit service, a continued fiscal capacity to provide such services, and ensuring fairness in doing so. Fare policy is one important lever agencies use to achieve these goals. It comprises decisions about how to price, differentiate, and collect fares from travelers. These decisions are made at the level of the individual municipality or region, meaning there are stark regional variations. When determining fare policy, agencies weigh many considerations including their mission and internal policies, governmental requirements, budget goals, and local travel patterns. One output of this process is the fare structure, which comprises a set of criteria used to determine the cost of each individual journey taken. Walker provides a selection of common factors considered in determining the fare structure: should trip distance or number of transfers impact cost? Will discounts be provided for passes or advance purchases? How will fares vary over the course of a day, and are they impacted by system capacity? (*1*).

Defining Fare Equity

Among US transit agencies, formal transit equity regulations center on the application of Title VI of the Civil Rights Act of 1964, which requires that transit agencies conduct an analysis ensuring no disparate impact on defined demographic groups prior to a major change to infrastructure, fares, or service (*2*). However, this process does not address the equity of the system as-is or the evolution of its equity over time, independent of the proposed change the agency seeks to analyze (*3*). We find diverse definitions of equity in the academic and policy literatures, with inherently contradictory implications for transit policy. For example, equity may be conceived of as procedural, concerned with inclusion and engagement in policy processes; distributional, concerned with the fair distribution of benefits and burdens across different segments of a community; structural, concerned with historical, cultural, and institutional dynamics that result in privilege and disadvantage; and transgenerational, concerned with the impact of policies on future generations (*4, 5*). Taylor additionally outlines three types of equity of concern to transportation practitioners: market equity, in which transportation resources are proportional to collected revenue; opportunity equity, in which resources are available equally; and outcome equity, in which the spending and resources create equal levels of service, mobility, or access. These three often-contradictory notions of equity can be applied at the scales of geographies, groups, and individuals (*6*).

Fare equity research is mostly concerned with the scale of groups (segments of a community) and market equity, where fares constitute the type of revenue to which transportation resources should be made proportional (*7*). In this paper we are likewise concerned with market equity among groups, and further operationalize the definition of distributional equity. Specifically, we are interested in how the cost of a trip is distributed across race and income. We conceive of fare policy as a lever that has distributional impacts on the aforementioned transit costs, which may change over time given the evolution of a given transit network alongside the service area's demographic composition and spatial distribution.

Measuring Fare Equity

This paper is situated within the body of scholarship that assesses current fare structures (*8*) and hypothetical fare structures (*7, 9, 10*). When assessing such fare structures, Cervero points to the diversity of criteria one could use, and to the difficulty, if not impossibility, of satisfying these criteria simultaneously (*11, 12*). Nuworsoo et al. summarize these criteria as the "benefit criterion", which holds that fares should be proportional to the benefit the rider receives; the "cost criterion", which holds that a trip's fare should be proportional to the cost of providing that trip; and the "ability to pay criterion", which holds that fares should be proportional to the rider's wealth (*13*). However, the choice of how to define and quantify the benefits of transit leads to divergent results when applying the benefit criterion. For example, one can define the benefit as a "trip", in which case flat fares are judged equitable, or as the travel distance, which requires uniform per-mile rates to be considered equitable. Methodologies used to assess fare equity according to the benefits criterion have used metrics including fare paid per mile (*7*), the average transit fare (*9, 14*), and changes in both the average fare and the number of trips taken (*13*). We opt to use the metric of fare per linked trip, which we believe is more in line with how riders experience transit, as a tool to access specific amenities as opposed to travel a certain distance. We also report relative changes in the number of trips taken by different rider segments.

The equity implications of distance-based fares in particular is a perennial question among academics, transit policymakers, agency executives, and the transit advocacy community. Academics have developed methodologies for assessing the equity of fare regimes, especially distance-based ones. They have variously identified the conditions under which flat fares and distance-based fares are better from an equity perspective, though their findings are highly context-dependent (*7, 9, 9, 10, 14*). For instance, recent research has found that distance-based fares would improve equity among Utah Transit Authority and LA Metro riders (*7, 9*), while flat fares would result in improved equity outcomes in Stockholm, Sweden (*14*).

Methods and Data Sources for Fare Equity Research

The recent development and widespread adoption of automated fare collection (AFC) and automated vehicle location (AVL) systems promise rich datasets that agencies can use to learn about how passengers use transit and how they pay for it (*15, 16*). The integration of these automated systems using origin, destination, and transfer inference (ODX) models further enable the granular study of individual travel behavior (*17, 18*). Though ODX has been used to understand travel behavior and better plan transit service (*19*), we are not aware of its application to assess the equity of transit fare structures. Fare equity studies often rely on travel diary data containing detailed demographic data, as opposed to revealed travel behavior captured through automated systems which lack demographic information. Studies employing transit agency datasets largely rely on neighborhood-level demographics to inform rider demographics based on inferred home locations, but this approach falls prey to the ecological fallacy. The ecological fallacy refers to the methodological error of assuming that characteristics of an entire group apply equally to each member of that group. In the context of this research, it is important to remember that the demographics of a neighborhood do not necessitate that an individual rider from that neighborhood shares the same demographic information. This study presents methods that integrate stated demographics from travel diaries and other sources with revealed travel behavior captured through ODX. Compared to solely using travel surveys, ODX provides more precise estimates of travel time, path and circuity, and transfer information.

Fare Equity in Washington, D.C.

The question of distance-based fares in the Washington, D.C. region is especially important given the complexity of WMATA rail fares. Though this question has received substantial attention in the popular press and transit advocacy community (*20–23*), it has not enjoyed equivalent scholarly attention. In considering alternative fare scenarios, agency staff have defended the economic logic and fairness of the rail fare structure, and raised potential Title VI equity concerns should distance-based fares be replaced with a flat fare in a revenue-neutral fashion (*24*). Such an assertion can be scrutinized more completely in light of the analysis we undertake in this paper.

