How far are we from transportation equity? Measuring the effect of wheelchair use on daily activity patterns.

Gregory S. Macfarlane[a,*], Nate Lant[a]

[a]*Brigham Young University, Civil and Construction Engineering Department, 430 Engineering Building, Provo, Utah 84602*

Abstract

The mobility needs of individuals with travel-limiting disabilities has been a transportation policy priority in the United States for more than thirty years, but efforts to model the behavioral implications of disability on travel have been limited. In this research, we present a daily activity pattern choice model for multiple person type segments including an individual's wheelchair use as an explanatory variable. The model results show a strong negative impact of wheelchair use on out-of-home travel, exceeding the impact of other variables commonly considered in such models. We then apply the estimated model within an activity-based model for the Wasatch Front region in Utah; the results suggest a shift in tour making of sufficient scale — among both wheelchair users and those in their households — to warrant further scrutiny and analysis.

Keywords: Transportation equity; travel behavior

1. Introduction

In 1990, the United States Congress passed the Americans with Disabilities Act (ADA), seeking to protect individuals with qualifying disabilities from discrimination while using public services including transportation systems (Title II), in public accommodations (Title III), and various other specific situations. For transportation service providers, ensuring equal access for wheelchair users is a critical design constraint for vehicles as well as stations and the surrounding areas (Federal Transit Administration, 2015). Buses and trains had to be redesigned with low floors and access ramps; elevators and ramps needed to be installed in stations alongside escalators and stairs. Even today, most traditional automobiles remain inaccessible to wheelchair users — at least without substantial modification. This last challenge is a particular concern for emerging mobility providers — who often use private vehicles owned by individual operators — and for public transit agencies who are beginning to cooperate with such providers to operate first/last mile services (Macfarlane et al., 2021; Shaheen and Chan, 2016).

Though the ADA only requires agencies to provide reasonable accommodation on public conveyances and does not try to establish equity in outcomes, the passage of 30 years provides a convenient time to

*Corresponding Author
Email addresses: gregmacfarlane@byu.edu (Gregory S. Macfarlane), natelant@gmail.com (Nate Lant)

consider what gaps and challenges persist for wheelchair users in accessing and using the transportation system. Specifically, what gap exists in the observed travel behavior outcomes of wheelchair users *vis a vis* the non wheelchair using population, all else equal? And more importantly, how should this gap be applied within travel forecasting models and related planning activities?

In this paper, we investigate the degree to which daily activity patterns are influenced by an individual's use of a wheelchair. This involves two separate analyses: first, we model daily activity pattern choice using responses to the 2017 National Household Travel Survey (U.S. Department of Transportation and Federal Highway Administration, 2017), incorporating the individual's wheelchair use as an explanatory variable. Second, we apply the behavioral estimates obtained from the choice analysis in a modified activity-based model for the Wasatch Front metropolitan region in Utah to estimate the population-level effects of introducing wheelchair status in a regional travel demand model.

The paper proceeds in a typical fashion. A literature review discusses prior attempts to evaluated and quantify the travel behavior of users with disabilities. A section describing the methodology of the choice analysis and model application is followed by a discussion of the results from both analyses. The paper concludes with a discussion of limitations in this analysis and associated avenues for future research and policy intervention.

2. Literature

Recent analysis (Brumbaugh, 2018) of the 2017 NHTS (U.S. Department of Transportation and Federal Highway Administration, 2017) suggests there are 13.4 million individuals individuals in the US with travel-limiting disabilities — as defined by a specific question in the NHTS and encompassing sight, ambulatory, hearing, and other disabilities. Of these individuals, 20 percent (or 2.7 million) self-report as using wheelchairs. With the relative aging of the U.S. population, the share of Americans with all disabilities as well as those using wheelchairs is likely to rise substantially (Laplante, 2003; Sweeney, 2004). The question of how the travel behavior of individuals with travel-limiting disabilities varies from the travel behavior of individuals without these disabilities has been addressed previously in a number of studies.

With regards to travel patterns, surveys of the general population and surveys specifically targeted at individuals with disabilities both reveal significant and meaningful differences compared to individuals without disabilities. Specific findings include that individuals with disabilities leave their homes on fewer days if if they leave at all (Sweeney, 2004), make fewer daily trips (Brumbaugh, 2018; Schmöcker et al., 2005) make fewer work trips and more healthcare maintenance trips (Ermagun et al., 2016), rely more on others for their travel (Sweeney, 2004) and have considerably restricted mode choices (Rosenbloom, 2007; Ruvolo, 2020). These differences in mobility and activity patterns have important and observed negative implications for the individual's access to opportunity for employment (Lubin and Deka, 2012; Rosenbloom,

2007) and social interaction (Bascom and Christensen, 2017; Velho et al., 2016). Some recent studies have also looked at the meaningful role of developmental (Wasfi and El-geneidy, 2007) and intellectual (Feeley, 2019) disabilities on travel patterns.

