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Measuring Multimodal Transport Level of Service

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Abstract

One of the challenges facing intermodal integration is that the planning framework needed for it lacks appropriate measures of level of service that cut across the modes involved and the connections between them. In this study we develop a framework and a set of metrics of level of service in a multimodal context. We propose a conceptual framework in which we identify the various attributes of level of service and the method of their integration. These measures of performance are defined from two perspectives: the user's perspective (*the demand side*) and the provider's perspective (*the supply side*). An analytical framework is then proposed in which a working definition of a "multi-modal corridor" is adopted and a methodology for defining and combining measures of performance for such a corridor is developed. The methodology is defined in the context of evaluation for the purpose of choosing among alternative corridors. The approach is grounded in utility theory and quantitatively these measures of performance are defined as indirect utility functions of the type used in choice models.

In combining the measures of performance for different elements of a multi-modal corridor, the methodology recognizes that some are additive, either simply or with appropriate weights, while others are not additive at all and exhibit phenomena such as *weakest link*, or *maximal effort*. Safety is a good example of this. The basic proposition is that many level of service metrics are non-additive and their combination for a multimodal systems requires specific models that reflect the way the attributes impact users of different modes and during different segments of a multimodal journey.

This study concludes by recommending some research directions to develop the models needed for the integration of level of service measures for multi-modal corridors and for their inclusion in indirect utility function.

Table of Contents

Table of Figures

1 Introduction

One of the challenges to the planning of multimodal transportation systems is the development of measures of performance that properly reflect the level of service provided by these systems. In thinking about multimodal level of service measures we face conceptual and analytical challenges that stem from the need to integrate the measures of performance for different components of a multimodal system. This is especially the case when these measures are categorical, or non-additive, which complicates their integration into evaluation models. Similar metrics are commonly used to reflect the level of service of different elements (time, cost, and so forth,) but they are considered for each mode separately, even though the transition from a metric to a measure of level of service will take on different scales in the different modes, as well for the intermodal connection. The resulting distortion can mean inadequate assessment of the impact of intermodal connections on overall multimodal performance. Simply comparing the sums of these elements among different multimodal alternatives is not a sound basis for evaluating overall performance. This can be seen in the issue of "*the weakest link*". As it appears in the decision-making process, and especially for issues such as reliability, rather than looking at the average of the entire picture, people have more concern about the link that provide the least level of guarantee. With inadequate integration methodology, the problem may be underestimated or even overlooked. Multimodal systems work only if the modes are integrated well at the interface, and it is this integration that suffers the most from inadequate level of service definition and measurement. A new analytical framework for multimodal MOP is indispensible.

Besides the challenges in the integration process, it should be also noted that two parties would perceive the performance of the network: the demand side and the supply side. Their perception will have different focus but still related. Measures of performance have a multifaceted purpose and are needed in a wide variety of planning, design and policy analysis of transportation systems. Level of service measures represent set of all the measures of performance needed for transportation analysis and reflect primarily the attributes of the system that affect user perception of the quality of service. In this report, the demand side is discussed as "*the user's perspective*" (Section 4), because it represents the response of the user and the market; whereas the supply side being " *the supplier's perspective*" (Section 5), level of service perceived by a system.

There are multiple levels of integration: the integration of decision factors of one mode, the intermodal integration, and the integration of individuals across the society. These attributes may be *additive* (such as monetary cost) or *non-additive* (such as safety, reliability, etc), or even more complex and needs to be evaluated from multi-perspectives (such as travel time). We will try analyzing their features more into details in later sections.

In this research we looked at the various measures of level of service for an array of multimodal transportation systems and categorize them in terms of the feature in which they are to be combined. With this conceptual framework in place we would move toward defining a quantitative framework with models for combining the various measures to come up with overall multimodal metrics. In this we would rely on choice model theory to consider the way in which separable metrics can be combined. We relied on probability theory to consider the combination of probabilities metrics such as reliability. We discussed

the possibility and validity means of assessing some subjective, such as comfort and convenience. We also reviewed existing literature to come up with numerical examples to illustrate the framework. We developed improvements of existing methodological systems of transportation analysis rather than defining completely new methodologies. The reason for this is to overcome the inertia of adoption and to facilitate expediency in use of our research findings.

We produced is a framework and a set of metrics for evaluating the level of service of transportation systems at a multimodal level. Our scope includes urban and regional transportation and the focus, empirically, is on California. We identified innovative methods of providing these connections, and their impact on the effectiveness of intermodalism. We also provide innovative institutional and legislative perspectives that may contribute to the policy debate on how to achieve a true multimodal transportation system. Furthermore, we identified the issues that should be further investigated into in the future.

The second section of this report will be the literature review. The third section is our conceptual framework: identifying the attributes, and their respective roles in from different perspectives (demand, supply). In section 4 and 5, we will introduce a simple illustrative multimodal transportation network trying to demonstrate the analytical framework we developed. In section 4, we will try to model the decision making process from a user's point of few, and come up with an indirect utility function and a demand function for multimodal transportation network. In section 5, we will be constructing the evaluating framework from the suppliers' perspective. In the last section, we will make policy recommendations basing on these analytical results.

2   Literature Review

Literature related to the topic lies in two aspects: multimodal system evaluation and the impact of each attribute we are trying to look into.

Multimodal transportation

The work of Lyons, Harman, Austin and Duff (2001) is based on the U.K.'s ten year plan (starting from year 2000), trying to provide the public with the opportunity to compare travel options across public and private transportation modes, seeking to offer a one-stop-shop journey planning. By reviewing abundant literature across the globe, the work identified critical topics, their findings and limitations. The topics mainly lie in the government's planning perspective, its feasibility and information gathering process. The report offers highlights on the challenges during the government's decision-making.

Li and Wachs (2000) proposes a set of inter-modal performance indicators in which service input, service output and service consumption are measured by total cost, revenue capacity, and unlinked passenger trips/miles respectively based on economic principles and evaluation objectives, and concluded that their enhanced inter-modal performance indicators are more appropriate for comparing the efficiency and effectiveness of different modes or combination of transit modes. The concern of inter-modal performance can be view as a proof of the importance of differences in multimodal transportation planning process.

In the study of Richard H. Pratt and Timothy J. Lomax (1996), Performance Measures for Multimodal Transportation Systems, they observed the importance on: Match performance measures with objectives; Understand the effect of improvements; Address people and goods; Use common denominators; Development of measures should not be governed by data concerns; Employ both multimodal and mode-specific measurement; and Remember the audience.

In the work of Robert A. Johnston (1994), *the evaluation of multimodal transportation systems for economic efficiency and other considerations*, the concern of multimodal transportation evaluation an planning is highlighted. The work shows that the concern of multimodal transportation planning in improving planning efficiency. The paper deals the issue more from an ITS point of view.

In the DOT's strategic plan 2006-2011, the strategies, milestones, and outcome as well as goals of the U.S. Department of Transportation is highlighted, offering the guidance of emphasis of policy making, which is important in the suppliers' perspective in our on-going project. The plan stands from a more political point of view, whereas the technical perspective is not a major issue of concern.

Modeling Attributes

Despite the abundance of literature on transportation measures of performance, there is little that has addressed the question of the multi-modal integration of   attributes of level of service. In our literature reviewing process, we found the following issues are more of global research interest:

- **Time**

In the work of Bates et. al. (1987), travel time variability is classified into three categories:

i.   Inter-day variability caused by seasonal or day-to-day variations: demand fluctuation, accidents, road construction and weather charges;

ii.   Inter-period variability, which reflects the impact of differences in departure times and the caused charges in construction;

iii.   Inter-vehicle variability mainly due to individual driving styles and traffic signals

Noland and Polak(2002) used similar categories to represent travel time variability; differences in travel time from day-to-day, over the course of the day and even from vehicle to vehicle

In Bates et al.(2001), it is further added that on the demand side, after considering seasonal effects, day-of week variation another systematic variations, the residual day-to-day variations are essentially random, whereas the randomness on the supply side is mainly due to incidents, such as vehicle breakdowns, signal failure, etc.

Bates et al. 2001, Hollander 2006, Hollander and Steer Davies Gleave 2009 emphasis the stochastic feature of travel time variability, and defined travel time reliability as random variation in travel time.

In Noland and Polak (2002) identified the difference between travel time variability and congestion, as a transportation system with severe congestion may have very stable day-to-day travel time.

Many measures of travel time variability have been developed in the extant literature, while one common feature is the recognition that travel time distribution is impacted by day-to-day fluctuation on the demand side as well as the supply side of the traffic

Travel time variability is most commonly represented by lognormal distribution (e.g. Rietveld et al. 2001, Giuliano, 1989). Bates et al. found that a generalized Poisson distribution to better describe the delay distribution for train travel time.

