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Accessibility for Bus Transportation Planning in Rural Areas

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Keywords

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1. Introduction

In rural areas, many people drive private car to participate in daily life activities such as job and shopping. The private car enables people to move wherever and whenever they want. Because of its convenience, not only the number of households owning cars but also the number of cars per household has increased. This tendency incurs the decrease of the number of passengers of public transportation. Currently, the number of passengers of public transportation service is small in rural areas, but the main users of public transportation service such as those who do not own a private car really needs the service. Thus it is still important for local government to maintain the public transportation service to provide non-car-users the opportunity of basic daily life activities.

To plan the public transportation service, it is important to know the opportunity of daily life activities in each district in target area. Specifically, the opportunity provided by the current/planned bus transportation service is one of the critical information for the planners since the bus transportation service is often the only service in rural areas. Although the bus transportation provides the opportunity of daily life activities, it partially restricts the opportunity because the route and time of bus transportation service is generally fixed. To assess the opportunity provided by the bus transportation service, it is appropriate to consider how the service restricts the opportunity in terms of fixed route and time.

The accessibility measure is useful to assess the opportunity of daily life activities. It has been widely used in various areas. However, it is not obvious that it is suitable to assess the opportunity provided by the bus transportation service. This study reviews the types of accessibility measure and discusses which type is useful to access the opportunity for bus transportation planning in rural areas. In addition, we develop new accessibility measure which explicitly considers the restriction which derives from fixed time of the bus transportation service.

In section 2, we review the accessibility measures developed in previous studies and discuss which type of measures can account for the restriction to the opportunity provided by the bus transportation service. In section 3, we develop the accessibility measure in order to assess the opportunity restricted by fixed route and time. Then we show its characteristics. In section 4, we show numerical examples followed by the conclusion in section 5.

2. Accessibility Measure for Planning Public Transportation Service

Since 1970, many types of accessibility measures have been developed. Several authors have written review articles such as Song (1996), Handy and Niemeier (1997), Pirie (1979), Kwan (1998), Niemeier (1997), and Geurs and Wee (2004). We classify the accessibility measures as shown below.

2.1. Infrastructure based measure

It measures the performance or service level of transportation infrastructure, such as level of congestion and average travel speed on the road network. It ignores the aspect of the daily life activities. i.e., how accessible to daily life activities by utilizing the infrastructure is not the concern of this measure.

2.2. Cumulative opportunity measure

The measure describes the level of accessibility to spatially distributed activities, such as the number of hospitals within 30 minutes travel time from origin location.

2.3. Utility based measure

It measures the benefits that people derive from access to the spatially distributed activities. It is based on random utility theory, in which the probability of an individual making a particular choice depends on the utility of that choice relative to the utility of all choices.

2.4. Space-time prism

This type of measure is founded in the space-time geography of Hägerstrand (1970). It measures the limitations on an individual's freedom of action given by the time budget and the transportation service.

Let us discuss what type is appropriate. This study aims to assess the opportunity of daily life activities provided by the bus transportation service. In addition, the opportunity restricted by fixed route and time should be considered. It is noted that fixed route limits the users' choice set of destination. Also, fixed time limits the users' choice set of time to move. Thus the accessibility measure for the purpose of this study should account for these two choice sets.

To assess the opportunity in rural areas, in which we have already mentioned that the service level is low, it is important to pay attention to the needs formation of the people living there. As Sen (1988, 1992) suggested, the needs of people may be shaped by the environment. i.e., the needs of daily life activities may be affected by current level of the bus transportation service. The tendency that people adjust their needs to their possibilities has been also investigated in sociology and psychology (for example, Elster (1983) and Frederick et al. (1998)). If this tendency is not negligible, the people under low service level form their needs to be modest. Because of modest needs formation, the needs satisfaction under low level of service may not be different so much from people under high level. i.e., the scarcity of opportunity cannot be captured well by the accessibility based on needs satisfaction. It is noted that the needs satisfaction is based on individual utility. Thus the accessibility measure should not be based on utility.