The argument that flat fares raise a Title VI equity concern in particular rests on a combination of two travel behavior assumptions: that low-income Washingtonians disproportionately take shorter trips and that they disproportionately travel off-peak. However, it is important to empirically test these assumptions, especially in light of changing demographic patterns. Demographic trends, including in the Washington, D.C. region, show that suburban areas are becoming less wealthy, less white, and less-educated relative to the metropolitan area as a whole (*25*), substantiating what Ehrenhalt terms the "great inversion" (*26*) or what Renn terms "the new donut" (*27*): the idea that the revitalization and gentrification of sections of the urban core and the suburbanization of poverty create a "donut" of poverty with a wealthy outer ring and a wealthy "donut hole" in the city center. The suburbanization of poverty results in the increased concentration of lower-income populations in more auto-centric areas, thereby obstructing their travel and reducing their access (*28*). These demographic trends and their adverse effects point to the need for progressive policies, including a reevaluation of fare structures.

METRORAIL FARE STRUCTURE

WMATA Metrorail provides a unique environment to explore fare equity, as the cost of a single trip varies based on the distance traveled, the time the trip is taken, the day of the week, and until recently, whether a transfer to bus was needed as part of the same journey. Reduced fares are also available to riders based on age and disability status (*29, 30*).

Metrorail utilizes a tap-in/tap-out method for its smart card payment system, called Smar-

Trip. As a SmarTrip card is used to enter and exit each Metrorail station, AFC data provides information on the origin and destination station for each trip on Metrorail, and whether that trip is linked to bus travel on the same journey. As there are no alternative fare media on Metrorail, utilizing AFC data captures all paying riders.

At the time of writing, Metrorail's fare structure is distance-based on weekdays before 9:30 pm and flat after 9:30 pm and on weekends (*29*). During weekdays, fares are further differentiated by time of travel (peak versus off-peak travel). For both peak and off-peak travel on weekdays, the process of calculating the required fare remains the same, but the base costs, incremental charges, and maximum fares differ. When tapping out of the Metrorail system at the end of a trip, the distance from the origin station is used to calculate the mileage cost, which is rounded to the nearest \$0.05. A minimum fare covers the first 3 miles of travel, beyond which a distance-based charge is levied. The per-mile cost is charged at one level for miles three to six; distances beyond six miles incur a lower per-mile rate until the maximum fare is reached. Fare minimums, maximums, and per-mile charges are given in Table 1.

The distance measure used to calculate trip length for fare purposes is the mean of the straight-line ("crow flies") distance and the distance along Metrorail's rail network ("track-miles" distance) between the origin and destination stations. This mean distance is termed the "composite distance"(*31*), and its use as the measure of distance influences fares for trips of different directness.

TABLE 1: Current Metrorail Fare Inputs (Weekdays before 9:30 pm)

	Peak (\$)	Off-Peak (\$)
Minimum fare (first 3 miles)	2.250	2.000
Per-mile rate 1 (miles 3-6)	0.326	0.244
Per-mile rate 2 (miles 6+)	0.288	0.216
Maximum fare	6.000	3.850

DATA AND METHODOLOGY

Equity Metrics

Guided by a focus on cost-to-rider measures, we analyze Metrorail trips representative of overall system ridership considering three primary metrics. The first measure is the fare per linked trip, which captures the direct monetary costs of traveling on the system. Secondly, we measure the difference in these average fares between rider segments. Lastly, we evaluate estimated changes in trip volume. When evaluating hypothetical changes in fare levels, expected changes in travel volume must be considered to understand the extent to which average fares are impacted by travel increases or decreases, and how such changes occur within rider segments.

Demographic and Travel Information

To ensure an appropriately large sample of Metrorail trips with associated race and income identifiers, we employ an innovative method to collate detailed information on self-reported demographics alongside observed travel patterns from three separate but complementary data sources. These data sources include traditional household travel surveys and WMATA fare card data. Traditional travel surveys provide a good source of demographic information on respondents, but sample sizes are often small, especially when there is a need to focus on subpopulations of interest (e.g. low-income riders or riders of color). On the other hand, fare card data provides detailed travel information that can be used to create a very large sample, but that sample is often lacking in important demographic details. By leveraging the information available from both travel survey and fare card data, and synthesizing to ensure comparable data, we demonstrate the utility of combining these sources to enlarge the sample of transit travel data linked with rider demographics, enhancing the robustness of our findings.

Our first source of demographic information are the Metropolitan Washington Council of Governments (MWCOG) Regional Travel Survey (RTS) (*32*) and WMATA's SmarTrip registered card database. RTS reports detailed travel and demographic information, including race and income, from a large sample of over 16,000 Washington-area households. Each household was assigned a single weekday between October 2017 and December 2018. On that day, information on all journeys and travel modes was gathered for each respondent. When reporting a Metrorail trip, respondents provided the origin and destination rail stations. From this detailed trip-level travel information, we used a framework of logical rules based on stated origin station, destination station, travel mode sequence, and time of journey to match a representative trip from WMATA's implementation of ODX to each RTS record.

Our second source of demographic information is WMATA's internal SmarTrip card registration records. Riders use the optional registration process to access tax-advantaged transit benefits and to ensure transit value can be recovered from lost or stolen cards. Of the SmarTrip cards that have been registered with WMATA, there is a subset for which the registrant has provided demographic information including race and income. This subset of just under 4,000 registrants, anonymized so that only race, income, a unique customer identifier, and hashed identifiers for each SmarTrip card are available, provides another avenue to link Metrorail trips in ODX with stated income and race.