- **Reliability**

In the study of Rietveld et. Al. (2001), the issue of reliability is studied in a multimodal perspective, in the case of public transportation system in Netherlands. The study shows explicit attention on one missing the connection between elements on a chain. The data from various unimodal resources, partly thin, need to be combined. Customer valuation of unreliability is estimated by means of a stated preference approach. The result is, however, difficult to transfer into other countries due to the high popularity of bicycles in Netherland.

Li, Hensher and Rose (2010) studied the issue of reliability in terms of willingness to pay with reviews of empirical evidences from the Europe, the U.S. and also provides new evidence from Australia. The review focuses on car, rail and bus, each by their single mode, showing the significance of reliability in travelers' decision making.

- **Safety**

Moen studied the determinants of safety priorities in transport, from the perspective the effect of personality, worries, attitudes and willingness to pay in his work 2007. The study is conducted by means of survey, and receiving 1727 returned questionnaires. Several factors

were found to be important to priority of safety. The three personality assets: trust, excitement seeking and anxiety, were measured along with measurements of optimism, worry, attitudes and willingness to pay. They were all tested by factor and reliability analysis. The results were satisfactory and the measurements were used in both a regression analysis and a SEM-path analysis to predict priority of safety.

Jessup et. Al. conducted a feasibility study evaluating transportation security systems and associated multi-modal efficiency impacts. The issue of terrorism attack is the major concern study. In this study, a constrained transportation optimization model was developed to estimate the effects that security related impacts had on an electronic firm's supply chain of televisions through the six major west coast ports. This modeling effort was developed using primary data obtained through interviews with the firm, and maritime experts.

- **Energy and Emission**

Delucchi (2000) suggested in his Environmental Externalities of Motor-vehicle Use in the US, that the marginal impact is increasing with the existing pollutant level. The perceivable impact includes human illness, visibility reduction, agricultural loss, etc. Although there remains considerable uncertainty in all stages for modeling the damage cost, the results enriches cost-benefit and pricing analyses from a larger extent. The estimation of external costs has been used for comparing the social costs of different transport technologies or modes, evaluating the trade-offs between different environmental impacts, and analyzing policies.

There are more literature on this issue from the perspective of taxing, (Ramseur and Parker, 2009; GAO 2010), and emphasize on the measurements of control rather than evaluation.

3 Multimodal Measures of Performance – A Conceptual Framework

The measure of performance of a multimodal transportation alternative describes both its positive and negative impact. Depending on the perspective, (demand or supply) there can be multiple criteria and objectives. We therefore use an analytical framework grounded in utility theory leading to the construction of indirect utility function for any multi-modal alternatives, such that the elements of that function can vary depending on the perspective, and the use for which the function is intended.

3.1 A Multimodal Alternative: Definition

Before introducing the metrics we adopt a working definition of a multimodal transportation alternative. There is clearly some flexibility in defining a multimodal transportation system. Essentially all transportation is multimodal, but a working definition permits the focus on important elements. When more than one mode is involved, each mode provides "access" to the next in a chain connecting an origin to a destination. Accessing a bus at a stop may require walking to the stop or driving to a park-and-ride site. Whether either of these two configurations is modeled as a multimodal network or a single mode network with walking access depends on the purpose of the model. The framework adopted for this analysis accommodates this flexibility in model design and identifies the following elements of a multimodal system. But first a clarification of terminology: We use the term '*multimodal*' to represent the system with more than one mode, and the term '*intermodal*' to represent the connection between any two of these elements.

Access: The concept of access is usually mode specific. As mentioned above it is possible to consider that each mode is providing access to the next, but for the purpose of this analysis we reserve the term "access" to represent the first link connecting between a trip origin and the first mode to be used in the multimodal system. From a door-to-door perspective this begins from the moment the user gets out of the *door* to the point when he/she enters the system of the mode. This process may include composite links (walking, bicycling etc.) but they are all consolidated together as an access link. If any of these links is itself the subject of analysis, then it would have to be modeled as a separate mode. In urban transportation modeling it is customary to consider the access process as individual travel, such as walking or bicycling,.

Waiting: This is defined as the duration between the a user's arrival to a transport terminal and the actual entry into the vehicle of the mode in question.

In-vehicle travel: This is the duration of time on the vehicle.

Transfer: This is defined as the duration between one getting out of the previous mode and arriving at the entrance point of the following mode.
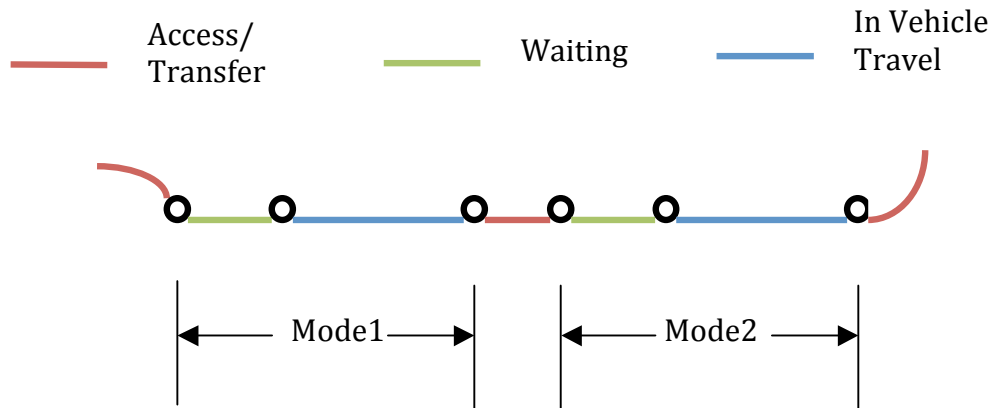
Figure 3-1: Case Study Network

The use of these definitions to model a multimodal system has to be case specific. Firstly, overlapping will arise in cases such as a coordinated system. For example, to transfer between flights at an airport, and if the check-in is completed already, there will not be much distinction between transfer and waiting. This is, because the reasons to distinguish between them – reliability, security, and etc.- lose their importance. Secondly, the consistency in scale will help us better construct the alternative and simplify the analysis. For instance, if one drives 20 minutes to the airport to take a 1-hour flight, the driving will certainly be considered as the first mode in the trip. However, if the flight is 15 hrs, it makes more sense to consider the driving as access to the transportation alternative. Therefore, the definitions are flexible and should be adjusted depending on the specific scenario, and the purpose of the application.

3.2 Decision Perspectives:

As mentioned earlier, multimodal measures of performance are defined from two perspectives: the user's perspective and the supplier's perspective. To analyze the user's perspective we focus on the individual's response emphasizing the assessment of user costs and benefit, as measured by the perceived utility. This can be aggregated later to represent community welfare impacts. This aggregation can be done using the usual procedures used in social welfare analysis and based on socioeconomic distribution.

The supplier perspective reflects a producer's optimization process, or a public agency's process of evaluating global impacts. In other words, the supplier can be the government or private companies. In the context of this report, we are more inclined to consider the government as the supplier, as their concern is on overall social welfare rather than final profit. The user's assessment of benefit is part of the supplier's optimization objective. But the supplier is also concerned with other attributes such as investment cost, agency cost, externalities, and with weighing all these aspects as part of a planning, policy making process.

3.3 Framework: Integration of Measure of Performance

The combination of measures of level of service across modes is the main subject of this study. An important distinction to make here is between measures that are *additive* and ones that are *non-additive*. Most measures of a multimodal system are of the second category

and require a modeling framework for combining them. To illustrate this point consider the example of comparing the door to door travel time between two multimodal systems, a high speed rail with auto access to stations and an air transport journey with transit access to the airports. To simply add up the travel time components for each of these multimodal systems and then compare them ignores important differences in the incidence of these various components and their contribution to the disutility of travel. It ignores the different impact of access time and line-haul time. It also ignores the complex question of reliability and the variance in travel time. It therefore misrepresents the relative performance of these two alternatives and can lead to invalid conclusions and possibly wrong forecasts.

Even the most obviously additive measure, out-of-pocket cost, which is uniformly measured in money terms and can be simply added for the components of a multimodal service, can sometimes behave in a non-additive manner when the different elements of cost have different tax implications, or subsidy potential. An example of this could be line haul costs that may be tax-deductible or subsidized by employers but terminal costs (parking or access to station) that may not be. Or different cost elements that can be paid at different times thereby having different impact of the user's budget. The challenge for dealing with multimodal measures of performance is how to address the issue of non-additive metrics. Some of these are separable in that they may be combinable with some linear function. An example would be line-haul time and access time combined according to incidence parameters that are estimated from a discrete choice model. Others are non-separable in that they combine in nonlinear ways and require complex functions. An example of this can be found in reliability and safety measures that reflect the performance of the *weakest link* of the multimodal system. Another example comes from the various measures that reflect variance of individual metrics requiring the nonlinear combination of standard deviations. The detailed description of the various measures of level of service is in the following session.