Summarizing the discussion, we have three criteria to find appropriate type of measure as shown by:

- The measure must focus on the daily life activities
- The measure must accounts for the choice set affected by limited destination and time to move.

- The measure should not be based on individual utility

From the first criteria, infrastructure based measure is not appropriate because the daily life activity is not the concern. From the third, utility based measure is not appropriate. Cumulative opportunity measure can consider limited destination but time. Thus it is not appropriate from the second criteria. Space-time prism can account for the space-time constraints in some ways and the area of the prism can be interpreted as the abundance of possible daily life activity. In addition, it is not based on utility. Thus it seems to satisfy all criteria.

However, it has disadvantages in dealing with the choice set of time to move. Supposing that you live in district A. For the simplicity of the explanation, the geographical space extends straight east and west. You have free time to go out between time t_1 and t_2. The bus transportation service provides you two routes. One route is between district A and W and another is between district A and E. The number of the services of both routes is twice per day. If you can depart home t_1 and return home t_2 just in time by the bus transportation service, your space-time prism is described by Fig. 1 (1). Two paths, (a-1) and (a-2), show possible daily life activities excluding stay at home all day. If the number of the services is much enough that you can move any time, your choice set of time to move is enhanced and the possible paths are added to (a-1) and (a-2). Fig.1 (2) illustrates additional three examples of your daily life activities, (b-1), (b-2) and (b-3). It is noted that the shapes of the space-time prism in Fig.1 (1) and (2), shaped by diamond, are completely same. This is because the area you can go using your time resource is same in both cases. This means that the choice set of time to move cannot be accounted by space-time prism directly. In addition, the prism does not tell us which activities you can access. It just shows the geographic area you can access but no information about the accessible activities in the area. To eliminate these disadvantages, counting the paths by which you can access the activities is the most useful.

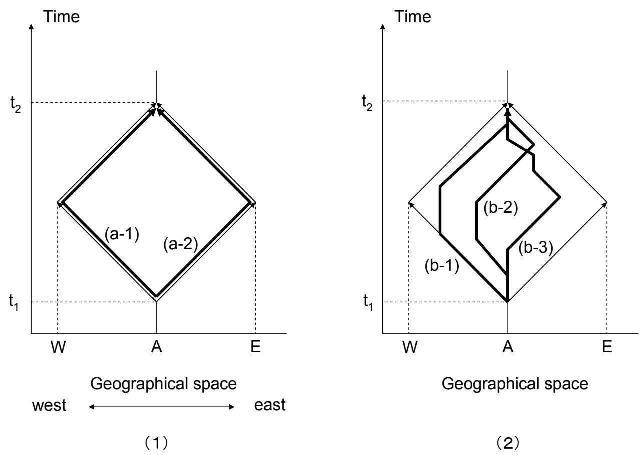

Fig.1 Space-time prism with different transportation service

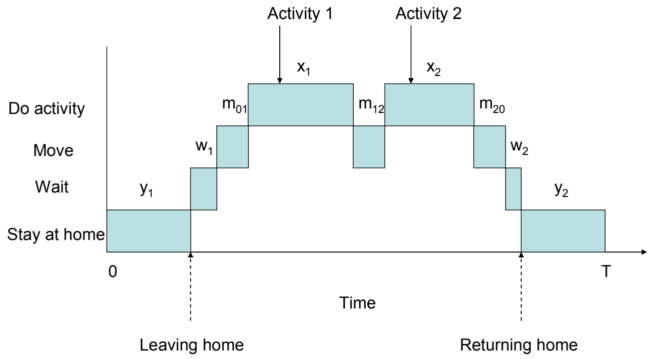

Fig.2 Diagram of daily life activity

3. Formulation

3.1. Basic formulation

Fig. 2 illustrates an arbitrary daily life activity by which a person goes to urban area to do two activities. His/her time budget is T. Total travel time is given by $M = m_{01} + m_{12} + m_{20}$ where m_{ij} represents the travel time when he/she goes to the place for activity j from where he/she does activity i. It is noted that $i = 0$ represents stay at home. He/she has to wait for bus transportation service until it coming. The waiting time is represented by $w = w_1 + w_2$ where w_1 and w_2 represent waiting time when leaving and returning home respectively. We assume that waiting time is negligible when moving in urban area. Let us represent the time staying at home is $y = y_1 + y_2$ where y_1 and y_2 represent the time before leaving and after returning home respectively. The time for activity 1 and 2 are represented by x_1 and x_2 respectively. Balancing the time, we have:

$$x_1 + x_2 = T - M - w - y \tag{1}$$

Let us denote $T - M - w - y$ by α. We assume that y is constant for a while. Given α, his/her arbitrary daily life activity can be represented by (x_1, x_2). From equation (1), however, x_2 is automatically determined if x_1 is determined. Thus his/her arbitrary daily life activity can be represented by x_1. From equation (1), x_1 can be given between 0 and α. Thus the accessibility measure $\theta_2(y)$, by which access the choice set of possible daily life activity is represented, can be formulated by:

$$\theta_2(y) = \int_0^{\alpha} 1 dx_1 = \alpha \tag{2}$$

In similar way, we can formulate the accessibility measure if the number of activities is n. In this case, equation (1) can be modified by:

$$\sum_{k=1}^{n} x_k = T - M - w - y = \alpha \tag{3}$$

Then the accessibility measure can be obtained by:

$$\theta_n(y) = \frac{\alpha^{n-1}}{(n-1)!} \tag{4}$$

This equation can be derived as follows.

Proof:
If $n = 2$, it is easily confirmed that equation (4) is equal to equation (2). We assume that we have equation (4) for $n = k$. Then we have:

$$\theta_k(y) = \frac{\alpha^{k-1}}{(k-1)!} \tag{5}$$

If the number of activities is $k + 1$, we have $\sum_{i=1}^{k+1} x_i = \alpha$ as well as equation (3). From this equation, we have $\sum_{i=1}^{k} x_i = \alpha - x_{k+1}$. This equation is given by equation (3) with replacing α by $\alpha - x_{k+1}$. For this equation, we have next equation from equation (5).

$$\theta_k(y) = \frac{(\alpha - x_{k+1})^{k-1}}{(k-1)!} \tag{6}$$

Because x_{k+1} can be given between 0 and α, accessibility measure $\theta_{k+1}(y)$ is given by:

$$\theta_{k+1}(y) = \int_0^{\alpha} 1 \cdot \theta_k dx_{k+1} = \int_0^{\alpha} \frac{(\alpha - x_{k+1})^{k-1}}{(k-1)!} dx_{k+1} = \frac{\alpha^k}{k!} \tag{7}$$

Equation (7) means that equation (5) is satisfied for $n = k + 1$. By the mathematical induction, the accessibility measure is given by equation (4).

[Q.E.D]

Our accessibility measure is calculated by choice set of daily life activity (x_1, x_2,..., x_{n-1}) which satisfies equation (3). Thus the accessibility measure can be represented by shadowed areas in Fig.3.

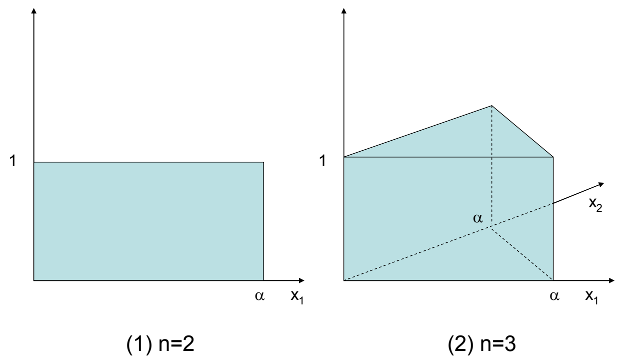

Fig.3 Graphical description of $\theta_n(y)$

If the number of reachable activities by public transportation service is m, a person can make a choice of which activity to participate. Thus the accessibility is given by $\sum_{n=1}^{m} \theta_n(y)$.