The underlying reasons why wheelchair users and others with disabilities exhibit different travel patterns than other individuals are varied, but are likely to include both technical and attitudinal barriers. Technical barriers include poor access to private vehicles (Van Roosmalen et al., 2010), poorly maintained sidewalk and pedestrian infrastructure (Frackelton et al., 2013), lack of physical access to TNC vehicles (Ruvolo, 2020), bus ramp complication and malfunction (Velho et al., 2016), and numerous other problems across many modes. Attitudinal barriers include feeling embarrassment, for instance when a safety tone alerts all passengers that the wheelchair ramp is being deployed drawing attention not only to the user and his or her disability, but also to the fact that the transit vehicle is being delayed (Velho et al., 2016). Additionally, some wheelchair users and others with disabilities have faced outright discrimination from private transportation service operators (Bascom and Christensen, 2017).

In spite of this relatively mature literature and the variety of findings on the topic, the research to date might be described as fragmented in both scope and application. That is, the literature reviewed here typically considers a single specific disability within the wide variety of relevant disabilities manifested in the NHTS results. But more importantly in the context of this research, the literature consists largely of ad-hoc studies conducted on specially collected datasets rather than holistically considering how disability manifests at within an established transportation decision-making process. Specifically, there has not to our knowledge been a rigorous evaluation of the travel behavior of individuals with disabilities within the framework of a travel activity model.

As a result, recent attempts to simulate or model services aimed at this population have needed to make simplifying assumptions. In an attempt to model demand for a modern mobility system targeted at wheelchair users in Berlin, Bischoff (2019) simply assumed demand for this service would be similar to current demand for the regional paratransit system, augmented by a mode shift from taxi. Though paratransit patrons in the United States, Germany, and other similar contexts may use wheelchairs, the use of a wheelchair alone does not usually qualify a user for paratransit service. Further, in the initial modeling by Bischoff (2019) there was no link between the trips and the daily activities of the wheelchair users; there was not even a good understanding of likely trip origin, destination, or length distribution.

Including wheelchair users or wheelchair use status in a regularized travel model framework would help to fill two important gaps in the current literature. First, the comparison would help to illuminate the travel behavior characteristics of this important population within a framework that is readily understandable *vis a vis* other population segments. Second, researchers engaged in policy and planning work for this population could replace simplifying assumptions with plausible daily activity patterns rooted in observed behavior.

3. Methods

To begin the process of evaluating the effect of wheelchair use on travel behavior, we have developed a two-stage methodology. First, we estimate a daily activity pattern choice model using data from the 2017 NHTS. We then apply the coefficients obtained from that model in an activity-based model representing the Wasatch Front Region in Utah.

Activity-based models are a relatively mature construct in travel behavior research and in practical demand forecasting (Rasouli and Timmermans, 2014). Activity-based models attempt to recreate the long- and short-term decision patterns of synthetic individuals using a chain of econometric and statistical choice models. The specific sub-models included in this chain can vary between specific implementations, but a recent open-source project — ActivitySim (AMPO, 2020) — implements a popular set of models developed by Davidson et al. (2010). Specifically, the ActivitySim demonstration model is a implementation of the "Travel Model One" model for the Metropolitan Transportation Commission (MTC, San Francisco Bay) (Erhardt et al., 2012). For simplicity and potential future comparison with other models, we apply the ActivitySim model in this research.

3.1. Choice Model

The first step in the ActivitySim model chain is a *daily activity pattern* model of the type described by Bradley and Vovsha (2005). This model allows individuals to choose one of three daily activity patterns:

- Mandatory (M) daily patterns revolve around school and work activities that are typically considered non-discretionary. These activities and the travel to them anchor an individual's daily schedule, though other tours are possible.
- Non-Mandatory (NM) daily patterns involve only discretionary activities: shopping, maintenance, etc.
- At-Home (H) daily patterns describe the schedule and activities of individuals who never leave the home during the travel day.

The choice between the daily patterns is described with a multinomial logit model (Domencich and McFadden, 1975), where the utility functions for each option are determined by an individual's socioeconomic characteristics and person type segment. The specific innovation of the Bradley and Vovsha (2005) model is that the daily activity patterns are coordinated, or that the choice of one individual in a household influences the choice probability of other household members.

Data for this study comes from the 2017 NHTS (U.S. Department of Transportation and Federal Highway Administration, 2017), which includes responses from across the United States involving rural, urban, and suburban areas. We restrict the data to households residing in an metropolitan statistical area (MSA) between one and three million in population. There are 76,367 individuals in 36,497 households that responded to the NHTS from these areas, though not all of these records are useful due to missing or incomplete data in key variables.