3.3.1 Travel Time

The two main components of the cost of traveled that is incurred by individual users are: time and money. We begin with travel time. The measurement of travel time is fairly easy, but the difficulty is in quantifying user's perception of time especially as it varies between the different components of the total travel time. . On the individual level, the evaluation of perceived travel time is based on the definition in the beginning of this section: access, waiting, transfer, and in-vehicle traveling.

IN VEHICLE TRAVEL TIME

The weight of in-vehicle travel time of different modes in total perceived travel time depends on the overall level of service provided by the mode, such as level of comfort, sense of security, etc. For example, the perceived travel time of taking a bus is usually longer than driving, for the same time of actual time spent. Therefore, again, these can be interrelated or even overlapping. In addition to adding the different components of time together with appropriate weights, it is not unusual to define weights that reflect some attributes that affect the perception of time, such as comfort, and security. But that would require detailed information as might be obtained from in-

depth user surveys. . In the absence of such detailed information the alternative is to we introduce these attributes as stand-alone categorical variables.

TRANSFER TIME

Due to the uncertainties that may arise during transfer, the transfer time is usually more heavily weighted than in-vehicle traveling time. The higher weight reflects 1) effort involved, such as walking; 2) reliability issue and the uncertainty regarding the intermodal connection being made.   Therefore, if one enters into a coordinated system then the weight should be less than in an uncoordinated connection between different modes.

ACCESS TIME/ACCESSIBILITY

From our definition, access time acts in a similar manner as the transfer time in user's perception. Meanwhile, access time is a measure of accessibility, especially in public transportation. Maintaining adequate public transit accessibility is a responsibility of the government, and also a concern of the transit agency. The issue of accessibility also involves the equity issue.

WAITING TIME

The waiting time is usually heavily weighted, partly because people usually perceive it as a waste of time. At the same time, safety problem may arise during waiting, especially for modes such as bus with a significant crime rate at the stop, which gives more reason to assign heavier weight to waiting time in decision-making. Scheduling and coordination may help improve the negative impact of waiting.

Also as the concept is widely adopted, in public transportation, the waiting time is usually directly related to transit headway or service frequency. However, from the perspective of the agencies, what is perceived is the increased cost of increasing service frequency.

TOTAL TRAVEL TIME

The definition of each element allows some overlapping and should be case-sensitive. Even with all the weighting factors being considered, the evaluation of total travel time in the utility function may still follow non-linear pattern. As it appears in existing literature, people's budget (money and time) per day is limited, and therefore, when the travel time exists a certain level, there can be a sudden increase in value of time. The same issue applies to monetary cost. However, the problem is never analyzed into depth from this perspective, and should be a point of research interest in future.

3.3.2 Monetary Cost

The measurement of monetary cost is rather direct, and clearly additive. Complications involved in the issue mainly lies in how the user perceives to the cost. The monetary cost can be directly out of pocket, or less perceivable. At the same time, bundle between agencies may affect the perception too.

OUT OF POCKET COST

Out of pocket cost includes taxes, ravel tickets, tolling fees, etc. It is the part of cost incurs directly to the user during one's travel. The cost is usually on a one-trip basis.

INDIRECT COST

Indirect cost can be partly hidden, such as gasoline, car insurance, mileage cost, maintenance etc. The cost is usually paid collectively, and not during the trip. As a result, the traveler may become less sensitive to it, and perceive partially.

BUNDLE BETWEEN AGENCIES

Bundle between agencies usually occurs as discount. For example, a traveler may get a free shuttle bus ticket when he/she books from a certain airline. Furthermore, bundle may imply coordination between agencies

From the user's perspective, the perceived monetary cost is the one that matters and appears in the utility function. However, from the supplier's perspective, all the costs collected are weighted equally enters the revenue..

3.3.3 Safety

Besides its impact on perceived time by travelers, the safety factor may have other impacts on the user's decision making before planning the travel. For example, while the travel time is perceived during the trip, before deciding which alternative to take, the user may evaluate the issue of safety basing on his/her knowledge, probably information from newspapers. As a result, safety has the property of "the weakest link", as when it comes to a multimodal transportation alternative, no matter how the safety factors of the other modes are, the safety factor of the entire trip is only determined by the worst link.

The evaluation of safety is perceived as the risk taken due to insecurity. However, the risk has a wide range, from monetary cost to fatal risk, and therefore quite difficult to translate onto the same scale. Besides, user's perception to risk cannot be assumed to be linear. So the evaluation of safety is a problem that is not easily quantified. We will discuss about this issue later in the analytical framework.

3.3.4 Reliability

No transportation mode can be perfectly reliable. In a multimodal transportation system, the arrival time of one link is the starting time (which is decided by previous modes) plus the travel time (which is generally independent of previous modes). Both of the elements would not be accurate, but usually follows some probabilistic distribution. The reliability is the possibility that the arrival time falls into a certain confidence interval.

Existing work on the reliability issue usually look from the perspective of willingness to pay, which studies the reviewed preference between reliability and other travel disutility (usually time or monetary cost). The assessment of reliability can be achieved from historical data of each mode within the alternative. Trying to achieve more insights of the issue, in this report, we considered the reliability problem as the expected penalty from delay.

Unreliability causes extra waiting or delay, the later of which is more heavily weighted. Reliability can be partly considered as a "weakest link" factor as well. However, the arrival time distribution of the last link requires intense analytical work. As when the risk of missing the next link becomes part of our concern, the risk of delay performs rather non-linearly. The scenario also depends on the degree of coordination between modes. The most common example exists when the user need to transfer between flights. If the two connected flights belong to the same airline, the connection can be considered as perfectly coordinated (comparing with other types of connection). Whatever accidental events occur to the first flight, the airline company is responsible for arranging the connected flight. A certain level of service is guaranteed. Whereas if the flights are from different companies, there is no guarantee exist. If the first flight is delayed, the user is responsible for all the monetary and time cost that rises from it. The difference can be also referred to as "inside the system" versus "get out of the system", where system refers to the condition when two connected modes are coordinated. However, coordination means investment cost. In some cases, coordination may not necessarily improve the situation. For example, to transfer between the airtrain and the flight does not require coordination, especially when the airtrain has a high service frequency. We will further demonstrate this quantitatively in the following section.

3.3.5 Flexibility

In our definition of a multimodal transportation alternative, the illustrative structure is a corridor. When it comes to a transportation network, the overlapping between alternatives raises complication in numeration. The number of available alternatives may even exceed the total number of links involved. The network structure may provide convenience, especially in the case when one link in an alternative is shut down, the user may switch to another alternative without sacrificing much of the utility. For example, to transfer from a flight to the train, which means from an airport terminal to the air train station serving it, a user may choose from several options, such as walking, taking a shuttle bus, or though a linking bridge. Even though the modes proceeding and following this link are the same. Therefore each of these choices indicates a transportation alternative, as we defined. From the point of view of utility, one of the alternatives may be dominant (shuttle bus), and the rest may be considered as redundancy (walking). But in case when shuttle bus is not in service (due to accidents or service hour limits), users planning to choose that alternative have the flexibility of switching onto another one (walking) without much delay. In other words, if there are not walking routes or any other substitutes available, the user will need to go all the way back to the directory to search for a taxi.

We define flexibility as an indicator of the level of service It describes the ability of a network to adapt to changes (either due to user's behavioral change or the network setup change). It is overlapping with the reliability issue, as they are both concerned with accident possibility. To some extent, flexibility may contradict with other indicator. For example, direct service provides better LOS in terms of time cost, but sacrificing flexibility. This is also why when direct service and indirect service are usually both offered.

The concern of flexibility also accounts for the fact that some transportation modes, especially public transportation, has limited service hour. And therefore, the flexibility of using the mode, or the alternative, is measured by the service hour. Flexibility has similar properties as accessibility, which is also an alternative specific "weakest link" factor.

Also as it is mentioned before, in a multimodal network design, redundancy must be included to provide flexibility. The redundancy should be provided such that, when one link in an alternative is broken (due to foreseen or unforeseen reasons), the user will not be "stuck" in the alternative. He/she can switch onto another alternative and continue with his/her trip with none (or little) sacrifice of utility. It is difficult to accommodate flexibility in common utility-based analysis, because flexibility is not an independent indicator between alternatives. A common method to include flexibility in the design without much mathematical challenge would be adding redundancy to the network after the arteries are designed. On the other hand, in terms of evaluation, the value of flexibility requires more strategic and numerical effort, which could be a field of interest in future research.

3.3.6 Energy

Although energy consumption is a monetary cost concern to the user, the energy issue under discussion here is from the supplier's perspective, highlighting the concern of externality. Therefore to evaluate a certain source of energy, we need to discuss four aspects: the cost of generation, the renewability, the efficiency during production and its emission. The result, however, is subject to technological constraint. So there may be innumerous number of existing resources, our discussion always falls between electricity and gasoline (sometimes diesel).