Each passenger is then classified by race and ethnicity as white or as a person of color. The latter group, whom we also refer to as "riders of color", includes people of non-white race or of Hispanic ethnicity. Passengers are additionally classified by household income as earning above or below the livable wage. We define the livable wage using the Living Wage Calculator for Washington, D.C., at the beginning of the RTS data period in October 2017 (*33*). This calculator adjusts for regional variation in costs and spending. We refer to riders whose household income is below the nearest dataset threshold to the living wage of $32,686 as "low-income".

Given this subset of SmarTrip cards with labeled demographics, we mimicked the RTS travel diary process to create a synthetic RTS dataset, ensuring a direct comparison with the collected travel diary responses. The synthetic RTS data was generated by randomly assigning each registered, labeled SmarTrip customer a single weekday during the RTS period. Once assigned, we queried WMATA's ODX travel records database for all journeys by each customer on their specified travel day.

After matching travel records representative of the RTS travel records, and creating synthetic RTS data, we combined our data into a final dataset of Metrorail trips that contain the necessary travel and demographic identifiers. The resulting combined dataset is representative of systemwide Metrorail travel. It comprises 6,174 unique riders taking 12,129 Metrorail trips. 2,916 of these riders were identified using RTS responses and 3,258 were identified using registered SmarTrip cards. Similarly, 5,486 of the Metrorail trips are from RTS data; the remaining 6,643 come from registered SmarTrip cards. All 91 active Metrorail stations are represented as a trip origin and a trip destination. Within the dataset, there are 1,973 unique station pairs, representing 48.2% of potential rail station origin-destination combinations. However, origin-destination pairs do not experience equal travel volumes; correspondingly, the 1,973 station pairs captured in our data are responsible for 86.5% of trips taken on the Metrorail system during the RTS period.

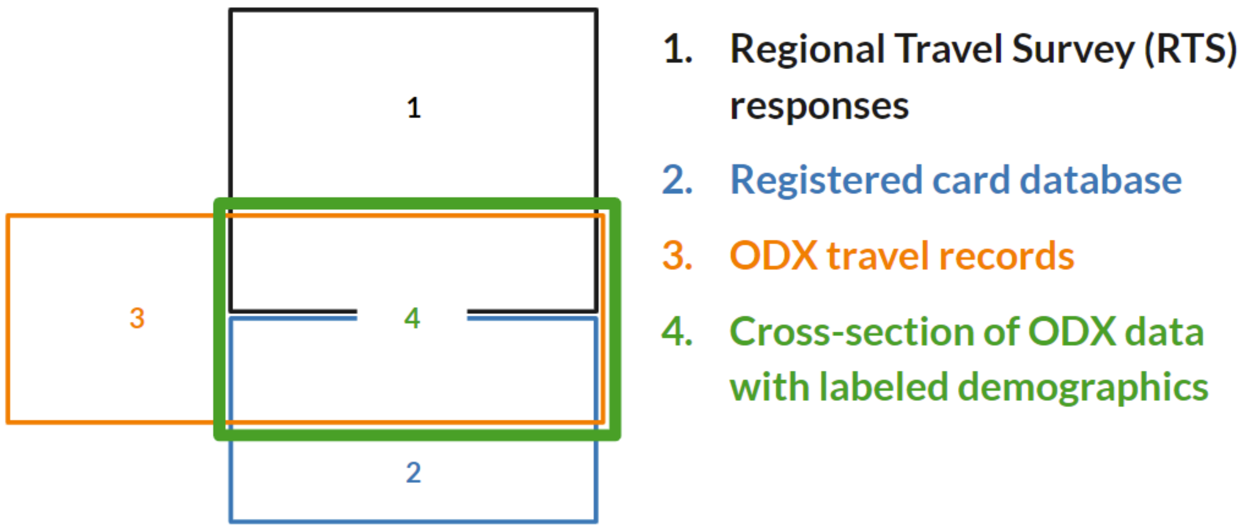

FIGURE 1: **Schematic representation of assembled Metrorail travel data with labeled rider demographic information.**

To ensure that our travel data is representative of all Metrorail riders, we employed iterative proportional fitting to calculate appropriate weights for each individual Metrorail trip within our dataset. Weights were calculated to control for income, race, and peak travel; each is a necessary dimension given our focus on fare equity and a rail system with peak-pricing. Application of the resulting weights resulted in a precise match with contemporaneous Metrorail ridership demographics. Our weighted sample, which already covered the majority of all Metrorail travel in spatial terms, is also representative of all Metrorail travelers demographically. The weights calculated for trips based on these three dimensions can be seen in Table 2.

Evaluating Alternate Fare Scenarios

Given rider travel patterns and a formula for fares, one can easily calculate average fares across rider segments. However, that alone does not provide a complete understanding of whether a fare structure is performing equitably; there is therefore a need for comparison scenarios against which the performance of the current fare structure can be compared. To fulfill this need we created realistic fare structures and estimated equity metrics under each.

Alternate fare scenarios were developed through consideration of previous fare policies,

TABLE 2: Calculated Weights

	Riders of Color		White Riders	
	Below Livable Wage	Above Livable Wage	Below Livable Wage	Above Livable Wage
Peak travel	3.796	1.276	2.065	0.694
Off-peak travel	4.391	1.476	2.388	0.803

review of formal and informal fare proposals, attention to prior WMATA board discussions, and conversations with WMATA staff. To ensure direct, unbiased comparisons between fare scenarios, fare levels within each fare scenario were first calculated to be revenue neutral, assuming unchanged ridership. Once fares were set in each scenario we relaxed the assumption of constant ridership to estimate rider response.

