A TRANSPORTATION AFFORDABILITY INDEX

by

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ABSTRACT

Transportation affordability refers to people's financial ability to access important goods and activities such as work, education, medical care, basic shopping and socializing. Increasing transport affordability can provide large economic and social benefits by reducing burdens and expanding opportunities to disadvantaged people. Increased transport affordability is equivalent to increased income.

There are many factors to consider when evaluating transportation affordability, including housing affordability; land use factors that affect accessibility; the quantity, quality and pricing of mobility options; and individuals' mobility needs and abilities. Conventional planning tends to consider a relatively limited range of transport affordability impacts and objectives. More comprehensive analysis can help decision makers better understand affordability impacts and identify more effective strategies for improving transport affordability. However, to take transportation affordability into account there should be practical ways of evaluating it.

This paper investigates the concept of transportation affordability and suggests a quantitative index for its measurement. The index calculates affordability based on the tradeoffs that households make between transportation and housing costs. The total transportation costs include the costs for auto ownership, auto use, and transit. The index can be adjusted for any spatial zone (e.g. neighborhood or other) to reflect the average expenditure and the price that inhabitants intend to pay for transportation costs.

1 Introduction

Affordability, in principle, refers to people's ability to purchase important goods and services. In a similar vein, transportation affordability refers to people's financial ability to access important goods and activities such as medical care, basic shopping, education, work and socializing (Litman, 2009).

Transportation inaffordability causes significant problems since it imposes financial burdens on lower income households and constrains people's opportunities. Some people may be forced to commute long distances in old cars, leading to stress and unreliability. Some others may stay on social assistance rather than move to areas with more jobs but high living costs. Of course, all households are not equally affected by inaffordability. Some may accept inferior housing in exchange for a better quality of life or long-term economic opportunities. But once this tank is dried, businesses must pay higher wages to attract additional employees. The result is less economic activity and lower profits than would occur with more affordable transportation and housing. This suggests that considering transportation affordability in the design of transport policies and strategies is very important, particularly in remote or isolated areas (Panou, et al. 2007) and in rapid growth communities that wish to expand industries that rely significantly on low- and medium-based employees or to attract students, retirees, artists and other innovators. Put differently, increased transport affordability is equivalent to increased income, since it can provide large economic and social benefits by reducing burdens to physically and economically disadvantaged people.

Many planning decisions affect transportation affordability. Modern transport planning responds well to demands of wealthy travelers but not to the needs of the poor. Current planning supports automobile, air and freight transport but does much less to improve affordable modes such as cycling or public transit travel. This aggravates economic problems since many workers find it difficult to access education and employment, and because motorized modes require costly infrastructure, impose external costs, and are resource-intensive, leading to increasing dependence on imported fuel.

There are many factors to consider when evaluating transportation affordability, and many possible ways to achieve transport affordability objectives, some of which tend to be ignored in conventional planning. Transport affordability can be increased by improving the quantity and quality of affordable transportation options, and by improving land use accessibility to reduce travel distances. Some of these strategies help achieve other planning objectives, such as congestion reduction, road and parking facility cost savings, improved safety and health, energy conservation and pollution reductions. Moreover, some transport affordability strategies are mere economic transfers, i.e. cost shifts rather than true cost reductions, which tend to be economically inefficient because they violate the principle that prices reflect marginal costs, and so encourage inefficient consumption. For example, driving is made more affordable by financing parking facilities within building budgets which reduces housing affordability, a portion of roadway costs are borne through general taxes rather than user fees, and automobile insurance is made affordable to higher-risk drivers by overcharging lower-risk drivers.

Apparently, the concept of transportation affordability is important for transport or spatial development planning, and as such it should not be overlooked in any relevant decision. To take transportation affordability into account there should be practical ways of evaluating it and reflecting upon a quantitative scale. This paper investigates transportation affordability and suggests an index, which can be used to measure in quantitative terms people's financial ability to achieve basic access.

2 Review of Previous Related Work

Various methods can be found in the literature that may be used to evaluate transportation affordability. Most of them take into account the portion of household expenditures devoted to transportation, housing affordability, the quantity and quality of affordable transportation options available to a particular group or for a particular type of trip, and the quality of accessibility for non-drivers compared with drivers.

Leigh, Scott & Cleary (1999) have developed a method for assessing transportation affordability based on the concept of mobility gap. Mobility gap is defined as the amount of additional transit service required for households without a motor vehicle to have a comparable level of mobility as vehicle owning households. The larger the mobility gap of a community the less affordable is transportation in that area.

The method considers a variety of factors when evaluating a community's transit needs and the mobility gap between residents who drive and those who do not. These include vehicle ownership (residents of households that do not own a motor vehicle tend to rely significantly on transit), age (residents in the 10-21 and 65+ year age ranges tend to rely on transit more than those 21-65), income (lower-income people tend to use transit more than higher-income people), and residency status (immigrant residents tend to rely more on transit than native residents). In typical areas evaluated by the authors it was found that only about a third of transit needs were met, indicating a level of service rating D, based on the ratings shown in Table 1.