The environmental impact is largely a government evaluation concern. Individual travelers may be aware of the issue, but it rarely affects their decision-making. With the increasing urgency of environmental concern in the contemporary society, the issue of environmental impact is taking on increasing weight in the government's decision making. Emission is the subsequent impact of fuel combustion, which includes non-pollutant such as CO_2, which causes green house effect, and pollutant such as NO_x, SO_2, VOC and etc, which are detrimental to human health. Emission should be evaluated by unit volume/pax, for passenger movement, and unit volume/unit weight for freight movement. Generally speaking, it is directly electricity is related to fossil fuel combustion, and therefore, the fuel type; and is also related to fuel efficiency; which is why electricity is usually considered as a clean energy in terms of emission. Emission is usually a government concern, as the commuters and transportation agencies cannot perceive it directly.

3.3.7 Investment and Agency Cost

The investment and agency cost is the major constraint to the supply side. In the case of public transport service, the objective of the agency is to provide social welfare, and usually cannot cover all its expense. Therefore the agencies rely on the government's subsidy. The government's decision of giving its financial support is based on the measurement discussed before. Because the focus of this report is not on the business strategy of private companies, in the framework we are introducing, the government is responsible of all the expenditure that cannot be covered by the revenue.

3.3.8 Equity

The issue of equity is relatively complicated; as it involves factors such as travel cost, accessibility, and emissions, under a specific sociodemographic distribution. At the same time, due to the concern of equity, the transportation agency may offer lower fares to the low-income group, and may be obligated to provide adequate accessibility to each area.

Therefore, equity is an issue that experienced by travelers in a non-uniform fashion, occurs largely under government regulation, and the relative consideration is implemented by transportation agency. Meanwhile, when it comes to investment, the resultant scenario of the improved service should also be evaluated from the perspective of equity. The evaluation can be achieved from a small-scale implementation.

The equity issue can be quantified from the indirect utility model. If we can obtain sufficient information about the social make-up of the community and the respective indirect utility perceived by each group, we are able to observe the variance of utility in the community, so as to obtain the evaluation of equity. For example, equity can be described by the standard deviation of indirect utility of a community.

3.4 Angle of Perception

USER'S PERSPECTIVE

Users' perception of a composite of travel modes is usually captured by the utility function. As analyzed in the previous session, standing at the users' perspective, the factors perceptive includes travel cost, safety, reliability, travel flexibility and etc.

Concerning multimodal alternative $i = 1, \dots, n$, including modes $j = 1, \dots, m$

	Indicator (data input)	Elements
Disaggregate Factors	**Time(s)**	Access
		Waiting
		In Vehicle Traveling
		Transfer
	Money($)	Out Of Pocket
		Indirect
		Bundle
Aggregate Factors	Safety	Risk of Insecurity
	Reliability	Risk of Delay and Waiting
	Flexibility	Feasible Duration of Taking the Mode

Figure 3-2: Users' Perception

The resultant demand will be following market response, such that the demand will increase with the level of service.

SUPPLIER'S PERSPECTIVE

There are two groups of suppliers: the government – the policy maker, and the agencies – the actual implementer.

GOVERNMENT'S PERSPECTIVE

From the perspective of the government, the issues that are of her concern will be

LINK j	
Indicator (data input)	**Property**
Equity	Variance of Utility
Energy	**Efficiency**
	Renewability
Emission	**Weighted Volume**
Monetary Cost	
Level of Service	

Figure 3-3: Government's Perception

The issues under the government's concern can be considered as independent, and their relative weight in the final decision largely depends on the current need and the policy maker's final call. Therefore, these weighting factors are out of the scope of the discussion in this report.

AGENCY'S PERSPECTIVE

From the perspective of an agency providing the mode i, its profit is affected by

Property	Assessment
Agency Cost	Agency cost $\propto$ Level of Service $\propto U_1$
Revenue	
Subsidy	

Figure 3-4: Agency's Perception

Therefore, during the operation, it should be at least guaranteed that the agency should be able to maintain the balance of its income and expense. The government is responsible to provide the subsidy covering the gap between revenue and agency cost. So from our conceptual framework, the agencies only act as a budget constraint to the government's policy making. To simplify our analysis, in the following analysis, the supplier's perspective is represented by the government's perspective.

In the following two sections, we would introduce the analytical framework we developed, from the user's perspective and supplier's perspective respectively. The analytical framework will be a numerical representation of the conceptual framework we are discussing over here, and based on a simplified network.

4 Analytical Framework - Users' Perspective

In this section we construct a user indirect utility function for the intermodal network defined in Fig. 3.1, and shown below. The simplification to two modes should not result in any loss of generality. As is commonly done in transportation utility analysis, we consider the perceptions of level of service attributes to be deterministic when measures at a dis-aggregate
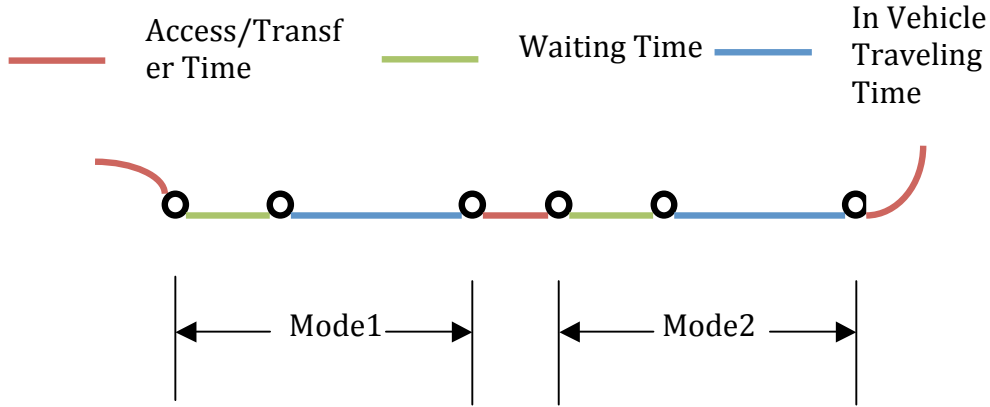
individual level. The aggregation to a group of users introduces stochastic effects resulting in a variance of perceptions across the relevant population. We build the elements of the utility function for each attribute (time, money, etc.) and then these are combined to form the total function for a multimodal alternative. The structure of the indirect utility function is assumed to be basically a linear function of the attributes, with the parameter of each attributes reflecting its relative influence on the utility function. As such, some attributes may be allowed to share parameters, as is shown below.

4.1 Time Cost: Perceived Travel Time

For the transportation alternative defined as above, the travel time elements and their weighting factors are defined as:

Time	Attribute	Mode 1			Mode 2			
		Access Time 1	Waiting Time 1	IVTT 1	Transfer Time	Waiting Time 2	IVTT 2	Access to Destination
	Denotation	A_1	W_1	T_1	A_2	W_2	T_2	A_3
	Parameter	α_a	α_{w1}	α_{t1}	α_a	α_{w2}	α_{t2}	α_a

Figure 4-1: Time

Therefore, the indirect utility function for travel time (factorized travel time) is

$$V_t = \alpha_a(A_1 + A_2 + A_3) + \alpha_{w1}W_1 + \alpha_{w2}W_2 + \alpha_{t1}T_1 + \alpha_{t2}T_2$$

Where V_t is a negative, monotonically decreasing function of A_i, W_i, T_i

The non-factorized total travel time is

$$T = A_1 + A_2 + A_3 + W_1 + W_2 + T_1 + T_2$$

For simplification, denote $W_1 = T_3$, $W_2 = T_4$, $A_1 = T_5$, $A_2 = T_6$, $A_3 = T_7$ and the parameter is named accordingly.

It is noted that with different compositions of T, V_t may increase with increasing T. The condition of interest would be:

$$\frac{dV_t}{dT} \approx \frac{\Delta V_t}{\Delta T} = \frac{\sum dV_t(dT_i)}{\sum dT(dT_i)} = \frac{\sum \alpha_i dT_i}{\sum dT_i}$$

or

$$\begin{cases} \sum \alpha_i dT_i > 0 \\ \sum dT_i > 0 \end{cases}, \text{ such that } \frac{dV_t}{dT} > 0$$

An interesting research question would be to explore situations under which this condition obtains, which means situations when the trade-off between transfer and line haul times is such that an individual would prefer a longer total travel time to avoid a certain amount of transfer time. This is illustrated by the following example.

EXAMPLE:

We consider a case when $\alpha_1 = \alpha_2$ and $\alpha_3 = \alpha_4 = \alpha_5 = \alpha_6 = \alpha_7$ Also $\alpha_i < 0$. We define:

$$TT = T_1 + T_2$$

$$WT = A_1 + A_2 + A_3 + W_1 + W_2$$

If TT changes by ΔTT, WT changes by ΔWT

$$\Delta V_t = \alpha_1 \Delta TT + \alpha_3 \Delta WT$$

Start with $\Delta TT > 0$, if $\Delta WT \leq -\frac{\alpha_1}{\alpha_3} \Delta TT$, $\Delta V_t > 0$

A reasonable assumption is that $\alpha_1 > \alpha_3$, i.e. $\frac{\alpha_1}{\alpha_3} < 1$.