The NHTS releases public data in separate tables for persons, households, trips and vehicles; to determine the daily activity pattern for a given individual it was necessary to transform the trips table into a table of activities. We did this by reconstructing a schedule for each person from the reported trip origin and destination activity codes. We then determined whether each reported tour (a chain of activities away from the individual's home) contained a mandatory school or work activity. If any tour contained a mandatory activity, the person's entire daily activity pattern was classified as "mandatory"; if not, the daily activity pattern was "non-mandatory." By identifying respondents in the persons table without records in the trips table, we can determine individuals with a "home" daily activity pattern.

The NHTS has a number of questions where respondents can indicate a disability for themselves or other household members. Each respondent is asked "Do you have a condition or handicap that makes it difficult to travel outside of the home?" If the answer is yes, several follow-up questions are asked, including "Do you use any of the following medical devices? Select all that apply." The list of medical devices respondents can indicated includes canes, walkers, seeing-eye dogs, crutches, motorized scooters, manual wheelchairs, motorized wheelchairs, or something else (other). For this study, we identify wheelchair users as respondents who report using a manual wheelchair, mechanical wheelchair, or motorized scooter.

The specific variables included in the daily activity pattern choice models are based initially on the variables used in MTC Travel Model One (Erhardt et al., 2012). The variables available in the NHTS include the age of the person and the household income treated as categorical ranges; gender, work, and college degree status are treated as binary values. Automobile availability is included via a binary "sufficiency" variable where a household with at least as many vehicles as adults is considered "auto sufficient." Descriptive statistics of the model variables are given in Table 1.

Table 1: Model Estimation Data: Descriptive Statistics

		Full-time worker (N=16188)		Non-worker (N=3723)		Part-time worker (N=4028)		Retired (N=10060)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Bachelors or more		0.6	0.5	0.4	0.5	0.5	0.5	0.4	0.5
		N	Pct.	N	Pct.	N	Pct.	N	Pct.
Age	05-39	5762	35.6	1450	38.9	1356	33.7	8	0.1
	40-64	9570	59.1	2239	60.1	1705	42.3	1833	18.2
	65-79	836	5.2	33	0.9	903	22.4	6321	62.8
	80+	20	0.1	1	0.0	64	1.6	1898	18.9
Wheelchair	FALSE	16161	99.8	3609	96.9	4010	99.6	9619	95.6
	TRUE	27	0.2	114	3.1	18	0.4	441	4.4
Income	< \$25,000	872	5.4	961	25.8	663	16.5	1825	18.1
	\$25,000 - \$50,000	2235	13.8	632	17.0	713	17.7	2437	24.2
	\$50,000 - \$100,000	5312	32.8	953	25.6	1203	29.9	3245	32.3
	> \$100,000	7476	46.2	1102	29.6	1333	33.1	1975	19.6
Sex	Male	8820	54.5	1192	32.0	1487	36.9	4488	44.6
	Female	7368	45.5	2531	68.0	2541	63.1	5572	55.4
	I prefer not to answer	0	0.0	0	0.0	0	0.0	0	0.0
	I don't know	0	0.0	0	0.0	0	0.0	0	0.0
Works from Home	-1	0	0.0	3721	99.9	267	6.6	10060	100.0
	-7	2	0.0	0	0.0	1	0.0	0	0.0
	-8	1	0.0	0	0.0	1	0.0	0	0.0
	-9	728	4.5	0	0.0	0	0.0	0	0.0
	01	1718	10.6	0	0.0	940	23.3	0	0.0
	02	13739	84.9	2	0.1	2819	70.0	0	0.0

We adopt the person type segmentation strategy employed by ActivitySim; segmentation allows for heterogeneity in available alternatives and utility coefficients between individuals with highly divergent expected behaviors. For example, full time workers and pre-driving age school children will have strongly different responses to income, automobile availability, and other variables in determining their most likely daily pattern. ActivitySim classifies persons into seven person segments, though we only consider four types in this study, defined as follows:

- Full-time workers (FW) - reported working "full-time" at their primary job.
- Part-time worker (PW) - reported working "part-time" at their primary job, as well as any person who reported being a "non-worker" or "retired" who nevertheless reported a work or school activity.
- Non-working adults (NW) - reported "unemployed" as their primary activity of the previous week, as well as individuals over 18 who were not classified elsewhere.
- Retired (RT) - reported "retired" as their primary activity of the previous week, or who are over the age of 65 and reported that they were not workers.

The other three person types are university students, schoolchildren under driving age, and driving-age schoolchildren. A limited number of individuals who could plausibly be considered university students responded to the NHTS, so we cannot estimate reliable choice models. Among schoolchildren of any age, too few report using wheelchairs to justify including these segments in this study.