3.2. Deterrence

It is hard for us to travel and stay out for a long time. Also, it is hard to wait for bus transportation service for a long time. If such time gets longer, the probability that the person resigns to go to urban area gets higher because his/her ability is not enough to do so. We represent the deterrence probabilities for time $x + M$ and w given by:

$$f(x) = e^{-\beta(x+M)} \tag{8}$$

$$g(w) = e^{-\gamma w} \tag{9}$$

where β and γ are the deterrence parameters for $x + M$ and w. From equations (4), (8) and (9), the accessibility measure with deterrence considered is given by:

$$\theta_n(y) = e^{-\beta(M+\alpha)-\gamma w} \frac{\alpha^{n-1}}{(n-1)!} \tag{10}$$

Because $T - M - w - y = \alpha$, equation (10) can be rewritten by:

$$\theta_n(y) = e^{-\beta(T-w-y)-\gamma w} \frac{(T-M-w-y)^{n-1}}{(n-1)!} \tag{11}$$

We assumed that y is constant. However, y is one of the elements of his/her daily life activity. Formally, the plan is given by $(x_1, x_2, ..., x_{n-1}, y)$. Because the time staying at home can be given between 0 and $T - M - w$, we derive the accessibility measure when y can be chosen as shown by:

$$\theta_n = \int_0^{T-M-w} e^{-\beta(T-w-y)-\gamma w} \frac{(T-M-w-y)^{n-1}}{(n-1)!} dy = e^{-\beta M-\gamma w} \frac{\Gamma(n)-\Gamma(n,\beta(T-M-w))}{\beta^n \Gamma(n)} \quad (12)$$

where Γ represents Gamma function which is represented by:

$$\Gamma(n,a) = \int_a^\infty t^{n-1} e^{-t} dt \quad (13)$$

Note that Γ(n) is given by Γ(n, 0). Equation (12) can be rewritten by factorial series such as:

$$\theta_n = \frac{1}{\beta^n} e^{-\beta(T-w)-\gamma w} \left\{ e^{\beta(T-M-w)} - \sum_{k=0}^{n-1} \frac{\beta^k (T-M-w)^k}{k!} \right\} \quad (14)$$

3.3. Simplification

Let us represent $z = \beta(T - M - w)$. Then equation (14) is given by:

$$\theta_n = \frac{e^{-\beta M-\gamma w}}{\beta^n} \left\{ 1 - e^{-z} \sum_{k=0}^{n-1} \frac{z^k}{k!} \right\} \quad (15)$$

By Maclaurin expansion, e^{-z} can be given by:

$$e^{-z} = 1 - z + \frac{z^2}{2!} - \frac{z^3}{3!} + \cdots \quad (16)$$

Then we have:

$$e^{-z} \sum_{k=0}^{n-1} \frac{z^k}{k!} = \left(1 - z + \frac{z^2}{2!} - \frac{z^3}{3!} + \cdots \right) \left(1 + z + \frac{z^2}{2!} + \frac{z^3}{3!} \cdots + \frac{z^{n-1}}{(n-1)!} \right) \quad (17)$$

By n-th approximating, we have:

$$e^{-z}\sum_{k=0}^{n-1}\frac{z^k}{k!} \fallingdotseq 1-\frac{z^n}{n!} \tag{18}$$

By equations (15) and (18), the accessibility measure can be simplified by:

$$\theta_n = e^{-\beta M-\gamma w}\frac{(T-M-w)^n}{n!} \tag{19}$$

3.4. Normalization

We can normalize the accessibility measure so that the value is 1.0 when $M = w = 0$, which means that time budget T is completely at a person's disposal. Let us represent the accessibility measure when $M = w = 0$ by θ_n^*. Then we have normalized accessibility measure φ_n is given by:

$$\varphi_n = \frac{\theta_n}{\theta_n^*} \tag{20}$$

Assuming that $T = 1$, say T is also normalized, normalized accessibility measure for simplified version shown by equation (19) can be represented by:

$$\theta_n = e^{-\beta M-\gamma w}(T-M-w)^n \tag{21}$$

The illustrative performance of normalized accessibility measures for equations (12) and (19) is shown in Fig.4. The parameters are given by equation (32) in next section. The simplification is successful because the difference is negligible.