Incorporating Fare Elasticities

Changes in the number of trips are an important component of fare equity, and a key layer to understand alternate fare scenarios. The ability of riders to travel on Metrorail is not captured solely by measures of average fare; an unobservable aspect of fare equity is the number of trips not taken because the cost is prohibitive. Riders are sensitive to price changes; higher costs will result in less travel. But to gauge the extent of rider responses, and to capture differences across rider segments, we need to integrate measures of price sensitivity. We use the price elasticity for transit fares as this measure. Price elasticity is calculated as the percentage change in demand for a given percentage change in price. In regards transit fares, the fare elasticity is the percentage change in transit journeys given a change in the cost of each trip. The more sensitive a rider is to price changes, the more responsive their travel behavior will be, and the higher the corresponding fare elasticity.

Given that we developed alternate fare structures to be revenue neutral in aggregate while holding ridership constant, the cost of individual rail trips correspondingly fluctuates with some becoming more expensive and others less so. To capture rider responses to fare changes, we applied elasticity estimates developed specifically for the Metrorail system by The National Center for Smart Growth at the University of Maryland (*34*). These granular elasticity estimates are differentiated by journey and rider characteristics. Given the trip and demographic information collated in our trips dataset, we selected the most elastic option for a given trip based on the rider's race, income, access to transit benefits, and the number of bus-rail transfers on a given journey.

After assigning fare elasticities, we used the detailed characteristics of each trip in our dataset to calculate the fares due under each fare structure. Although the price of trips between origin and destination pairs change in divergent ways, not all pairs are equally traveled. To determine system-wide travel volume changes, we applied estimates to calculate trip changes for each station pair and aggregated across all station pairs and travel periods.

DEVELOPING ALTERNATE FARE STRUCTURES

Alternate fare scenarios were developed to encourage consideration of a diversity of realistic structures. The constructed scenarios vary the fare impacts ascribed to a Metrorail trip's distance, time of travel, and specific journey characteristics in order to isolate the importance of each. Altogether, these variations provide clarity on how the interplay between trips and fare structures combine to affect fare equity outcomes. We have grouped our alternate fares into five scenarios, each comprising fare implementations that share a high-level organizing principle.

TABLE 3: **Summary of Alternate Fare Structures**

Fare structure	Type	Distance basis	Peak surcharge	Core surcharge
1a	Distance-based	Composite miles	*X*	
1b	Distance-based	Composite miles		
1c	Distance-based	Composite miles	*X*	*X*
1d	Distance-based	Composite miles	*X*	
2a	Distance-based	Crow-flies miles	*X*	
2b	Distance-based	Track miles	*X*	
3a	Zonal	Zonal difference	*X*	
3b	Zonal	Zonal difference		
3c	Zonal	Zonal boundary crossings	*X*	
3d	Zonal	Zonal boundary crossings		
4a	Flat-fare	–	*X*	
4b	Flat-fare	–		

Scenarios 1: Variations on the Composite Distance-Based Structure

The current Metrorail fare structure, as previously described in the background section, is our baseline scenario and referred to as scenario 1a.

Fare structure 1b diverges from the existing structure in that there is no peak-pricing differentiation. The off-peak minimum fare ($2.00) becomes the minimum fare for all Metrorail trips. The maximum fare is set at $5.50; this is nearer the current peak maximum fare ($6.00) than the off-peak maximum fare ($3.85), although it is between the two. The first per-mile charge, for miles 3 to 6, and the second per-mile charge, for distances further than 6 miles, are calculated to be $0.312 and $0.275, respectively.

Fare structure 1c mimics the current fare structure, but incorporates a small surcharge of $0.30 for all trips entering into, terminating at, or traversing the system core during the peak periods. The core is defined as the section of the Metrorail network comprising stations that experience maximum passenger loads along each rail line. To offset this core surcharge, the minimum peak fare is reduced to $2.00. This matches the off-peak minimum, resulting in a single minimum fare. The maximum fare in the peak is adjusted down by $0.25 to $5.75. The distance-based costs are unchanged from the existing structure.

Fare structure 1d utilizes existing peak and off-peak differentiation, but with a single, consolidated fare per-mile for all Metrorail journeys beyond 3 miles. The existing per-mile charge for distances between 3 and 6 miles is applied to all distance-based charges. The per-mile charge for all off-peak trips is recalculated to be $0.110 given the additional revenue generated during the peak. There are no changes to the minimum or maximum fares.

Scenarios 2: Per-mile Structures with Alternate Measures of Distance

As described, the current WMATA Metrorail fare structure uses a composite measure of distance to determine fare, calculated as the the average of two components: the crow-flies distance between the Metrorail stations at which a trip begins and ends and the miles traveled along the WMATA rail network between those stations. The two structures considered in this scenario each use a single component of composite distance as the distance basis. They retain the current minimum and maximum fares in both the peak and off-peak periods.

To determine per-mile costs under alternate measures of distance, we designed the costs based on three principles. First, regardless of how distance is measured, the percentage of trips that pay the minimum fare should remain unchanged. Second, the percentage of trips that incur the maximum fare should remain unchanged. Third, revenues generated during peak and off-peak periods should individually remain revenue neutral, assuming constant ridership.

Fare structure 2a uses the crow-flies distance between origin and destination rail stations to calculate the distance-based fees. The minimum fare covers the first 2.5 miles traveled, a higher per-mile rate ($0.348 peak / $0.254 off-peak) covers travel between 2.5 and 5 miles, and a lower per-mile rate ($0.307 peak/ $0.224 off-peak) is charged beyond 5 miles until the maximum fare is reached. Such a structure would remove any additional fare burden currently incurred for traveling between stations not directly linked.