Table 1: Transit Level of Service Ratings

Portion of Demand Met	Transit Level-of-Service
90% or more	A
75-89%	B
50-74%	C
25-49%	D
10-24%	E
Less than 10%	F

For a more detailed discussion on the ratings of table 1 the reader can refer to Leigh, Scott & Cleary (1999), p. VIII-3.

Another interesting approach to transportation affordability is the transit-oriented development method. Living in a transit-oriented community tends to reduce total household transportation costs which results in increased transportation affordability. According to research comparing U.S. cities based on the quality of their transit system (Litman 2004; Polzin, Chu and Raman 2008; FTA 2008), the portion of total household expenditures devoted to transportation (automobiles and transit) tends to decline with increased transit ridership and is lower, on average, in 'large rail cities' (as called in this research the cities with high quality transit systems). Residents of large rail cities devote just 12.0% of their income to transport, compared with 15.8% in 'small rail cities' (cities with modest rail transit systems), and 14.9% in 'bus-only cities' (cities that lack rail transit). International comparisons show similar patterns (Kenworthy and Laube 2000).

Transportation affordability can also be evaluated from society's perspective, that is, the overall costs and cost efficiency to the entire community, including indirect, external and non-market costs (Litman 2005). For example, some transportation cost reduction strategies, such as reducing fuel taxes, and funding roads and parking facilities through general taxes or development costs, may increase vehicle travel affordability but also increase other costs. If any of these indirect costs are borne by lower-income people (for instance, through increased housing costs or taxes) they may experience an overall reduction in affordability. Similarly, overall affordability may decline if under-pricing motor vehicle travel causes increased congestion delays, accidents or pollution damages, particularly if these costs burden lower-income people. To assess transportation affordability in this context, it is important to account for economic transfers, such as subsidies and external costs, and distinguish them from true resource costs and resource cost savings. There also some methodological implications to consider, for example, the analysis should account for all economic impacts, including indirect, external and non-market benefits and costs, which are not always very easy to compute.

The Housing and Transportation Affordability Index, developed by the Center for Neighborhood Technology (CNT) and the Center for Transit Oriented Development (CTOD), is perhaps the most workable approach to affordability (CTOD and CNT, 2006). The Index estimates true housing affordability by taking into account not just the cost of housing, but also the intrinsic value of place, as quantified through transportation costs. This work is a project of the Brookings Institution's Urban Markets Initiative and is the most comprehensive study to-date of the Housing & Transportation Affordability Index. That study found that the three primary dependent variables in the household transportation model are auto ownership, auto use and transit ridership and that the two primary independent variables are residential density and household income. The second phase of the project models neighborhood-level data for 52 different metropolitan areas in the U.S. with results available through an interactive mapping website[1].

Because of its innovative characteristics the Housing and Transportation Affordability Index was used as the basis for the development of the Transportation Affordability Index suggested in this paper.

3 Building the Affordability Index

The Transportation Affordability Index (TAI) builds on the analysis and theory of the Location Efficient Mortgage. Its added value regarding existing state of research lies with the fact that it uses a fully parameterized mathematical function which allows fine-tuning to the housing, transportation costs, household expenditures and other factors that effect affordability such as location and user characteristics. Before introducing the TAI, it will be useful to set out what are the key aspects to be taken into account for the overall development of the Index.

3.1 Main aspects

Transportation affordability analysis should consider housing and transportation costs together

Households often face tradeoffs between income, housing costs and travel costs. Several studies have investigated these tradeoffs. In many situations, lower-cost housing is located in areas with high transportation costs, resulting in no overall affordability gain. For example, Lipman (2006) found that in the U.S. transportation

[1] See http://www.brookings.edu/metro/umi_overview.aspx

expenses are often higher than housing costs for middle-income households. This study showed that transport costs range from about 10% in multi-modal communities up to about 25% in automobile dependent communities. Miller, et al. (2004) found similar results in the Toronto region, estimating that a typical household would spend about €4.200 annually in additional motor vehicle costs if located in a suburban area. Makarewicz, et al. (2008) found similar patterns in the Minneapolis-St. Paul region. Location efficient development, which locates affordable housing in areas with good travel options and reduces residential parking costs, can therefore increase overall affordability (Arigoni 2001; CTOD and CNT 2006; CNU 2008; ULI 2009).

Transportation affordability should consider a variety of transportation costs

There are various specific costs that affect affordability, including: vehicle purchase costs and fees, road tolls and parking fees, vehicle insurance and registration fees, transit and taxi fares and fuel prices. For instance, an increase in vehicle insurance and registration fees, parking and road tolls, fuel prices, or transit fares tends to reduce transportation affordability for the affected groups. Tradeoffs also exist, for example, reductions in fuel prices may provide little overall increase in affordability if it encourages vehicle purchasers to select less fuel-efficient vehicles or stimulates more dispersed, automobile-dependent land use development. For all these reasons it is important that any attempt to develop a Transportation Affordability Index should take into account as many related costs as possible and be based on total rather than unit costs.