Therefore, when $\Delta WT \in (-\Delta TT, -\frac{\alpha_1}{\alpha_3} \Delta TT)$, $\frac{dV_t}{dT} > 0$

Otherwise, $\frac{dV_t}{dT} < 0$

For example, as mostly appears in the existing literature, the waiting time has twice the weight of IVTT, when $\Delta WT \in (-\Delta TT, -0.5 \Delta TT)$, $\frac{dV_t}{dT} > 0$. So when the waiting time is reduced by more than half the increase in vehicle travel time, the passengers' perceived utility may be increasing as the total travel time increases.

The resultant increase in total travel time starts from 0, may reach up to $\frac{\alpha_3 - \alpha_1}{\alpha_3} \Delta TT$. Also if we consider the uncertainty in travel time, as the weight of waiting time increases, the schedule may be more relaxed without sacrificing the overall utility

CASE STUDY: US ENVIRONMENTAL PROTECTION AGENCY (2000)

The work reviewed 50 US studies and concluded that the perceived time of walking time is 2.0 to 2.72 times that of in-vehicle time, i.e. $\frac{\alpha_1}{\alpha_3} \in (0.368, 0.5)$, the possible increase in utility with respect to increase in total travel time and different values of $\frac{\alpha_1}{\alpha_3}$ can be plotted as
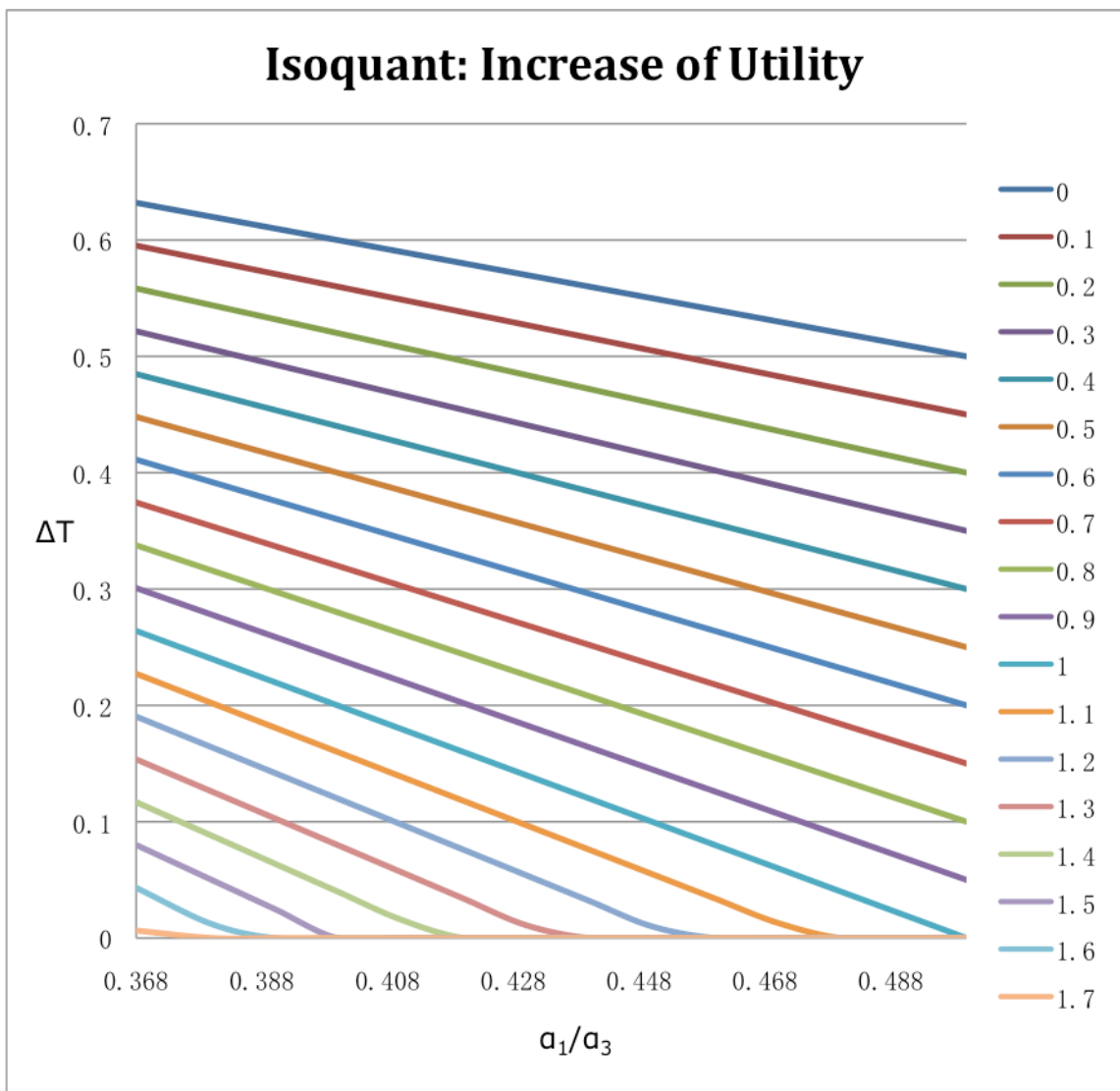

Figure 4-2: Utility VS. Total Travel Time

4.2 Monetary Cost

For the simplest case, assume all the cost is 100% perceived by the user. And therefore, there is usually no perception difference in monetary cost for the same customer, so there is only one parameter, which can be applied to all the monetary costs.

Monetary Cost		Mode 1				Mode 2		
	Link	Access Time 1	Waiting Time 1	IVTT 1	Transfer Time	Waiting Time 2	IVTT 2	Access to Destination
	Measure of Performance	C_3	C_4	C_1	C_5	C_6	C_2	C_7
	Parameter	α_c						

Figure 4-3: Monetary Cost

Also in the usual case, there is no monetary cost for accessing/waiting/transfer, so

$$C_3 = C_4 = C_5 = C_6 = C_7 = 0$$

The total monetary cost can be calculated as $C = C_1 + C_2$

There are, still, several complicating issues involved in the evaluation in monetary cost, the two major ones are:

a. Bundling: to achieve optimal social welfare, agencies sometimes bundle, or coordinate between transportation services provided by different suppliers. This results in discounts of fare during transfer.

b. Discount for a specific groups: In situations when pricing schemes are not uniform and depend in part on some socioeconomic characteristics of the users, such as senior or student fares, the assessment of cost will have to be differentiated on the bases of these characteristics.

4.3 Reliability

Travel time is should be considered to be stochastic due to the uncertainties surrounding it. While considering stochastic effects, early arrivals may not be a major concern, as the earliness usually results in shifting of waiting time rather than the reduction of the total travel time. But delayed arrival is a major issue, and also leads to the discussion of travel time reliability. In this session, we discuss reliability mainly in terms of the risk of delay. Travel time variability is most commonly represented by a lognormal lateness distribution (e.g. Rietveld et al. 2001, Giuliano, 1989). Generally, the distribution of time (starting time, line-haul time, waiting time, transfer time, etc.) can be characterized by a distribution $f(x)$ that is described by two major parameters: p_D: the probability of delay; and σ: the variance of delay; The cumulative distribution may be described by:

$$F(x) = P(\text{Delay} < x) = P(Delay < x | p_D) \times p_D$$
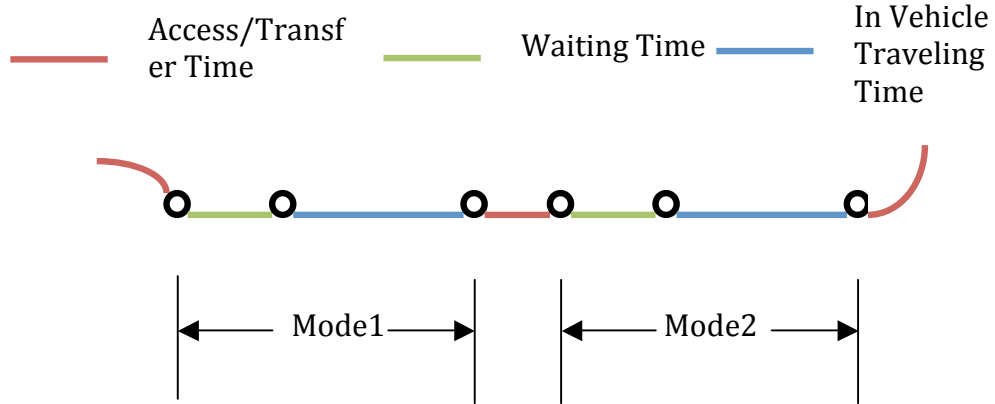
		Mode 1			Mode 2			
Reliability	Link	Access Time 1	Waiting Time 1	IVTT 1	Transfer Time	Waiting Time 2	IVTT 2	Access to Destination
	Measure of Performance	R_3	R_4	R_1	R_5	R_6	R_2	R_7
	Parameter	(p_{D3}, σ_3)	(p_{D4}, σ_4)	(p_{D1}, σ_1)	(p_{D5}, σ_5)	(p_{D6}, σ_6)	(p_{D2}, σ_2)	(p_{D7}, σ_7)

Figure 4-4: Reliability

$$R_i = 1 - p_{Di}$$

In practice, perfect reliability of access time, waiting time and transfer time can be assumed, as it is not within the planner's control. Therefore, $p_{D3} = p_{D4} = p_{D5} = p_{D6} = p_{D7} = 0$, and the respective reliability factor drop out of our discussion.