Fare structure 2b considers track miles traveled on the Metrorail network between origin and destination as the distance basis. The track-miles distance is assumed to be the shortest path along the rail network, regardless of how close the stations are geographically. The minimum fare covers the first 3.5 miles of travel, a higher per-mile rate ($0.285 peak / $0.205 off-peak) is charged for travel between 3.5 and 7 miles, and a lower per-mile rate ($0.251 peak / $0.180) is charged beyond 7 miles until the maximum fare is reached.

Scenarios 3: Zonal Fare Structures

Zonal fares would retain some benefits of a distance-based fare system while simplifying the calculation of station-to-station fares compared to the current system. However, such systems can have unexpected consequences, as expensive zonal boundaries make short inter-zone trips costlier than longer intra-zone trips.

Zonal systems can charge passengers based on two fare bases: the absolute difference in the zone numbers of the origin and destination station ("zonal difference fare basis") or the number of zonal boundaries crossed in the course of travel ("boundary crossings fare basis"). The former would discount longer suburb-to-suburb trips relative to trips between the system core and the suburbs, while the latter charges passengers proportionally to the total length of their trip.

In collaboration with WMATA staff, we developed a zonal map for the Metrorail system that includes five zones. We determined zonal boundaries algorithmically based on the track distance of each station to the center of the Metrorail system. We defined the center of the system as the 0.3 mile segment between Metro Center and Gallery Place-Chinatown stations. These two stations are centrally situated in Washington, D.C. and together serve all Metrorail lines. The distance from a given station to the center of the system is then defined as that station's track distance to the closer of the two stations. The track distance cutoffs defining the zonal boundaries were first determined using the Jenks natural breaks classification method, then heuristically adjusted to achieve specific desirable characteristics, such as restricting Zone 1 to a smaller region of the District of Columbia and ensuring that each non-terminus station is adjacent to at least one station within the same zone.

Given the zonal map, and the two fare bases, four zonal structures were developed: a zonal fare structure with zonal difference fare basis and peak pricing (3a); a zonal fare structure with zonal difference fare basis and no peak pricing (3b); a zonal fare structure with a boundary crossings fare basis and peak pricing (3c); and a zonal fare structure with a boundary crossings fare basis and no peak pricing (3d).

Under scenario 3a and 3b, passengers pay on the zonal difference fare basis, meaning a passenger who crosses 8 zonal boundaries and ends up in the same zone pays the minimum fare. Under 3a, with peak pricing, fares are designed to closely mirror the current fare system, ranging from $2.00 to $4.00 in the off-peak periods and $2.25 to $6.00 in peak periods. Under 3b, with no peak fare differentiation, the fares range from $2.25 to $5.05 in even $0.70 increments.

Scenarios 3c and 3d utilize a boundary crossings basis. Fares are composed of the minimum fare, one charge that increments for each boundary crossed up to four crossings, and then a discounted charge that increments for all remaining boundary crossings. The result is that long suburb-to-suburb trips traversing the network core are costlier than the longest suburb-to-core trip. Scenario 3c has the same minimum fares in the peak and off-peak periods as the current system, but has a slightly higher maximum fare in both periods due to small additional charges for travel crossing more than four zonal boundaries ($6.05 peak / $4.40 off-peak). Scenario 3d follows the same logic as scenario 3c, but with no peak pricing differentiation, resulting in fares that range from $2.00 to $5.80.

Scenarios 4: Flat Fare Structures

Lastly, we evaluate two flat fare structures that remove the distance-based component of Metrorail's fare structure. One scenario includes continued price differentiation between the peak and off-peak periods (4a) and the other charges a single fare for all trips regardless of distance and time of journey (4b).

To calculate the revenue neutral flat-fare equivalent with peak pricing (4a), all fare revenues collected during peak transit hours were spread evenly across all of the journeys taken during peak hours. Likewise, all fare revenues generated in the off-peak were divided among all off-peak trips. This resulted in flat fares of $3.45 in the peak and $2.70 in the off-peak.

Finally, we determined a revenue neutral flat fare such that all fare revenues generated by the existing distance-based structure were spread evenly across all Metrorail trips taken (4b). The calculated flat fare in this scenario is $3.20.

RESULTS

Dataset Description

Table 4 displays summary statistics for trips grouped by both race and income. While our analysis focuses on race and income separately, this table provides useful background when exploring rider segments. The average travel distance, in crow-flies miles, and the ratio of peak travel both influence fares under the current system. So does the directness of each trip, included in the table as travel circuity. This metric captures the indirectness of trips taken on Metrorail are, defined as the ratio of Metrorail track distance to crow-flies distance. A value of 1 indicates that the distance along the rail network is a direct line matching the crow-flies distance; as the circuity measure increases, so too does the detour required to navigate from origin to destination using Metrorail. The circuity metric is illustrated in Figure 2.

TABLE 4: **Combined Trips Dataset Summary Statistics**

		People of Color		White	
Weighted Metrics	All riders	Below Livable Wage	Above Livable Wage	Below Livable Wage	Above Livable Wage
Trips	12,129	1,218	4,544	456	5,911
Pct. of total		10.0%	37.5%	3.8%	48.7%
Average distance *(Crow-flies miles)*	6.05	5.56	6.52	5.51	5.83
Travel circuity *(Track miles / crow-flies miles)*	1.29	1.46	1.30	1.33	1.27
Trips by period					
Peak	70.4%	54.6%	74.5%	63.4%	71.1%
Off-peak	29.6%	45.4%	25.5%	36.6%	28.9%
Average fare ($)	3.28	3.08	3.44	3.12	3.20

As shown in table 4, slightly under half of the trips in our weighted dataset were taken by riders of color. When considering income, low-income riders take just under 14% of Metrorail trips. Most low-income riders are people of color. Low-income riders, regardless of race, are more likely to travel during off-peak periods.