Transportation affordability should be evaluated relative to total expenditures

Affordability analysis may follow different paths as definitions and perspectives vary. Analysis results, for example, are affected by whether costs are measured relative to income or expenditures, whether non-income benefits (such as food and housing subsidies) are included, and whether residential parking costs are considered housing costs or transport costs. Many lower-income people receive non-income benefits or undeclared income, live in subsidized housing, grow food, receive charity, or use other strategies to stretch money. Some households have planned periods of low incomes to attend college, travel or retire.

Transportation expenditures are regressive when measured relative to household incomes, but not relative to household expenditures (EuroStat, 2008; BLS, 2007). This is because many lower-income households spend more than their current incomes (e.g. because they are retired and living on savings), and many lower-income households have minimal travel costs because they are retired or disabled. These factors help explain better why it was decided in this paper to evaluate affordability on the basis of households' total expenditures and not relatively to income, which is the common case. For a more detailed discussion on the advantages of using households' expenditures the reader can refer to Litman, 2009.

In the following section it will be described how the total transportation cost is estimated for the needs of the Index.

3.2 Transportation Costs

As concerns transportation costs, the Index builds on the analysis and theory of the Location Efficient Mortgage - LEM (Holtzclaw et al, 2000). The LEM uses actual vehicle miles traveled for millions of households in the San Francisco Bay Area, Southern California, and the Chicago region to generate models that predict auto ownership and vehicle miles traveled, based on residential density, transit availability, and neighborhood walkability. The model results in a 'location efficient value' for each neighborhood within these regions.

In the Transportation Affordability Index, household transportation costs are estimated as three separate components (Eq. 1): costs of auto ownership (*Cao*), auto use (*Cau*), and transit use (*Cpt*). These three components are the dependent variables in the model and are affected by the combination of nine independent built environment variables and two independent household variables (household expenditure and size). Together, these eleven variables (table 2) represent the independent spatial (e.g. neighborhood) and socioeconomic variables that predict household transportation costs at the census block group level, usually the smallest geography available to approximate neighborhoods. It is important to model these costs at a level close to that of a neighborhood, given that the independent variables can vary block by block.

$$\textit{Total Transportation Cost} = [Cao * Fao(Vle) * Gao(Vhh)] + [Cau * Fau(Vle) * Gau(Vhh)] + [Cpt * Fpt(Vle) * Gpt(Vhh)]$$

Eq. (1)

where C_x represents a cost factor (i.e., Euros per km driven), and F_x and G_x are generic functions reflecting the characteristics of the local environment (*Vle*) and the household income and size (*Vhh*).

Table 2: Independent and dependent variables in the transportation cost model

Independent variable	Data Source	Purpose
Households per residential acre	Census	Provides a measure of density, which influences auto ownership and use
Households per total acre	Census	Provides a measure of density, which influences auto ownership and use
Population per residential acre	Census	Provides a measure of density, which influences auto ownership and use
Population per total acre	Census	Provides a measure of density, which influences auto ownership and use
Average block size in acres	Census	Block size contributes to walkability of the area, which influences auto ownership, auto use, and transit use
Zonal transit density*	Bus operators, local transit agencies	Provides a measure of transit accessibility
Distance to employment centers	Census	Distance to nearby jobs influences auto ownership and auto use
Job density: number of jobs per square km	Census / Jobs and locations	Number of nearby jobs influences probability of working at the nearby employment center

Access to amenities	Census / Service jobs	Nearby services within walking distance influences auto use and ownership, as well as transit availability and use
Household expenditure	Census	Influences auto ownership and use
Household size	Census	Influences auto ownership and use
Dependent variable	**Source**	**Use**
Auto ownership (vehicles per household)	Modeled from independent household and local environment variables	To determine the number of autos a household owns and the associated ownership costs
Auto use (annual km driven per household)	Modeled using census data fitted to the independent variables	To determine the number of km a household drives each vehicle and the associated usage costs
Transit Rides per day	Modeled from independent household and local environment variables	To determine the number of transit rides per day per household

* *Daily average number of buses or trains per hour, times the fraction of the zone within 400m of each bus stop (or 800m of each rail or ferry stop or station), summed for all transit routes in or near the zone.*

For a more detailed discussion on the reasons for the selection of the above variables the reader can refer to Holtzclaw et al (2000). As shown in this study, all independent variables of the model correlate with all the dependent ones, but with different strength. The variables, for example, that correlate most strongly with auto ownership and auto use are the residential density variables[2] i.e. households/residential acre, households/total acre, population/residential acre and population/total acre. Similarly, the variables that correlate more with transit ridership are transit and job density.