		Mode 1	Mode 2
Reliability	Distribution	Start Time $ST_1 : (p_{Ds1}, \sigma_{s1})$	Start Time $ST_2 : (p_{Ds2}, \sigma_{s2})$
		Travel Time $T_1 : (p_{D1}, \sigma_{t1})$	Travel Time $T_2 : (p_{D2}, \sigma_{t2})$
		Ending Time: $ET_1 = ST_1 + T_1$	Ending Time: $ET_2 = ST_2 + T_2$

Figure 4-5: Reliability Statistics

Denote the lateness penalty per unit time as L, usually $\alpha_1 > \alpha_3 \gg L$, as L has significantly larger weight in negative utility. The problem of reliability can be accessed by the expectation of delay, denoted as $E(D_i)$. If the passenger misses his/her desired run in mode 2, he/she needs to wait for the next one, causing a delay of H_2.

EXAMPLE: UNIFORM DISTRIBUTION

As a demonstration of the impact of different parameters, we start our analysis by assuming that the delay is uniformly distributed between 0 and t_i

$$P_i(\text{Delay} < x) = P_i(\text{Delay} < x | p_{Di}) \times p_{iD} = \frac{p_{Di}}{t_i} x$$

Where t_i can be considered as a description of σ_i, and the distribution applies to ST_1, T_1, ST_2, T_2.

The expectation of delay is $E(D_i) = \frac{t_i}{2}$

Upon calculation, and assuming the line-haul traveling time and starting time are independent, it can be achieved that the delay of ET_i follows

$$p_{Dei} = p_{Dsi} + p_{Di} - p_{Di} p_{Dsi}$$

The expectation of ending time delay is $E(D_{ei}) = \frac{p_{Dsi} ST_i + p_{Di} T_i}{2}$

The reliability issue of mode 1 may affect not the duration of the trip (may even shorten it), but it will affect passengers' possibility of missing the following mode. From experiment, researchers should be able to find the transfer time required by the passengers, which can be assumed as a deterministic value A, $A < A_2 + W_2$.

Based on the previous assumptions, the distribution of ET is relatively complicated, but in order to simplify the analysis, we assume the distribution of delay in ET to be uniform. The assumption is reasonable in the sense that, 1) the objective here is to demonstrate some variation characteristics; 2) we start up with series of assumptions in the first place; and 3) even if we follow the previous assumptions, the resultant distribution is discontinuous, which is even less reasonable than uniform distribution. The distribution of ending time delay follows

$$P_{ei}(\text{Delay} < x) = P_{ei}(\text{Delay} < x | p_{Dei}) \times p_{Dei} = \frac{p_{Dsi} + p_{Di} - p_{Di} p_{Dsi}}{p_{Dsi} ST_i + p_{Di} T_i} x$$

UNCOORDINATED CASE

In the case that mode 1 and mode 2 are not coordinated, i.e. ET_1 and ST_2 are independent, and the scenario can be discussed as following:

In Vehicle Delay

Given the schedule of the multimodal transportation network, the expected penalty due to travel time uncertainty is determined by the weakest link i, such that p_{Dei} is the maximum for all i. (The weakest link is in terms of ET.) Denote the weakest link as p_{Di}, as calculated before, the expected delay penalty is

$$V_{dt} = L \times E(D_W) = L \frac{t_w}{2}$$

Transfer Delay

Usually there is more variance in ending time delay, so also assume $E(D_{e1}) > E(D_{s2})$. The expected penalty of missing the next run of mode 2 is

$$V_{d1} = LH_2 \times Prob[(ST_2 - ET_1) < A]$$

$$= LH_2 \times \int_0^{p_{Dsi}ST_i + p_{Di}T_i} P(D_{s2} = x) \times P(D_{e1} > A_2 + W_2 - A + x)dx$$

$$= LH_2 \times \int_0^{st_2} \frac{p_{Ds2}}{st_2} \times \left[1 - \frac{p_{Dsi} + p_{Di} - p_{Di}p_{Dsi}}{p_{Dsi}st_i + p_{Di}t_i}(A_2 + W_2 - A + x)\right] dx$$

$$= LH_2 \frac{p_{Ds2}}{st_2} \left\{\left[1 - \left(\frac{p_{Dsi} + p_{Di} - p_{Di}p_{Dsi}}{p_{Dsi}st_i + p_{Di}t_i}(A_2 + W_2 - A)\right)\right] st_2\right.$$

$$\left. - \frac{p_{Dsi} + p_{Di} - p_{Di}p_{Dsi}}{2(p_{Dsi}st_i + p_{Di}t_i)} st_2{}^2\right\} = LH_2(a \times st_2 - b \times st_2{}^2)$$

………………….………...(2)

The total expected delay penalty is $V_d = L\frac{t_w}{2} + LH_2(a \times st_2 - b \times st_2{}^2)$, where

$$a = \left[1 - \left(\frac{p_{Dsi} + p_{Di} - p_{Di}p_{Dsi}}{p_{Dsi}st_i + p_{Di}t_i}(A_2 + W_2 - A)\right)\right]$$

$$b = \frac{p_{Dsi} + p_{Di} - p_{Di}p_{Dsi}}{2(p_{Dsi}st_i + p_{Di}t_i)}$$

COORDINATED CASE

In the case of coordinated modes when the first mode is delayed, the second will be delayed accordingly, in order to ensure passenger connections. Therefore, there is neither the risk of missing the next run, nor the probability of catching up with the schedule during the transfer. The expected delay is then give by

$$E(D) = \frac{\sum_i p_{Dsi}ST_i + p_{Di}T_i}{2}$$

And the delay penalty is

$$V_d = L\frac{\sum_i p_{Dsi}ST_i + p_{Di}T_i}{2}$$

Comparing the result of coordinated and uncoordinated cases, it can be observed that: If there is: 1) an clear "weakest link", i.e. the expected delay from which is significantly

higher than the others, or 2) one of the links has high missing penalty/large headway, (such as in air travel), then there is an advantage for the transportation agencies to be coordinated (without considering the relative difficulty of coordination). The result is intuitive since it is rational to take the mode of high variance at the end of the traveling process.

4.4 Mode-specific Parameter

Besides all the alternative-specific characteristics discussed above, we may also introduce another set of characteristics of each mode that may not be easily quantified, but still affects the decision making process, such as safety, comfort, etc. All these factors may be essential to the level of utility, but too subjective to be measured on an objective scale.

D Potoglou et. al.(2010) studied the issue of safety as a tradeoff with privacy and liberty. The work assessed the people's preference across privacy, liberty and security, in the case of rail in UK, through discrete choice modeling. The results indicate that generally, respondents show higher willingness to pay for security improvements, and thus the issues of liberty and privacy are outweighed by their preferences for security. Meanwhile, they did identify segments in-the-sample that are against measures that sacrificing liberty and privacy, for example, the presence of uniformed military at rail stations.

The ranking of safety may not be useful from the system's perspective, as the safety of a system is not an issue that can be compromised. The level of safety is always at the best possible level. However, from the users' perspective, if we try to quantify the utility of safety among modes, one of the most obvious approaches is to rank the safety from users' perception, or from historical data.

However, the impacts of these factors cannot be ignored. Existing study shows that with all the mode-specific factors being equal, users still shows preference of one mode over another (train over plane). The result may be due to the impression of unsafe, or merely due to visual pleasure, which cannot be decided for certain; on the other hand, the situation may also change with time, for example, people's reluctance of choosing air traveling may be decreasing with its improvement of performance.