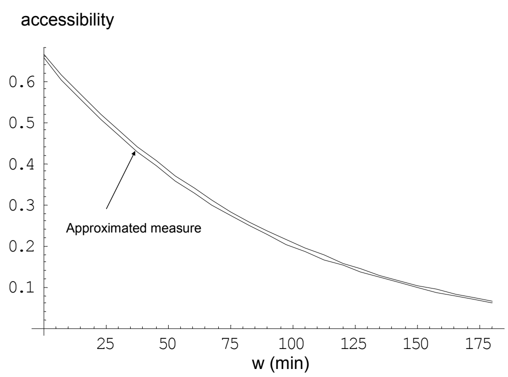

Fig.4 Performance of normalized accessibility measures for equations (12) and (19)

3.5. Characteristics of measure

We analyze the characteristics for accessibility measure θ_n. Normalized accessibility measure φ_n has same characteristics because θ_n^* is constant. By Maclaurin theorem, we have next equation for any n.

$$e^{\beta(T-M-w)} \geq \sum_{k=0}^{n-1} \frac{\beta^k (T-M-w)^k}{k!} \tag{22}$$

From equation (22), equation (14) is nonnegative. Thus we have:

$$\theta_n \geq 0 \tag{23}$$

Partial differentiating equation (14), we have:

$$\begin{aligned} \frac{\partial \theta_n}{\partial \beta} &= \int_0^{T-M-w} \frac{\partial}{\partial \beta} e^{-\beta(T-w-y)-\gamma w} \frac{(T-M-w-y)^{n-1}}{(n-1)!} dy \\ &= -n \int_0^{T-M-w} e^{-\beta(T-w-y)-\gamma w} \frac{(T-M-w-y)^n}{n!} dy \\ &\quad - M \int_0^{T-M-w} e^{-\beta(T-w-y)-\gamma w} \frac{(T-M-w-y)^{n-1}}{(n-1)!} dy = -n\theta_{n+1} - M\theta_n \end{aligned} \tag{24}$$

$$\begin{aligned} \frac{\partial \theta_n}{\partial M} &= \int_0^{T-M-w} \frac{\partial}{\partial M} e^{-\beta(T-w-y)-\gamma w} \frac{(T-M-w-y)^{n-1}}{(n-1)!} dy \\ &= -\int_0^{T-M-w} e^{-\beta(T-w-y)-\gamma w} \frac{(T-M-w-y)^{n-2}}{(n-2)!} dy = -\theta_{n-1} \end{aligned} \tag{25}$$

From equation (23), we have $\theta_n \geq 0$ for any n. Thus equations (24) and (25) are nonpositive. Then we have:

$$\frac{\partial \theta_n}{\partial \beta} \leq 0 \tag{26}$$

$$\frac{\partial \theta_n}{\partial M} \leq 0 \tag{27}$$

Furthermore, partial differentiating equations (24) and (25), we have:

$$\frac{\partial^2\theta_n}{\partial\beta^2} = -n\frac{\partial}{\partial\beta}\left[\int_0^{T-M-w} e^{-\beta(T-w-y)-\gamma w}\,\frac{(T-M-w-y)^n}{n!}\,dy\right]$$

$$-M\frac{\partial}{\partial\beta}\left[\int_0^{T-M-w} e^{-\beta(T-w-y)-\gamma w}\,\frac{(T-M-w-y)^{n-1}}{(n-1)!}\,dy\right] = -n\frac{\partial\theta_{n+1}}{\partial\beta} - M\frac{\partial\theta_n}{\partial\beta} \tag{28}$$

$$\frac{\partial^2\theta_n}{\partial M^2} = -\frac{\partial}{\partial M}\left[\int_0^{T-M-w} e^{-\beta(T-w-y)-\gamma w}\,\frac{(T-M-w-y)^{n-2}}{(n-2)!}\,dy\right]$$

$$= -\int_0^{T-M-w} e^{-\beta(T-w-y)-\gamma w}\,\frac{(T-M-w-y)^{n-2}}{(n-2)!}\,dy = -\frac{\partial\theta_{n-1}}{\partial M} \tag{29}$$