Bounded power fits ($y = A*[(x+B)/(X_{avg}+B)]^{-D}$) give the strongest single-independent-variable correlations which means that they can be used as a cell for the development of the F_x and G_x functions. Of course, the differences between the calibration parameters *A*, B and *D* reflect the zone-to-zone disparities in mobility patterns, level of accessibility, terrain layout, etc.

3.3 Formulation of the Index

As already mentioned the added value that the suggested TAI brings to existing research is the fully parameterized mathematical function which can be fine-tuned to the factors effecting affordability. From a mathematical perspective the Transportation Affordability Index is a continuous, smooth function which varies with transportation cost, while satisfying a series of affordability properties such as:

1. Considers housing and transportation costs together
2. Decreases when transportation cost increases
3. Decreases more rapidly when housing cost increases

[2] Vehicles per household and km driven tend to decrease as residential density increases.

4. Yields zero when transportation cost reaches a threshold C and one when it tends to zero.

In its general form the Transportation Affordability Index is shown in Eq. 2 below.

$$A^{C}_{\kappa,\lambda}(T,H) := \begin{cases} B_{\kappa,\lambda}\left(1 - T/(C-H)\right) & \text{if } 0 \le T + H \le C \\ 0 & \text{otherwise} \end{cases} \quad \textbf{Eq. (2)}$$

where, $B_{\kappa,\lambda}$ is the Beta function (see Eq. 3), T is the total transportation cost, H is the housing cost and C a positive constant defined by the user.

The development of the Index has followed a framework, comprising of three steps:

- Selection of mother-function and basic transformations
- Calibration of derived function
- Final configuration of the Index

Selection of mother-function and basic transformations

A family of functions adhering properly to the required conditions is the well known Cumulative Density Function of the mathematical Beta Distribution (Andrews, 1999). This family has formed the basis for the development of the Transportation Affordability Index, and underwent serious transformation in order to reflect the required properties.

Let us introduce the Beta Cumulative Density Function[3].

$$B_{\kappa,\lambda}(z) := \frac{\int_0^z t^{\kappa-1}(1-t)^{\lambda-1}\,dt}{\int_0^1 t^{\kappa-1}(1-t)^{\lambda-1}\,dt} = \frac{\Gamma(\kappa+\lambda)}{\Gamma(\kappa)\Gamma(\lambda)}\int_0^z t^{\kappa-1}(1-t)^{\lambda-1}\,dt \quad \textbf{Eq. 3}$$

where, κ, λ, z are complex numbers, and Γ a special function known as Gamma or Factorial Function (Press, et al. 1992).

Obviously $B_{\kappa,\lambda}(0) = 0$, $B_{\kappa,\lambda}(1) = 1$ and $B_{\kappa,\lambda}$ is strictly increasing in the unit interval [0,1] with values from 0 to 1. To fit to the required boundary conditions (property 4) and in order to make the Cumulative function strictly decreasing (property 2), the range of the function was mapped from the unit interval to the interval [0,*C*]. In addition, its monotonicity was inverted. The composite function that resulted for this transformation is shown below:

$$f^{C}_{\kappa,\lambda}(T) := \begin{cases} B_{\kappa,\lambda}\left(1 - T/C\right) & \text{if } 0 \le T \le C \\ 0 & \text{otherwise} \end{cases} \quad \textbf{Eq. 4}$$

where, C is a positive constant less than 1 and T is the portion of total household expenditure devoted to transportation.

[3] Also known as the Regularized Incomplete Beta Function (Abramowitz, et al, 1972).

To simplify this function we applied term by term integration for integer values of κ and λ. This resulted in $B_{\kappa,\lambda}(1-T/C)$ taking the following form:

$$B_{\kappa,\lambda}(1-T/C) = \frac{(\kappa+\lambda-1)!}{(\kappa-1)!(\lambda-1)!}\sum_{i=0}^{\lambda-1}\binom{\lambda-1}{i}\frac{(-1)^i}{(\kappa+i)}\left(\frac{C-T}{C}\right)^{\kappa+i}$$

$$= \frac{(\kappa+\lambda-1)!}{(\kappa-1)!}\sum_{i=0}^{\lambda-1}\frac{(-1)^i}{(\lambda-1-i)!\,i!\,(\kappa+i)}\left(\frac{C-T}{C}\right)^{\kappa+i} \qquad \textbf{Eq. 5}$$

where $\binom{\lambda-1}{i}$ stands for the binomial coefficient sequence in the expanded form of $(1-\cdot)^{\lambda}$.

In the above, $f^{C}_{\kappa,\lambda}$ is a ($\kappa+\lambda$ – 1) degree polynomial of T defined in [0,C], having C as root with multiplicity κ. Further, the polynomial $1-f^{C}_{\kappa,\lambda}(\cdot)$ has 0 as root with multiplicity λ.