Considering average trip distance and circuity, low-income riders take both the shortest trips as well as the least direct trips. Delving further, low-income riders of color take by far the most circuitous trips in our dataset. Riders of color with incomes above the livable wage take both the longest trips, and much more direct trips as compared to their low-income counterparts. Among white riders, those making above the livable wage take both longer and more direct trips, but the discrepancy is not as large.

Fare Equity Across Race

As shown in figure 3, when partitioning Metrorail customers into white riders and riders of color, the current fare structure results in riders of color paying, on average, 5% more per trip than white riders.

Fare structures maintaining the current composite distance basis (scenarios 1) result in varied average fares, but the prices across segments fluctuate together leaving the price differential unchanged. The only of these scenarios expected to result in a noticeable change in trips is scenario 1b, which removes peak pricing. The majority of trips, regardless of race and income, occur in the peak period; accordingly, without peak pricing the majority of trips would become cheaper. However, it is important to remember that the converse also occurs; trips in the off-peak, which low-income travelers take at higher frequencies, are saddled with higher fares. Altering the distance basis used to calculate fares (scenarios 2) results in minimal changes to fare levels and trips taken, but a switch to crow-flies distance as the fare basis provides a slight positive benefit to riders of color.

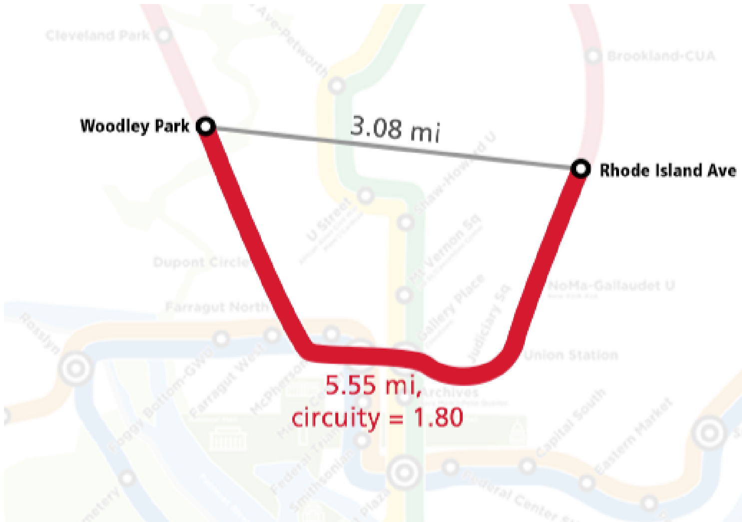

FIGURE 2: **Visual representation of circuity measurement using actual Metrorail network distance along Red Line.**

Zonal results differ across the basis used, with zonal difference implementations (3a, 3b) equalizing average fares across race. On the other hand, zonal boundary crossings structures (3c, 3d) have no impact on fare differential across groups. However, the impact of all zonal structures is to depress the number of rail trips, with white riders expected to decrease travel proportionally more in three of the four implementations.

Flat fares (scenarios 4) equalize the fare per trip, but lead to an expected drop in trips for all rider groups. This is intuitive; to reach a revenue neutral fare, assuming constant ridership, the calculated flat fare must be higher than the current fare for many short-distance trips, whereas longer trips see a price reduction. Given the distribution of trip lengths, there are many more short trips negatively impacted by this change than long trips benefitting from subsidized travel.

Fare Equity Across Income

As shown by figure 4, evaluating average fare per trip based on income indicates that low-income riders generally pay less per trip than their counterparts making above the livable wage.

Variations on the current composite-distance fare basis show less consistency across structures than when considering race. First, removal of peak pricing (1b) would reduce prices for all travelers, but is most beneficial to higher-income riders who experience a larger drop in average fare. On the other hand, structure 1d contemplates a single, consolidated per-mile rate coupled with a decreased off-peak per-mile charge. For low-income riders, this is estimated to reduce average fare and boost low-income trips with negligible impacts to higher-income travelers. Finally, a core surcharge (1c) provides slight benefits to low-income riders.

When altering the distance basis used to determine fare, a crow-flies basis (2a) benefits low-income riders, as they take the least direct trips. In comparison, track miles as a basis (2b) reduces the fare differential and benefits higher-income travelers who take more direct trips on the Metrorail system.

The equity impact of a zonal fare system, when considering rider income, varies based on its implementation. A zonal difference system with peak pricing (3a) provides a slight benefit to