3.2. ActivitySim Implementation

After obtaining an estimate for the relationship between wheelchair use and daily activity patterns, we wish to understand the impact of this variable on overall transportation demand forecasting. To do this, we can place the enhanced daily activity pattern model including this relationship within an Activitysim implementation. In this case, we use an implementation of ActivitySim in the Wasatch Front region of Utah; this implementation includes the Salt Lake City, Provo, and Ogden metropolitan areas.[1]

The synthetic population for this implementation is generated with PopulationSim (Paul et al., 2018), which uses American Community Survey Public Use Microdata Sample (ACS PUMS)(US Census Bureau, 2022) as seed table. Any variables from ACS PUMS can in principle be included in synthetic population and therefore in the model. The ACS PUMS includes a "disability" variable but not specific information on wheelchair use. The NHTS, however, does explicitly contain a wheelchair use variable as described earlier.

Using the NHTS data, we estimated a binary logit regression model where the probability for wheelchair use was determined to be a function of age,

$$P_{\text{wheelchair}|\text{disability}} = -2.59 + 0.014 * \text{age} \tag{1}$$

[1]This implementation is not the official regional travel demand model; the calibration and development of this model is described in (Macfarlane and Lant, 2021).

Other specifications of this regression equation did not result in substantively different model fit. For each person in the synthetic population with a disability as sampled from the ACS PUMS seed table, we determined the probability they would use a wheelchair based on the model in Equation (1). A random draw allocated these individuals into using or not using a wheelchair. Of the total synthetic population, those using a wheelchair consisted of 0.8 percent of all individuals.

With the synthetic population described above, we modified the ActivitySim daily activity pattern model to consider wheelchair use. We then compared two complete runs of ActivitySim on the same synthetic population of 2.47 million individuals, with and without the wheelchair use variable activated. As described earlier, the daily activity pattern model in ActivitySim is coordinated, meaining that when an individual has an increased likelihood of choosing an at-home tour, other members of the household will have an increased likelihood as well (Bradley and Vovsha, 2005). Thus it is important to evaluate not only the daily activity patterns of individuals who use wheelchairs, but also their household members.

4. Results

4.1. Choice Analysis

We estimated the daily activity pattern choice models using mlogit for R Croissant (2020). As described above, the alternatives for daily activity pattern choice are a Mandatory pattern where the individual's day involves a work or school tour, a Non-Mandatory pattern where only discretionary trips are taken, and a Home pattern where the individual does not leave home during the day. In the models estimated for this study, the Home pattern serves as the reference alternative with a utility of zero. Retired and otherwise non-working individuals choose only between Non-Mandatory and Home daily activity patterns.

The model estimates are presented in Table 2. The estimated coefficients are of the expected sign, though not all are significant. Some predictors that proved to be insignificant, such as automobile availability for full-time workers, were excluded from the estimated models. The overall model fit — as indicated by the McFadden ρ^2 with respect to a market shares (constants only) model — is not strikingly high. Were the purpose of this research to identify the best fit model of activity pattern choice for each person segment we would undertake an exercise to include, exclude, and identify potential transformations for different sets of variables. In this case, however, the goal of these models is simply to provide a plausible comparison point for the behavior of individuals using wheelchairs against the behavior of individuals in other person type segments.

The model coefficients indicate expected behavior for most included variables. All else equal, the model intercepts imply that full- and part-time workers are more likely to choose a mandatory daily pattern than either a non-mandatory home pattern. Men of all person types are less likely to choose non-mandatory patterns, and college graduates are more likely to choose any kind of out-of-home pattern. The effect of age