Diagram 1 illustrates the different shapes of the $f^{C}_{\kappa,\lambda}$ function assuming, for example, $\kappa=\lambda=3$ [4] and C ranging from 0.1 to 0.5 with step 0.1.

It can be seen that this family of functions satisfies the boundary conditions (property 4) and the requirement of decreasing monotonicity (property 3). It also satisfies property 3; that is providing for different decreasing rates as C varies.

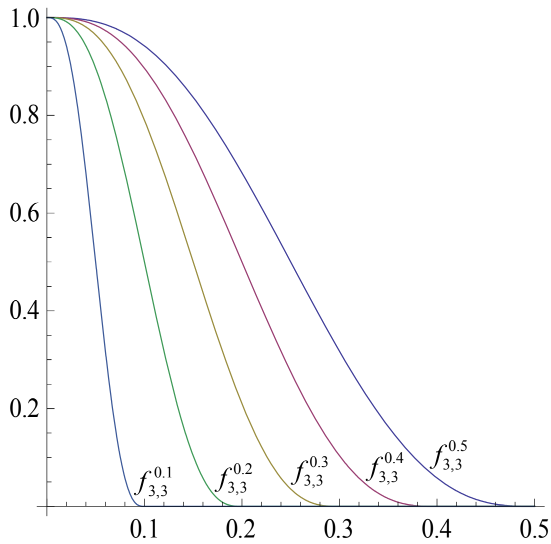

Diagram 1

Calibration of derived function

To calibrate $f^{C}_{\kappa,\lambda}$, the κ and λ parameters must be set. This requires a clear understanding of the relations between T, C, κ and λ and of how they affect the function.

To investigate the relations between the parameters we integrate Eq. 4. Then by changing the order of integration[5] of the next double integral we take:

$$\int_0^C\int_0^{1-T/C} t^{\kappa-1}(1-t)^{\lambda-1}dt\,dT = \int_0^1\int_0^{C(1-t)} t^{\kappa-1}(1-t)^{\lambda-1}dT\,dt = C\int_0^1 t^{\kappa-1}(1-t)^{\lambda}\,dt = C\frac{\Gamma(\kappa)\Gamma(\lambda+1)}{\Gamma(\kappa+\lambda+1)},$$

hence

$$\int_0^1 f^{C}_{\kappa,\lambda}(T)\,dT = \int_0^C B_{\kappa,\lambda}(1-T/C)\,dT = C\frac{\Gamma(\kappa+\lambda)}{\Gamma(\kappa)\Gamma(\lambda)}\,\frac{\Gamma(\kappa)\Gamma(\lambda+1)}{\Gamma(\kappa+\lambda+1)} = \frac{\lambda}{\kappa+\lambda}\,C \qquad \textbf{Eq. 6}$$

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[4] Here $f^{C}_{\kappa,\lambda}$ takes the polynomial form $f^{C}_{\kappa,\lambda}=(C-T)^3\left(6T^2+3CT-C^2\right)C^{-5}$

[5] The integration region of the left hand side integral $0 \le t \le 1-T/C$ and $0 \le T \le C$ is the same with $0 \le T \le C(1-t)$ and $0 \le t \le 1$.

A geometrical consequence of this property is that for any $0 \le C_1,\ C_2 \le 1$ the area ratio of the curves of $f_{\kappa,\lambda}^{C_1}$ and $f_{\kappa,\lambda}^{C_2}$ equals to the respected base ratio C_1 / C_2, i.e.

$$\frac{\int_0^1 f_{\kappa,\lambda}^{C_1}(T)\,dT}{\int_0^1 f_{\kappa,\lambda}^{C_2}(T)\,dT} = \frac{C_1}{C_2} \qquad \textbf{Eq. 7}$$

and:

$$I_{C_2}^{C_1} := \int_0^{C_2} f_{\kappa,\lambda}^{C_2}(T)\,dT - \int_0^{C_1} f_{\kappa,\lambda}^{C_1}(T)\,dT = \frac{\lambda}{\kappa+\lambda}(C_2 - C_1) \qquad \textbf{Eq. 8}$$

where $I_{C_2}^{C_1}$ is the area between $f_{\kappa,\lambda}^{C_1}$ and $f_{\kappa,\lambda}^{C_2}$ which is proportional to the base difference $C_1 - C_2$.

Diagram 2 shows the filled shapes of $f_{3,3}^{C}$ with C ranging from 0 to 0.5 and step 0.1. Using the same example as before ($\kappa = \lambda = 3$) it results that the five areas between the curves are equal to 0.05[6].