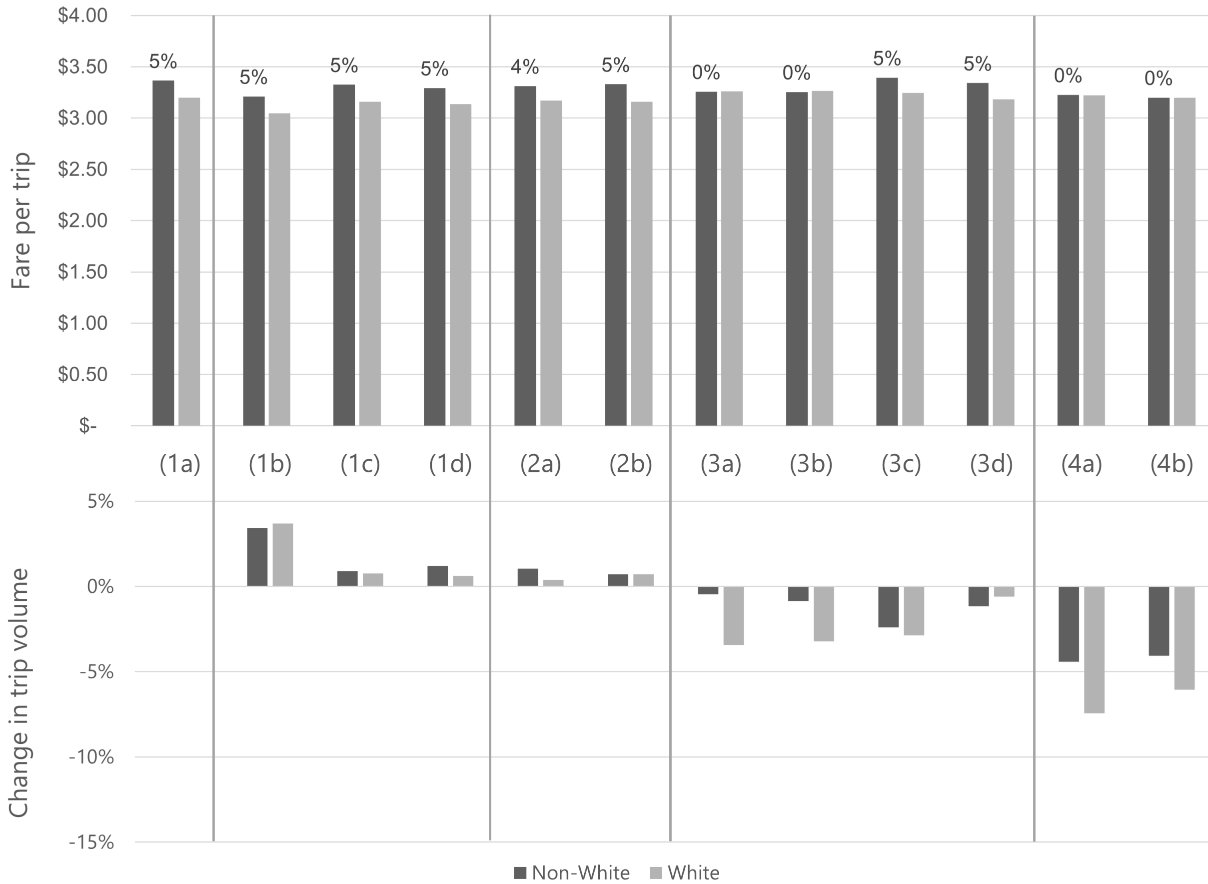

FIGURE 3: **Fare per linked trip and travel volume changes in all fare scenarios with riders segmented by race.**

low-income riders, but at the expense of a systemwide decrease in trips. Every other zonal implementation performs worse in terms of equity. Removing peak pricing from the zonal difference structure (3b) increases the fare differential between groups, but this is achieved through reduced travel for both segments. Boundary-crossings implementations (3c, 3d) have much larger negative impacts on low-income riders, who would experience higher costs and fewer trips.

Flat fares (4a, 4b) result in the largest expected decrease in travel. Low-income riders would pay higher prices and reduce travel to a larger extent than higher-income travelers, although all groups would take fewer trips.

ANALYSIS

Contrasting Results Across Race and Income

An interesting result from this analysis concerns differing fare scenario impacts on rider segments defined by race and income. These two groups are equally important when considering equity, but differing travel behaviors can result in contrasting recommendations. One clear example can be observed in the disparate impacts of flat fares (scenarios 4); within the Washington, D.C. area this would result in riders of color no longer paying higher per-trip fares, but low-income riders would face the burden of the largest fare increases. Further, a revenue neutral flat fare is expected