Table 2: Daily Activity Pattern Model Estimates

		Full-time worker	Non-worker	Part-time worker	Retired
(Intercept)	Mandatory	2.083 (15.207)**		1.545 (10.300)**	
	Non-mandatory	1.137 (7.854)**	0.591 (6.359)**	0.338 (2.088)	−1.169 (−1.506)
Uses wheelchair	Mandatory	−1.851 (−3.328)**		−3.315 (−3.906)**	
	Non-mandatory	−0.625 (−1.315)	−0.721 (−3.647)**	−1.866 (−3.560)**	−1.258 (−11.924)**
Male	Mandatory	0.008 (0.140)		−0.040 (−0.347)	
	Non-mandatory	−0.148 (−2.378)	−0.271 (−3.477)**	−0.219 (−1.828)	0.235 (4.798)**
College graduate	Mandatory	0.353 (5.716)**		0.360 (3.033)**	
	Non-mandatory	0.648 (9.834)**	0.501 (6.028)**	0.584 (4.815)**	0.349 (6.521)**
Income \$25,000 - \$50,000	Mandatory	−0.055 (−0.373)		0.169 (0.876)	
	Non-mandatory	−0.371 (−2.344)	−0.167 (−1.506)	0.444 (2.196)	−0.095 (−1.358)
Income \$50,000 - \$100,000	Mandatory	−0.175 (−1.272)		−0.160 (−0.971)	
	Non-mandatory	−0.312 (−2.146)	−0.052 (−0.506)	0.190 (1.096)	0.115 (1.643)
Income > \$100,000	Mandatory	−0.206 (−1.495)		−0.326 (−1.994)	
	Non-mandatory	−0.233 (−1.610)	−0.088 (−0.844)	0.127 (0.737)	0.036 (0.444)
Age 40-64	Mandatory	−0.006 (−0.104)		0.669 (5.094)**	
	Non-mandatory	0.026 (0.386)	0.433 (5.788)**	1.055 (7.805)**	2.241 (2.886)**
Age 65-79	Mandatory	0.179 (1.147)		0.395 (2.614)**	
	Non-mandatory	0.801 (5.081)**	1.690 (2.998)**	0.721 (4.647)**	2.132 (2.752)**
Age 80+	Mandatory	17.592 (0.004)		2.067 (2.293)	
	Non-mandatory	17.247 (0.004)	14.648 (0.008)	2.154 (2.391)	1.536 (1.980)
Works from home	Mandatory	−1.542 (−18.502)**		−1.340 (−9.830)**	
	Non-mandatory	−0.044 (−0.558)		0.112 (0.869)	
	N	15 895	3648	3912	9482
	AIC	26 550.18	4470.948	6965.196	10 689.72
	Log likelihood	−13 253.09	−2225.474	−3460.598	−5334.858
	ρ^2	0.031	0.019	0.055	0.026

Coefficients represent utility change relative to stay at home pattern.

t-statistics in parentheses, * p < 0.5, ** p < 0.01

group and income are less impactful for most trip purposes, with the exception of non-mandatory patterns being more likely to be chosen by individuals between the ages of 65 and 79. The strong coefficient seen on the choices of full-time workers over 79 years old is not significant, and is rather a relic of very few full-time workers of that age in the data set.

The use of a wheelchair is strongly significant for all person segments, and indicates wheelchair users are substantially less likely to make mandatory tours even if employed. For non-workers and retirees who use wheelchairs, their propensity to make non-mandatory tours is also substantially diminished. As a note, we considered making wheelchair use an independent person type segment; the results suggest that full-time workers who use wheelchairs are more similar to other full-time workers than they are to non-workers who also use wheelchairs. This justifies including wheelchair use as a variable within each person type segment. More notable than the significance of this variable alone, however, is the fact that its magnitude is so strong. Indeed, wheelchair use appears to be more influential on the choice of daily pattern than any other variable included in these models.

4.2. Activity-based Model

At the individual level, wheelchair use appears highly predictive. It still remains to be seen, however, what the effect of including this variable in a forecasting model will do to aggregate trip making. To examine this question, we placed the wheelchair use variable coefficients shown in Table 2 into the ActivitySim daily activity pattern model. We allowed the other coefficients to retain their values as originally specified, assuming that wheelchair use is orthogonal to the other variables.

Overall, 8,886 individuals of the 2,487,002 in the region changed their daily activity patterns changed from the base scenario after including wheelchair use as a utility variable. Though this is only 0.357% of individuals, it is worth considering the distribution of this change in more detail. Table 3 presents an aggregate summary of individuals who kept and changed their plans. Individuals with no wheelchair users in their household are not affected, other than through some random simulation error. For wheelchair users themselves however, the changes are relatively large. For example, 43 percent of the wheelchair users who were modeled as making mandatory tour patterns in the base scenario are now expected to make non-mandatory or stay-at-home patterns. Similarly, wheelchair users who previously chose non-mandatory patttens are considerably more likely to stay at home.

The coordinated nature of the ActivitySim daily activity pattern model also allows household members of wheelchair users to be affected. For these people, the changes are smaller in proportion but potentiall meaningful in aggregate: 30.7 percent of the household members who stay at home in the new scenario incorporating wheelchair use previously made out-of-home tours in the base scenario.

In addition to these aggregate numbers, it is also worth considering where the affected households are concentrated. Wheelchair use and disability in general is not distributed evenly through the region. Figure 1