This property follows from the fact that $B_{\kappa,\lambda}(1 - T/C)$ is a univariate polynomial expression of the composite variable T/C, which implies that if $0 \le T_1 / C_1 = T_2 / C_2 \le 1$, then $f_{\kappa,\lambda}^{C_1}(T_1) = f_{\kappa,\lambda}^{C_2}(T_2)$. Because $f_{\kappa,\lambda}^{C}$ is strictly increasing (and therefore 1-1) in the interval $[0,C]$, it follows that if $f_{\kappa,\lambda}^{C_1}(T_1) = f_{\kappa,\lambda}^{C_2}(T_2)$, for some $0<C_1,C_2<1$, then

$$\frac{T_1}{C_1} = \frac{T_2}{C_2} \text{ or equivalently } \frac{T_1}{T_2} = \frac{C_1}{C_2} \qquad \textbf{Eq. 9}$$

Eq. 9 suggests that the difference required between transportation costs T_1 and T_2 to achieve equal transportation affordability can be determined by equating their ratio with the ratio of C_1, C_2. This difference can be adjusted by properly selecting the κ and λ parameters. If equality is maintained between the κ and λ, for any given value of the two (e.g. $\kappa = \lambda = 4$) the same cost increment will be required between successive C_i in order to maintain the same levels of affordability. If different values are selected for κ and λ the horizontal separation of the family of curves will change, allowing for a diminishing effect as housing costs increase. It seems appropriate, however, to set up as a starting point a common value for κ and λ (e.g. $\kappa = \lambda = 3$) to apply across all C_is.

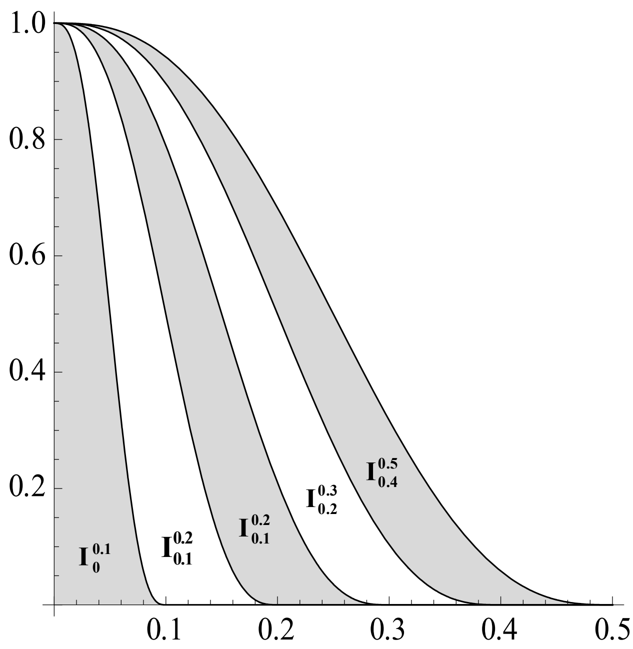

Diagram 2

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[6] It is $I_0^{0.1} = I_{0.1}^{0.2} = i_{0.2}^{0.3} = I_{0.3}^{0.4} = I_{0.4}^{0.5} = \frac{3}{3+3}\,0.1 = 0.05$

It should be noted that both the shape and the horizontal separation of the functions can be calibrated by properly selecting the κ and λ parameters.

As regards the parameter C, this can be fixed by the user. It represents the maximum portion of household total expenditure devoted to transportation and housing together, that is considered affordable. A typical value of C is 0,5 which results from the following reasoning: traditionally housing is considered affordable by planners, lenders, and most consumers if it accounts for roughly 30 percent or less of a household's monthly budget. Over that level of expenditure, any additional location or transportation cost will cause considerable reductions in other expenses, particularly food, clothing and entertainment. Transportation expenditures (excluding expenditures on luxury travel, such as long-distance vacation trips) can be considered unaffordable if they exceed 20% of a household's total expenditures Litman (2009). By summing the two inaffordability thresholds a value for C is estimated that equals 50%.

Final configuration of the Index

The Transportation Affordability Index is completed by introducing the housing cost variable (H) in the $f^{C}_{\kappa,\lambda}$ (this satisfies property 1). H is defined as the portion of total expenditures devoted to housing and is ranging in the interval $[0, C]$. The results of this transformation are shown in Eq. 10 below.

$$A^{C}_{\kappa,\lambda}(T,H) := f^{C-H}_{\kappa,\lambda}(T) := \begin{cases} B_{\kappa,\lambda}\left(1 - T/(C-H)\right) & \text{if } 0 \le T + H \le C \\ 0 & \text{otherwise} \end{cases} \qquad \textbf{Eq. 10}$$

It follows from Eq. 10 that if $0 \le T_i \le C - H_i$, for i=1,2, then

$$\frac{T_1}{C-H_1} = \frac{T_2}{C-H_2} \text{ is equivalent to } A^{C}_{\kappa,\lambda}(T_1,H_1) = A^{C}_{\kappa,\lambda}(T_2,H_2) \qquad \textbf{Eq. 11}$$

Eq. 11 reflects the same calibrating condition discussed before in Eq. 9; that is the required relation between transportation and housing costs to achieve equal transportation affordability. A schematical representation of this relation is given in diagram 3, assuming C = 0.5 and T / (0.5−H) = 0.2, 0.4, 0.6, 0.8, 1. The affordability values[7] that correspond to the T, H pairs satisfying these conditions are given in table 3 (second row). Diagram 4 depicts the overal variation of the Transportation Affordability Index with respect to housing and transportation costs.