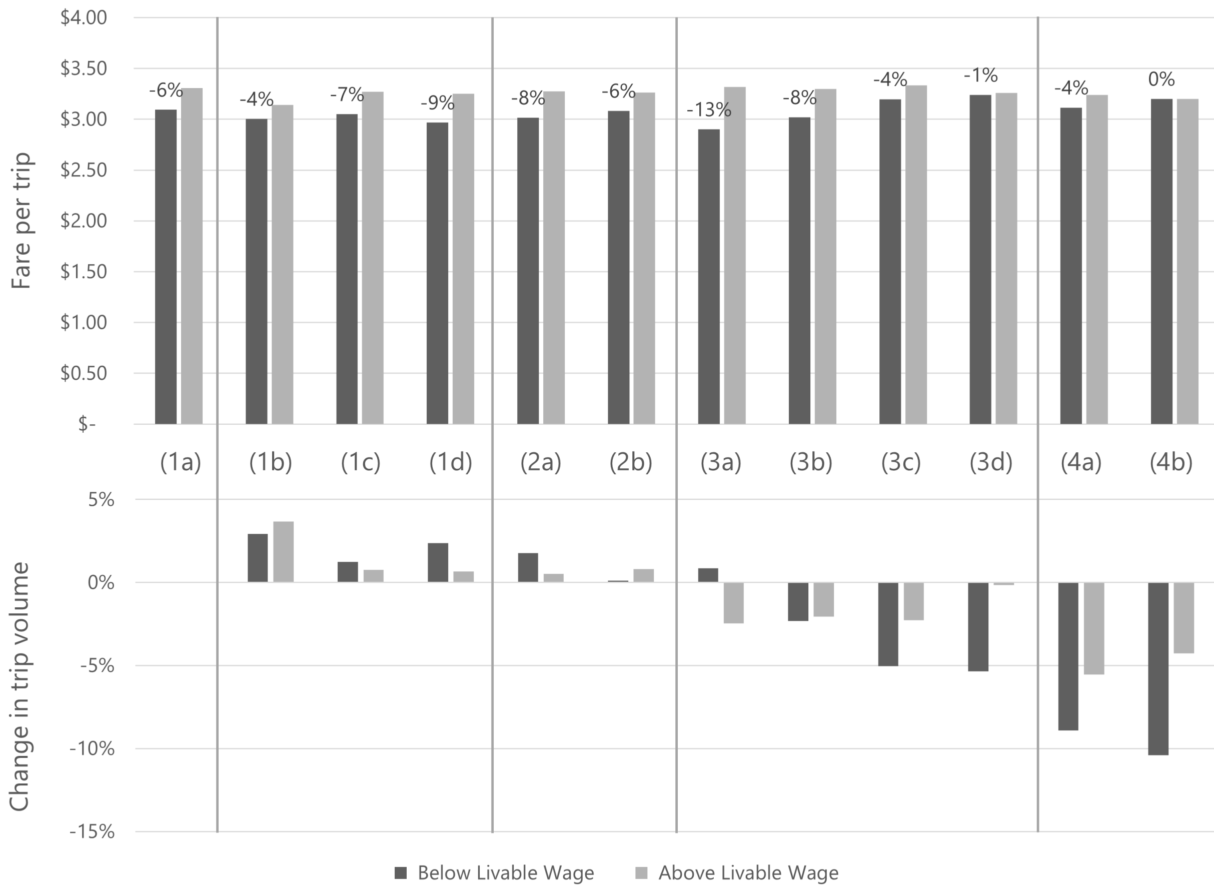

FIGURE 4: **Fare per linked trip and travel volume changes in all fare scenarios with riders segmented by income.**

to decrease travel for all groups, but it is expected to reduce trips taken by white riders to a greater extent than riders of color, and separately reduce trips by low-income riders more than riders earning above the livable wage. While flat fares may by some measures benefit riders of color, they would simultaneously disadvantage low-income riders.

Other investigated fare structures confirm that equity impacts do not always vary in concert across race and income. Consider the four potential zonal fare structures explore: estimates show that when considering race there is, at worst, no change in the fare differential and, at best, an equalization of average fares between riders of color and white riders. When evaluating the same zonal implementations based on rider income, however, the impacts range from a reduction in average low-income fares and a decrease in higher income travel (3a) all the way to fare increases and travel decreases almost solely for low-income riders (3d).

Commonalities Across Scenarios

Although there are differing impacts on fare equity when considering race and income, there are nevertheless attributes that show similar impacts across fare scenarios.

A clear result from this analysis is that peak pricing provides a net benefit to low-income riders without disadvantaging riders of color. When comparing white riders and riders of color

, fare implementations with and without peak pricing result in the same fare differential between groups regardless of fare basis. This holds across all scenarios evaluated. On the other hand, across the very same structure types any removal of peak pricing negatively impacts low-income travelers.

Penalizing indirect travel further reduces fare equity. This is most plainly evaluated by altering the distance measure used as a basis for fares (scenarios 1a, 2a, 2b). Whether considering race or income, utilizing crow-flies distance to calculate fare results in more advantageous outcomes for both riders of color and low-income rider segments. Conversely, using track miles along the WMATA network provides a slight advantage to white riders and those earning above the livable wage. Switching the current structure to a crow-flies distance basis would not only better align travel cost with the benefits received, but advantages both low-income riders and riders of color.

Similarly, when comparing zonal fare structures, implementing a zonal fare structure based on the difference between origin and destination zones provides the most benefit to low-income and riders of color. Basing the zonal fare on the number of zonal boundaries crossed, even with a lowered incremental cost for each additional crossing after the first four, results in worse outcomes for low-income and riders of color. Riders pay to travel from origin to destination, as quickly and safely as possible; charging them for taking circuitous trips penalizes them monetarily for something beyond their control, after already requiring more time to travel an indirect route.

Our results highlight an additional opportunity to reduce fare complexity, increase fare legibility, and simultaneously provide a benefit to low-income Metrorail users; consolidation of per-mile rates. Charging a single per-mile rate for all distances between the minimum and maximum fare, and combining this change with a single, lowered off-peak per-mile rate subsidized by increased peak revenues would provide a benefit to low-income riders with minimal impact on peak travelers.

Further Considerations

The policy tradeoffs considered by this analysis illuminate which elements of travel, when incorporated into fare policy, can enhance equity. Our results report weighted average fares and aggregated trip volumes under each fare scenario; a worthwhile extension would be to explore the distributional impacts of alternate fare structures within rider segments to understand how widespread benefits or disadvantages are experienced within each rider segment.

In this manuscript we have focused specifically on the monetary aspects of fare policy as it relates to the Metrorail system. Further research may quantify the burdens of riding transit to include fares, travel time, crowding, reliability, and transfers. While not explored in this analysis, WMATA's removal of the transfer fee for multimodal journeys likely advantaged both low-income riders and riders of color; our assembled data indicates these two groups take a higher proportion of trips requiring a transfer between bus and rail. Further examination of Metrobus riders in conjunction with Metrorail riders could provide insight on the non-monetary costs imposed by a fare structure. Such research could address the question of to what extent travelers may take inefficient bus journeys and avoid Metrorail due to the lower, flat cost of a Metrobus trip.

While the methodology and discussion presented in this paper are applicable to a large variety of cities, the results are context-dependent and sensitive to such factors as the specific demographic residential choice, development patterns, gentrification, and travel patterns, as well as Metrorail's relatively unusual role as a hybrid subway-regional rail system. We welcome the application of the methods presented in this work to other United States and international contexts as appropriate, and a comparison of the results and insights into fare equity and transit equity more generally.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: D.O., E.E., J.A., and J.Z.; data collection: D.O. and E.E.; analysis and interpretation of results: D.O., E.E., and J.A.; draft manuscript preparation: D.O. and E.E. All authors reviewed the results and approved the final version of the manuscript. The authors do not have any conflicts of interest to declare.

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