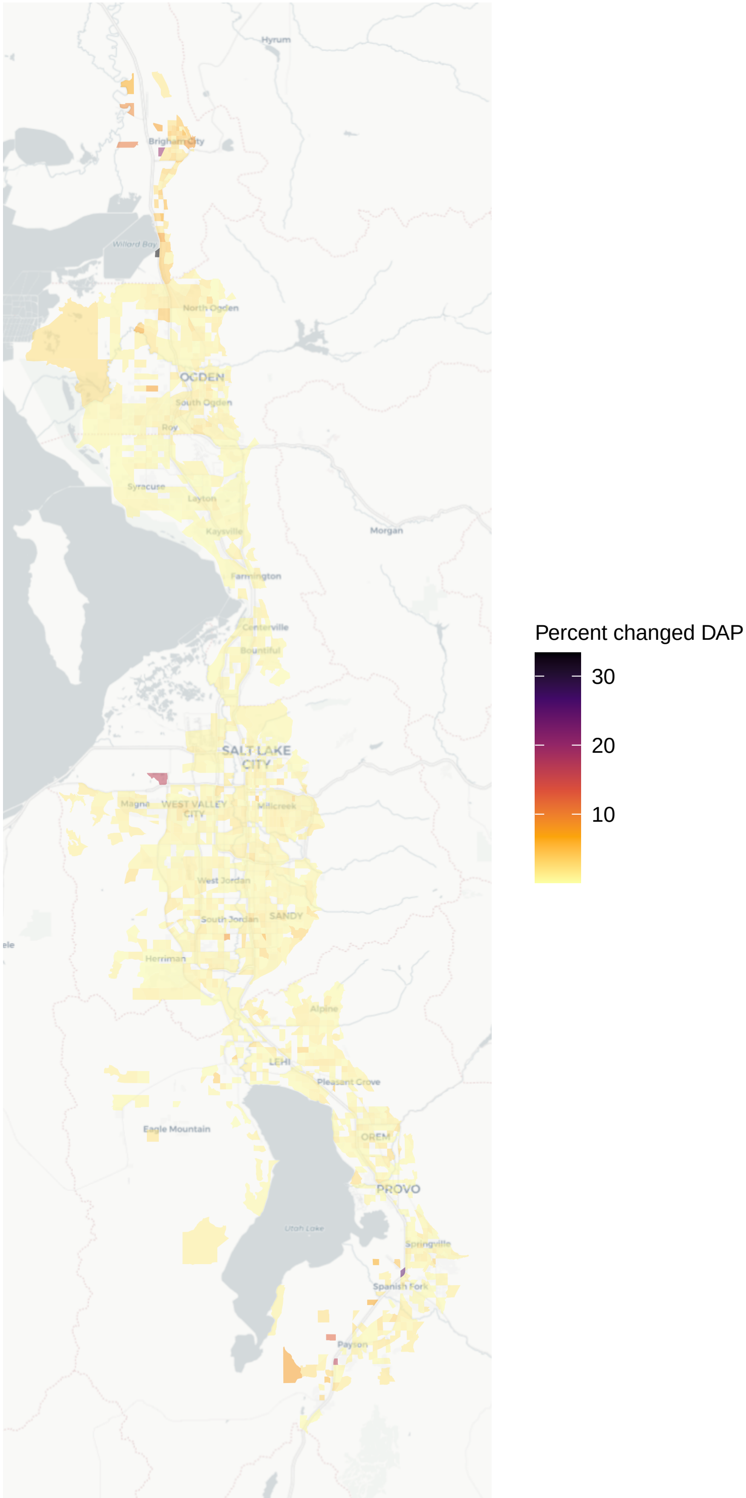

Figure 1: Percent of households with changed daily activity pattern between two scenarios.

Table 3: Daily Activity Pattern Change

		Considering Wheelchair Use		
Group	Base	H	M	N
Wheelchair Users	H	3369	20	459
	M	932	1642	308
	N	3584	23	10261
Household Members	H	4511	213	631
	M	759	15409	301
	N	1235	415	13119
Not Affected	H	309965	2	
	M	2	1460582	
	N		2	659258

shows the concentration of households where at least one member changed its chosen daily activity pattern between the scenarios by traffic analysis zone. Though most areas of the region experience little if any alteration, some zones see as many as 20% or 30% of their households change activity patterns.

5. Discussion

Disability status is almost never included in travel demand forecasting efforts for a number of reasons. First is a practical issue; each element of a population included in a model requires additional effort to not only catalog and calibrate in the base year, it requires forecasting that variable out into the future planning years. Limiting the variables considered to the typical set of age, employment status, household size, and income (among potentially a few others) reduces burden on planners and simplifies the data management pipeline. Second, the variety of possible travel-limiting disabilities and the perceived small size of the affected population might make understanding the travel behavior impacts of all potential disabilities a high-cost, low-impact proposal in the large scheme of a travel model.

There is an important philosophical argument to be had about the equity implications of considering disability within travel forecasting efforts. On one hand, excluding disability from travel behavior models might reinforce the "invisibility" of this population when developing transportation plans and other public policies. If a population is not modeled, it is difficult to evaluate how various policies would impact them within a model. Thus household income is left as virtually the only equity consideration in travel forecasts (Bills et al., 2012). On the other hand, current travel modeling practice assumes constant behavioral impacts into the future. Is is correct or fair to assume that the travel costs and obstacles currently faced by individuals with disabilities will continue unabated twenty or thirty years from now? Many of these same philosophical questions also apply to other variables that might be observed to affect travel behavior, such as race or ethnic group or religious affiliation (e.g., Vyas et al., 2015).