The impact of these factors will be described by a mode-specific factor M, therefore, in our case study, the mode specific factors will be

		Mode 1			Mode 2			
Mode Factor	Link	Access Time 1	Waiting Time 1	IVTT 1	Transfer Time	Waiting Time 2	IVTT 2	Access to Destination
	Measure of Performance	0	0	M_1	0	0	M_2	0

Figure 4-6: Mode Factor

M_i will be a weakest link factor, such that for the entire travel alternative, the resultant utility impact will be

$$V_m = MIN(M_1, M_2)$$

4.5 Sociodemographic Variables

Other than the alternative-specific variables, the other group of variables is sociodemographic variables. The sociodemographic characteristics of an individual determine his/her perception of the alternative specific attributes. Sociodemographic variables may cover the impact of different travel purpose (business, leisure, etc.), different income groups, age groups, and etc. Sociodemographic variables may be additive to the utility function, or can be considered as a variable that affects the evaluation of all the variables. For example, the income factor may affect the weight of monetary cost in ones decision, whereas the value of time may follow another pattern while varying with income. This feature also follows the survey result that the weighting of each factor in the utility function follows a certain distribution. While considering the impact of sociodemographic variables, what the transportation agencies may do is to design the survey such that the characteristics of each group can be captured. Therefore, the resultant utility function can be following certain sociodemographic distribution. For the community that is concerned, the utility distribution is

$$P(U = U_i) = f(U_i)$$

Therefore the expected value and variance of the distribution may be also observed for further use, such as equity, which will be discussed in next section.

4.6 Demand Modeling

The indirect utility (for a certain individual of a certain series of characteristics) is the summation of the utility of all the aspects mentioned before.

$$V = V_t + V_c + V_d + V_M$$

The assumption of indirect utility function follows the Logit model in mode choice modeling. Therefore, from the utility function calculated above, assuming there are other traveling alternatives with similar form of utility function, the probability of passenger choosing one alternative would be

$$P_i = \frac{e^{V_i}}{\sum_j e^{V_j}}$$

The total travel demand can be assumed to be a function of the expected indirect utility of an alternative as given by the log sum of indirect utilities across the whole choice set, such that

$$Q = fn\left[\log\left(\sum_j e^{V_j}\right)\right]$$

For simplicity, we may also assume the function to be linear, so

$$Q = a + b \cdot \log\left(\sum_j e^{V_j}\right)$$

Therefore, assuming all the revenue collected comes from the fee, the revenue will be

$$\pi_i = Q \cdot P_i \cdot C_i$$

4.7 Summary

Summarizing the previous analysis we obtain the following table of combined measures of performance as perceived by the user. The sum of the indirect utilities from the various components enters into the demand function, for example as a logsum in the case of a choice model formulation.

Time	Feature	Mode 1				Mode 2		
		Access Time 1	Waiting Time 1	IVTT 1	Transfer Time	Waiting Time 2	IVTT 2	Access to Destination
	Denotation	A_1	W_1	T_1	A_2	W_2	T_2	A_3
	Parameter	α_a	α_{w1}	α_{t1}	α_a	α_{w2}	α_{t2}	α_a
	Composited	$V_t = \alpha_a(A_1 + A_2 + A_3) + \alpha_{w1}W_1 + \alpha_{w2}W_2 + \alpha_{t1}T_1 + \alpha_{t2}T_2$						
Monetary Cost	Measure of Performance	C_3	C_4	C_1	C_5	C_6	C_2	C_7
	Parameter	α_c						
	Composited	$V_C = \alpha_c C_{OOP}$						
Reliability	Measure of Performance	R_3	R_4	R_1	R_5	R_6	R_2	R_7
	Parameter	(p_{D3}, σ_3)	(p_{D4}, σ_4)	(p_{D1}, σ_1)	(p_{D5}, σ_5)	(p_{D6}, σ_6)	(p_{D2}, σ_2)	(p_{D7}, σ_7)
	Uncoordinated	$V_d = L\frac{t_w}{2} + LH_2(a \times st_2 - b \times st_2{}^2)$ (Uniform Distribution)						
	Coordinated	$V_d = L\dfrac{\sum_i p_{Dsi}ST_i + p_{Di}T_i}{2}$ (Uniform Distribution)						
Mode Factor	Measure of Performance	0	0	M_1	0	0	M_2	0
	Composited	$V_m = MIN(M_1, M_2)$						

Figure 4-7: Demand Summary

The total indirect utility is given by $V = V_t + V_c + V_d + V_M$. Although this is quite simplified example, it can still demonstrate the framework of multimodal transportation evaluation, and the challenges that are involved in this process. From the utility function we can observe that:

1) The evaluation of multimodal transportation involves significantly more than the summation of attributes for the different modes involved.

2) The evaluation of different categories of travel time can be the most complicated aspect of multimodal evaluation. This is because times combine in many different ways and sometimes in ways that are counter-intuitive. Therefore a thorough

understanding of the trade-offs people make between different elements of travel time need special attention in travel surveys and behavioral studies.

3) Reliability in multimodal transportation can be an even more serious issue than in the case of a single modal. Multimodal reliability is always less or equal to that of the least reliable mode in a multimodal system.

4) Coordination between modes can change the scenario, however, not necessarily in a positive way from the user's perspective;

5) We believe that some of the attributes, such as safety, are not necessarily examined separately from the users' perspective, as their utility is very subjective. Therefore, we recommend treating all the other impact factors as a combined, mode specific factor;

6) In our framework, sociodemographic variables are important determinants of perception of attributes and result in the variance of the indirect utility function. They should be treated at as dis-aggregate a level as possible.

Also from the analysis, we are able to identify some of the issues may be of interest in future studies:

- **Tradeoff between waiting time and in-vehicle traveling time:**

    As illustrated in the case study, the change of proportion between different travel-time elements can be utilized in planning to improve the level of service. One advantage of it is the planning process does not involve much investment on facility. As a result, this issue may involve relatively short studying process and promising outcome.

- **Reliability issue in multimodal transportation:**

    Although we modeled the issue of reliability in the previous case study, the model is obviously an oversimplification. However, we can still observe that, the reliability issue in multimodal transportation is quite different from the single-modal case, and involves more challenges. It is a weakest-link type of issue, but one that is made more difficult by the complexity with which users perceive the cumulative reliability impacts of a number of modes integrated into one system. This is a subject that is ripe for further research.

- **Threshold Value in time attribute:**

Our treatment of travel time in this analysis has assumed the monotonic, continuous impact of time on utility. In reality is often arises that the impact of time is discontinuous at some threshold values. These are values that have to do with time of day, possibility of round trip in one day, and other impacts that arise in transportation. Despite the rich literature on time value and time budgets, little has been done on how the discontinuities in travel time valuation can be combined and used in the indirect utility functions of a multimodal transportation alternative. This topic is therefore a promising one for further research into measures of performance.

5 Analytical Framework - Suppliers' Perspective

The modeling of the government's decision-making process is relatively simpler as the evaluation seems more straightforward, as the complications between modes are not as significant as from the travelers' perspective. However, it can be more challenging as 1) there are no universal weighting factor for the measures of performance involved, neither there are well-justified judging criteria for evaluating the evaluation criteria; which makes the decision-making seems more arbitrary than it is from the users' perspective; 2) the actual scenario is difficult to model analytically, because especially when private companies take into play, the process will involve business strategy, which falls out of the scope of our discussion. Therefore, we try to make this discussion more from a government and public agency's point of view, where profit is not the dominant concern.

As analyzed in the previous sessions, there are five major issues that may affect the government's evaluation of a transportation system: equity, energy, and externality, level of service and cost.

5.1 Equity Issue

The issue of equity usually cannot be evaluated directly, but may require a dedicated studying process. In evaluating the equity issue of a multimodal transportation alternative, there can be two major challenges

QUANTIFYING THE VALUE OF EQUALITY

As illustrates in the utility function, there are a series of sociodemographic variables that represents the complexity of the construction of the society, each group of which has its own utility value. As a result, the equity issue can be observed from the difference of utility of different user groups.

The variance of utility among all the users (and non-users, if can be quantified) can be used as an indicator of the equity issue. Such that

$$S_{equity} = VAR(V_i)$$

Meanwhile, there is another issue that attracts our attention: the disutility of non-users. The emission problem, for example, is a serious concern that affects the social welfare of non-users, but these impacts are difficult to quantify.

MULTIMODALITY:

As the scope of this report is multimodal transportation, the resultant equity can be quite different from what has been discussed alone for each mode. There is possibility that the composite transportation alternative has an equity problem that is less serious than each of the modes. The problem of equity of each mode may add up as well as cancel out when they are composed, depending on specific situation, which also shows the necessity of evaluating a multimodal transportation alternative as a different issue than the direct summation of each single mode.