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[7] Estimated as follows: $A^{0.5}_{3,3}(T,H) = P\left(T/(0.5-H)\right)$, where $P(x) := 1 - 10x^3 + 15x^4 - 6x^5$ (derived from Eq. 5), and $x = \dfrac{T}{0.5-H}$

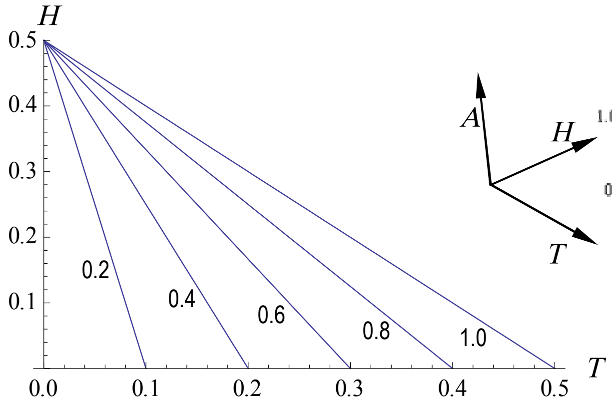

Diagram 3

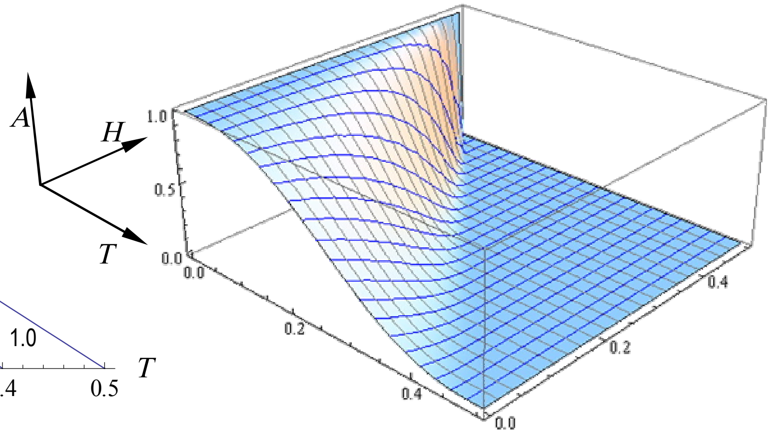

Diagram 4

Table 3: Relation between transportation, housing costs and affordability

$\frac{T}{0.5-H}$	0.2	0.4	0.6	0.8	1.0
$A_{3,3}^{0,5}(T,H)$	0.942	0.682	0.317	0.057	0

4 Testing the Index

The Transportation Affordability Index was tested in the Samos region, an island at the Eastern Aegean, to demonstrate easiness to use while attempting to meet a series of efficiency criteria such as:

- Is transparent
- Reduces the requirements in data collection
- Produces fairly reliable results when partial data is available
- Shows aspects not included in other methods.

A short survey was launched in the capital city of the island to assess the transportation and housing costs required for the analysis. Auto ownership (*Cao*), auto use (*Cau*) and transit use (*Cpt*) costs, including housing costs (H_T) and total average yearly expenditure of households (*E*) were evaluated based on the findings of the survey. Eq. 1 was not used here because it was difficult to obtain the necessary data to allow for the costs to be modeled from independent household and local environment variables. Although this example is not a full scale application of the Index it was considered sufficient for the purposes of this paper which, among others, is to demonstrate how the Index performs when poor quality data is available. The results of the survey that were used for the computation of the Index are shown in table 4.

Table 4: Transportation costs and household total expenditure used as input to the Index

Zone	***Cao*** **(€)**	***Cau*** **(€)**	***Cpt*** **(€)**	H_T **(€)**	**E(€)**
Zone A	2.236	1.613	62,40	5.760	33.860
Zone B	2.095	1.574	50,40	4.800	24.519
Zone C	1.830	1.852	42,00	4.200	23.352

Table 5 summarizes the output of the application example. It can be seen from the last column that zones B and C have similar transportation affordability which is a result of tradeoffs that exist between the zones' average transportation and housing costs (note the signs: T_2 - T_3 = - 0.007777, and H_2 - H_3 = 0.015911).

Table 5: Application example results

Zone	$T = \frac{Cao + Cau + Cpt}{E}$	$H = H_T / E$	$\frac{T}{0.5 - H}$	**Affordability Index**
Zone A	0.115517	0.170112	0.35017	0.764566
Zone B	0.151695	0.195767	0.498613	0.502602
Zone C	0.159472	0.179856	0.498127	0.503511

Finally, diagrams 5 and 6 depict the relative position of the tested zones in 2 and 3-dimentions, respectively. It can be noted that zones B and C are laying on the same affordability line (red in diagram 5, black in diagram 6).