This study suggests that omitting wheelchair use is not without cost. The impact of wheelchair use on individual travel behavior appears to be substantial, and is potentially of a scale to affect travel forecasting results in particular areas. Further research is required, but it is possible that wheelchair use could result in different outcomes for transit ridership and local trip production at least. The daily activity pattern model presented in this research is only the first step in a typical travel activity modeling process. Future research should undertake a rigorous evaluation of the effect of wheelchair use on vehicle ownership, tour frequency, activity location choice, and travel mode. It is possible that other disabilities will need to be investigated as well.

The NHTS provides a sufficiently large sample of individuals who use wheelchairs to undertake the analysis presented here. It is unlikely, however, to be useful for some of the other travel activity models just described. Activity location choice models require substantially more precise geographic detail — including detail on non-chosen alternative locations — than is provided in the NHTS. Local household travel surveys are unlikely to sample enough individuals who use wheelchairs to estimate robust effects without targeted oversampling techniques. The results of this study raise a question as to whether planning agencies ought to consider conducting this oversampling to enable future research.

The model specifications presented in Table 2 each consider wheelchair use independently from other variables. It is likely however, that there could be some interaction effects among the various individual attributes. To wit: do wheelchair users who hold bachelor's degrees behave differently with respect to activity pattern than wheelchair users with less education?

This study used information from all United States metro areas between one and three million in population. It is possible that the obstacles wheelchair users face in some of these metro areas are larger or smaller than others. It is also possible that larger or smaller metro areas would present different challenges or provide different resources to wheelchair users. The same logic extends to other countries besides the United States. Examining the role of wheelchair use on daily activity pattern in other national contexts is important, as would be further research on other categories of disability.

6. Conclusion

In the generation since the enactment of the ADA in 1990, much progress has been made in the United States in making public accommodations and transportation services available to all users regardless of their disability status. Despite this progress, the results of this research suggest that wheelchair users still face substantial friction in their daily travel after controlling for age, income, and other common sociodemographic characteristics. Though the size of the wheelchair-using population is relatively small — particularly within the context of a regional travel demand model — it may be spatially concentrated to the point where it could influence forecasts for individual transit services or local highway facilities.

As transportation planners are being asked to consider equity in more policies and contexts, the needs of wheelchair users and others with travel-limiting disabilities should be considered in more contexts. The exclusion of wheelchair users from travel models means that services and policies aimed at assisting this community may be devalued relative to highway capacity and other more traditional projects. The consequences of this exclusion should be investigated, as well as the exclusion of other variables that would enable a more holistic assessment of winners and losers in the transportation system.

Acknowledgements

Figures and tables in this paper were created with a variety of R packages (Arel-Bundock, 2021; Dunnington, 2021; Wickham, 2016). The authors would like to thank Chris Day and Christian Hunter for their help in preparing this analysis.

This work was supported by the Utah Department of Transportation and the Federal Transit Administration. The authors alone are responsible for the preparation and conclusions presented herein. The contents do not necessarily reflect the views, opinions, endorsements, or policies of the Utah Department of Transportation of the US Department of Transportation. The Utah Department of Transportation makes no representation or warranty of any kind, and assumes no liability therefore.

References

AMPO, 2020. ActivitySim: An open platform for activity-based travel modeling.

Arel-Bundock, V., 2021. Modelsummary: Summary tables and plots for statistical models and data: Beautiful, customizable, and publication-ready.

Bascom, G.W., Christensen, K.M., 2017. The impacts of limited transportation access on persons with disabilities' social participation. *Journal of Transport & Health* 7, 227–234. https://doi.org/10.1016/J.JTH.2017.10.002

Bills, T.S., Sall, E.A., Walker, J.L., 2012. Activity-based travel models and transportation equity analysis:research directions and exploration of model performance. *Transportation Research Record* 2320, 18–27. https://doi.org/10.3141/2320-03

Bischoff, J.F., 2019. Mobility as a Service and the transition to driverless systems 148.

Bradley, M., Vovsha, P., 2005. A model for joint choice of daily activity pattern types of household members. *Transportation* 32, 545–571. https://doi.org/10.1007/s11116-005-5761-0

Brumbaugh, S., 2018. Issue BrIef Travel Patterns of American Adults with Disabilities.

Croissant, Y., 2020. Estimation of random utility models in R: The mlogit package. *Journal of Statistical Software* 95, 1–41. https://doi.org/10.18637/jss.v095.i11

Davidson, W., Vovsha, P., Freedman, J., Donnelly, R., 2010. CT-RAMP family of activity-based models, in: Proceedings of the 33rd Australasian Transport Research Forum (ATRF). Citeseer, p. 29.