Because we have $\frac{\partial\theta_n}{\partial\beta} \le 0$ and $\frac{\partial\theta_n}{\partial M} \le 0$ from equations (26) and (27) for any n, equations (28) and (29) are nonpositive. Thus we have:

$$\frac{\partial^2\theta_n}{\partial\beta^2} \ge 0 \tag{30}$$

$$\frac{\partial^2\theta_n}{\partial M^2} \ge 0 \tag{31}$$

4. Numerical Examples

Let us illustrate the accessibility measure. We assume that time resource is 480 (min). The parameters are given by:

$$\beta = 0.188,\ \gamma = 1.814,\ M = 60\ \text{(min)},\ n = 3 \tag{32}$$

We normalize the accessibility measure and time budget such as $T = 1$. Varying w from 0 to 180 (min), we have Fig.5. Because increasing waiting time is equivalent to decreasing the number of bus transportation services per day. i.e., the choice set of possible daily life activities shrinks. Fig. 5 shows that our accessibility measure clearly shows the choice set of time to move.

Fig 6 shows the difference of the accessibility measure between car-user and bus-user. The parameters are given by:

$$\beta = 0.188,\ \gamma = 1.814,\ w = 60\ \text{(min)},\ n = 3 \tag{33}$$

Car-user does not have to spend waiting time because he/she can move anytime. Thus we give $w = 0$ for car-user. In this figure, only the difference between them is waiting time. If the planner's concern is to minimize the difference between both users' accessibilities, it is useful to focus on Fig.6.

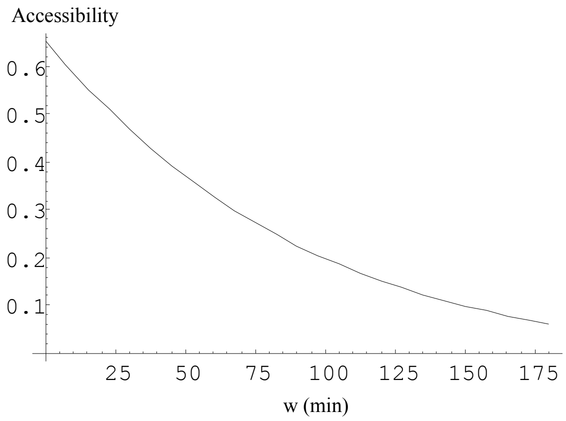

Fig.5 Illustration of accessibility measure

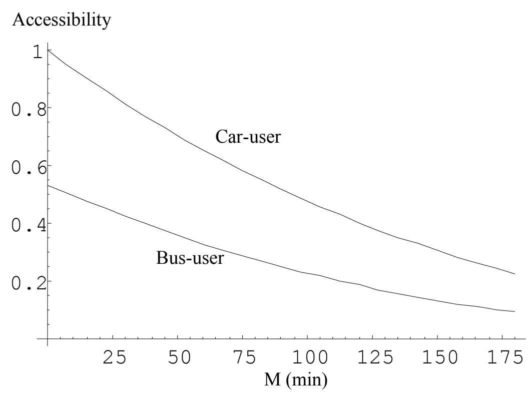

Fig.6 Difference of accessibility measure between car-user and bus-user

5. Conclusion

We study the accessibility measure for assessing the opportunity for planning bus transportation service in rural areas. To assess it, we argue that the opportunity restricted by fixed route and time by the bus transportation service should be formulated. At first, we discuss which type of accessibility measure which has been proposed in previous studies is suitable. It is found that time-space prism is appropriate but it should be modified so that the restriction in terms of fixed time can be considered explicitly. Then we develop new accessibility measure and show its simplified version.

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