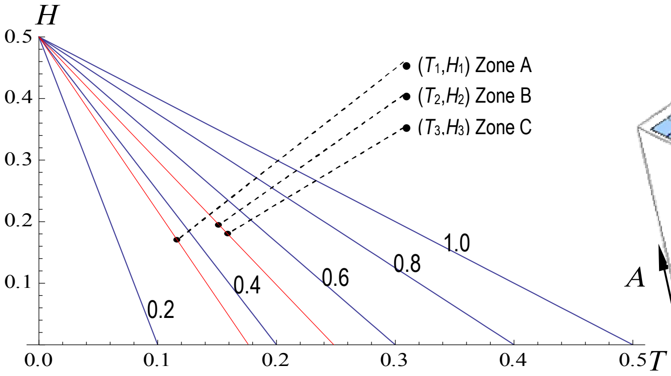

Diagram 5

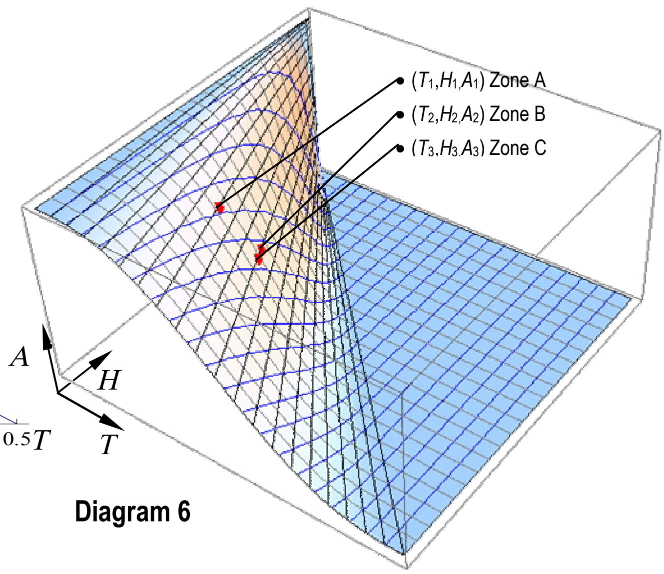

Diagram 6

5 Conclusions and Recommendations

Transportation affordability is an important economic and social issue. Unaffordable transport imposes significant financial burdens and reduces opportunities for disadvantaged people. Conventional planning considers a relatively limited range of transport affordability impacts and objectives. More comprehensive analysis can help decision makers better understand the affordability impacts of planning decisions, and to identify more effective strategies for improving transport affordability.

There have been several attempts to measure transportation affordability. Most of them take into account the portion of household expenditures devoted to transportation, housing affordability, the quantity and quality of affordable transportation options available to a particular group, and the quality of accessibility. From these approaches, the most innovative one is the Housing and Transportation Affordability Index, which has been used as the basis for the development of the Transportation Affordability Index presented in this paper.

The following aspects of transportation affordability were considered when building the Index:

- Combined transport and housing costs (to account for possible tradeoffs)
- Transportation costs (including all costs, not just fuel or transit fares).
- Total expenditure (to avoid intrinsic weaknesses of household income).

The Transportation Affordability Index is based on the trade-offs that households make between housing and transportation costs. Built on the Beta Cumulative Density Function, is using data sets that are available for every transit-served community in developed countries. The tool can be applied at the neighborhood or higher block level and provides transport policy-makers with the information needed to make better planning decisions, illuminating the implications of their policy and investment choices.

As a general reference, transportation expenditures can be considered unaffordable if they exceed 20% of a household's total expenditures, provided that the housing costs are at the range of 30 percent or less. For higher income households this allows virtually unlimited automobile travel, but for low-income households, affordable accessibility requires multi-modal transport systems with high quality public transit, car sharing and taxi services, plus accessible land use patterns, particularly affordable housing located in multi-modal locations well served by non-motorized modes and public transit.

These among others are considerations worth taking into account in the configuration of the Index. Future work aimed to improve the Index will consider a variety of factors affecting affordability such as people's mobility needs, transportation options and land use patterns. Mobility needs and abilities of people, for example, may influence transportation affordability. Some people can easily satisfy their access needs on a limited budget while others with limited physical ability or care giving responsibilities may need to spend much more to meet their access needs, so their transport costs are unaffordable. Transportation options also play an important role. They refer to the quantity and quality of transport modes and services available in a particular situation. In general, improving lower-cost transport options and increasing the number of destinations served by such modes tends to improve transport affordability. Various land use factors (density, mix, roadway and pathway connectivity) that control the amount of travel needed can also affect affordability. A more accessible land use pattern (called smart growth) means that less mobility is needed to reach activities and destinations. In general, suburban and rural communities tend to have less accessible land use patterns and more automobile-dependent transportation systems, leading to increased transport inaffordability.

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