Domencich, T.A., McFadden, D., 1975. Urban travel demand: a behavioral analysis. North-Holland Pub. Co.

Dunnington, D., 2021. Ggspatial: Spatial data framework for ggplot2.

Erhardt, G., Ory, D., Sarvepalli, A., Freedman, J., Hood, J., Stabler, B., 2012. MTC's travel model one: Applications of an activity-based model in its first year, in: 5th Transportation Research Board Innovations in Travel Modeling Conference.

Ermagun, A., Hajivosough, S., Samimi, A., Rashidi, T.H., 2016. A joint model for trip purpose and escorting patterns of the disabled. *Travel Behaviour and Society* 3, 51–58. https://doi.org/10.1016/j.tbs.2015.08.002

Federal Transit Administration, 2015. Americans with Disabilities Act: Guidance.

Feeley, C., 2019. Evaluating the Transportation Needs and Accessibility Issues for Adults on the Autism Spectrum in New Jersey.

Frackelton, A., Grossman, A., Palinginis, E., Castrillon, F., Elango, V., Guensler, R., 2013. Measuring walkability: Development of an automated sidewalk quality assessment tool. *Suburban Sustainability* 1, 4.

Laplante, M., 2003. Demographics of Wheeled Mobility Device Users. *Proceedings of the Conference on Space Requirements for Wheeled Mobility* 1–23.

Lubin, A., Deka, D., 2012. Role of public transportation as job access mode. *Transportation Research Record* 90–97. https://doi.org/10.3141/2277-11

Macfarlane, G.S., Hunter, C., Martinez, A., Smith, E., 2021. Rider perceptions of an on-demand microtransit service in salt lake county, utah. *Smart Cities* 4, 717–727.

Macfarlane, G.S., Lant, N.J., 2021. Estimation and simulation of daily activity patterns for individuals using wheelchairs.

Paul, B.M., Doyle, J., Stabler, B., Freedman, J., Bettinardi, A., 2018. Multi-level population synthesis using entropy maximization-based simultaneous list balancing, in: Transportation Research Board Annual Meeting.

R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rasouli, S., Timmermans, H., 2014. Activity-based models of travel demand: Promises, progress and prospects. *International Journal of Urban Sciences* 18, 31–60.

Rosenbloom, S., 2007. Transportation Patterns and Problems of People with Disabilities, in: Field, M.J., Jette, A.M. (Eds.), The Future of Disability in America. National Academies Press, pp. 1–592. https://doi.org/10.17226/11898

Ruvolo, M., 2020. Access Denied? Perceptions of New Mobility Services Among Disabled People in San Francisco. *The SAGE Encyclopedia of Higher Education* 52. https://doi.org/10.4135/9781529714395.n81

Schmöcker, J.D., Quddus, M.A., Noland, R.B., Bell, M.G.H., 2005. Estimating trip generation of elderly and disabled people: Analysis of London data. *Transportation Research Record* 9–18. https://doi.org/10.3141/1924-02

Shaheen, S., Chan, N., 2016. Mobility and the sharing economy: Potential to facilitate the first-and last-mile public transit connections. *Built Environment* 42, 573–588.

Sweeney, M., 2004. Travel Patterns of Older Americans with Disabilities. *Working Paper 2004-001-OAS, Bureau of Transportation Statistics* 1–36.

U.S. Department of Transportation and Federal Highway Administration, 2017. 2017 national household travel survey.

US Census Bureau, 2022. ACS PUMS: American community survey public use microdata sample.

Van Roosmalen, L., Paquin, G.J., Steinfeld, A.M., 2010. Quality of Life Technology: The State of Personal Transportation. *Physical Medicine and Rehabilitation Clinics of North America* 21, 111–125. https://doi.org/10.1016/j.pmr.2009.07.009

Velho, R., Holloway, C., Symonds, A., Balmer, B., 2016. The effect of transport accessibility on the social inclusion of wheelchair users: A mixed method analysis. *Social Inclusion* 4, 24–35. https://doi.org/10.17645/si.v4i3.484

Vyas, G., Vovsha, P., Paleti, R., Givon, D., Birotker, Y., 2015. Investigation of alternative methods for modeling joint activity participation. *Transportation Research Record* 2493, 19–28. https://doi.org/10.3141/2493-03

Wasfi, R., El-geneidy, A., 2007. Measuring the Transportation Needs of People with Developmental Disabilities. *Lancet* 369, 457. https://doi.org/10.1016/S0140-6736(07)60218-9

Wickham, H., 2016. ggplot2: Elegant graphics for data analysis. Springer-Verlag New York.