5.2 Energy Consumption:

The issue of energy conservation, as discussed before, is more of the government's concern. Due to the differences in production process, the renewability, the cost of one type of energy can be, therefore, weighted. As the monetary cost will not be the only issue that

the government is concerned with. The monetary cost of energy resources will be included in the agency cost. Therefore the indicator here only accounts for the extra weight of energy due to the type.

$$S_E = \sum_i \beta_i E_i$$

where β_i is the weighting factor of energy by type

5.3 Externality/Emission

In our case, the concern of negative externality lies in pollution, or more specifically, the emission of vehicles, and therefore, usually monetized. The monetization of emission can be quite complicated, as its impact varies rapidly with the pollutant situation of the circumstances. When the environment is already polluted, the marginal cost of emitting increases sharply, as the pollutant can be considered as more detrimental. In the work of Delucchi (2000), the cost of emission is studied as the cost of eliminating the amount of pollutant, and he simplified the environmental circumstances as two scenarios: highly polluted and lower polluted, each of which can be a reference of the government's interest. The externality can be indicated as the weighted summation of all types of pollutant:

$$S_P = \sum_i \varepsilon_i P_i$$

where ε_i is the weighting factor of pollutants by type.

5.4 Level of Service:

The level of service of the system can be calculated as the log-sum of utility value of all different transportation alternatives that are involved in the transportation system we are concerned with. The utility value is what we have been calculating from the users' perspective.

$$LOS = \log\left(\sum_j e^{V_j}\right)$$

5.5 Monetary Cost: investment cost, subsidy

The government may be responsible for the investment of a transportation system, or part of it. Furthermore, the government may need to keep the balances of transportation agencies' operational budget. In most of the cases, for public transportation agencies, with the objective of which being providing social welfare, and not profit driven, the government will need to provide subsidy to cover its cost. The subsidy needed can be calculated as the difference between the total agency cost and the revenue, which is usually collected from the users. The government may need to cover all the extra expenses:

$$S_s = \sum_i \left(I_i - \pi_i\right)$$

The actual scenario will be quite case-specific. For example, when transportation agencies shares mutual benefit, but these are usually the situation when profit-driven companies operate the mode, which can be beyond the scope of our discussion.

There are no universal applied weighting factors among these issues. The factors adopted are largely based on government's decision, depending on the specific situation. However, if all the previous mentioned information collected, the government will be able to construct its own optimization process, based on her goals. The relative weight between each criterion can be adjusted.

5.6 Summary

To sum up, from the government's perspective, the issues of concern can be evaluated as:

Measure of Performance	Evaluation
Equity	$S_{equity} = VAR(V_i)$
Energy	$S_E = \sum_i \beta_i E_i$
Externality	$S_P = \sum_i \varepsilon_i P_i$
Level of Performance	$LOS = \log\left(\sum_j e^{V_j}\right)$
Monetary Cost	$S_s = \sum_i \left(I_i - \pi_i\right)$

Figure 5-1: Supply Summary

It can be observed that:

1) The evaluation result can be significantly different from the summation of each single mode, especially for the issue of equity;

2) Cooperation among agencies can be essential from the government's perspective (although it is not necessarily the case from the users' perspective, as discussed before);

3) An optimization framework can be constructed, where the government's "*prioritize*" decision is the final link of the loop;

4) The measures of performance can be also utilized as monitoring criteria, in case of one of the issue becomes significantly problematic.

Issues that may be of interest in future research are:

• The disutility problem of non-users when a transportation system is constructed, which enables us to treat the issue of equity more rationally. Incorporating non-users' in our evaluation process can be a challenging topic itself.

6   On the Issue of "The last mile"

The perceived cost of transfer time is typically found to be much higher than in-link (linehaul) time. In some cases (e.g. PBQD Inc. 1993), the penalty of transfer is found to be so significant that it can be weighted up to the scale of hundreds of in-vehicle traveling time, which makes the transfer critical in the overall level of service. However, the traditional metrics of measure of performance, which usually emphasize on travel cost, are by all means oversimplified. Besides the readily quantifiable measure of performance, the negative utility of transfer is resultant from other elements that contributes to the perception of the existing measure of performance. For example, when people are transferring from a rail station to an airport, their preference of people mover or moving walk to walking is obvious. The preference, or the relative indirect utility, cannot be quantified by travel cost alone. Also because transfer is always a small potion in terms of measurable cost, its significance cannot be described by the traditional metrics. Another example would be that user sometimes rule out the option once out-of-system activity (crossing the street to transfer between rail lines) is involved due to the risk of confusion. In such cases, the problem of perception of travel cost does not even have the chance to arise, as the decision is made before any other measure of performance takes place. Therefore, people's perception of intermodal activity attributes is different from that of online activities. We analyzed the rationale behind the traveler behavior, especially the reluctance to transfer. However, to analyze and forecast the marginal benefit while designing the interface between modes, it is critical to understand user's behavior. In existing literature, the studies on user's reluctance to transfer are empirical, and the impact of transfer in utility function is consolidated into one dummy variable. Due to lack of analytical understanding, the dummy variable can only be quantified with large variance, which adds to numerical complication. We refined the study of transfer by looking into the analytical background of user's behavior, and to develop a conceptual framework. Although abundant empirical research is required to realize such framework, at this point, it will help investigating into the problem of "*the last mile*", so as to identify the critical factors in investment decision-making.

A categorical passenger service standard of rail access to airport (Kivett and Parsons, 2004) includes:

1. Number of mode changes en route;
2. Proximity of rail station to primary airport functions;
3. Walking distances, level changes and travel times;
4. Fare collection/control systems;
5. Baggage check-in and retrieval systems;
6. Signing, graphics and flight information;
7. Marketing, PR and IT systems;
8. Aesthetics

Of the eight elements, number 2, 3 and 4 are relatively objective standards, and widely adopted in existing metrics. No. 2 and No. 3 are overlapping, as distance is perceived by travel time, while No. 5 and 8 are out of the scope of this discussion. We investigated into more insights of the other elements, by constructing a qualitative analysis of the demand-supply mechanism of the last mile.

Meanwhile, there is also the supplier's perspective on this issue. First of all, we need to understand "what the suppliers can do". In order to provide better connectivity between modes, the supplier (or suppliers) can design the system by offering

- Scheduling coordination
- Physical Integration

6.1 Scheduling coordination

This is what we have been talking about by "*coordination*" in previous sections. The coordination in scheduling requires long-term cooperation and agreement between modes, and hence more easily implemented when the same company owns the both. For instance, travelers always prefer to book connected flights from the same airline; so that if the first flight is delayed, the airline is responsible of providing an alternative connection, and the traveler will not take the risk of misconnecting. We can consider the two coordinated modes a "*system*"; and in this case, once the traveler checks in, he/she is considered "*inside the system*", such that a certain *through* level of service is guaranteed at least as far as reliability is concerned. Most of the elements of scheduling coordination are discussed in the previous sections, and its related user's behavior is usually quantifiable by the conventional units – time and monetary cost, as well as probability and utility theory. As demonstrated in the previous case study, scheduling coordination is not enough to mitigate the disutility in transfer. There remains the element of physical integration at the intermodal connection.

EXAMPLE

In this example we adopt the result of Kanafani and Ghobrial (1985) who used a dummy variable to differentiate between different levels of intermodal connectivity. The utility of intermodal connection is reflected in their indirect utility function of route choice as follows:

$$V(r,j) = \alpha_1 T_{rj} + \alpha_2 F_{rj} + \alpha_3 f_{rj} + \alpha_4 D_{rj} + \alpha_5 C_{rj}$$

where,

T: travel time

F: daily frequency of service

f: one-way economy class airfare

D: dummy variable for aircraft size

C: dummy variable for connectivity service (0 for non-stop service, 0.5 for online service with stops, 1.0 for indirect connecting service)

r: denotes the route, j as the city pair.

α: is a coefficient.

In the context of multimodal transportation, and by our definition online service represents perfect scheduling coordination, while indirect connecting represents no coordination (but with physical integration, which will be discussed later). The coefficients were calibrated from data of 19 city pairs:

Attribute	Estimated Coefficient	T-value
Time (hour)	-0.897	-14.77
Daily Frequency	0.239	38.21
Fare (dollar)	-0.278	-6.7
Aircraft Type	1.461	15.4
Connectivity Pattern	-1.557	14
Chi-Square Value		3114
Log-Likelihood Value		-34.617

Figure 6-1: Calibrated Coefficients

Although the data are rather old, we use this result only as an example of how to reflect passengers' response. It can be observed that the connectivity pattern is critical in terms of weight. We will use some simple algebraic example here to illustrate its impact.

Imagine two transportation alternatives each made up of two connecting flights, one alternative with an online connection (alternative 1), and the other with indirect connecting service (alternative 2). The indirect utilities of the connectivity pattern are respectively:

$$V_{c1} = \alpha_5 C_1 = 0.5\alpha_5$$

$$V_{c2} = \alpha_5 C_2 = \alpha_5$$

$$\alpha_5 = -1.557$$

With all the other factors being equal, the ratio of market share of online connection to indirect connection is

$$\frac{e^{V_{c1}}}{e^{V_{c2}}} = \frac{e^{0.5\alpha_5}}{e^{\alpha_5}} = 2.178$$

TIME VS TRANSFER

For a utility maximizing passenger, the online service can take higher transfer time and still have a market share advantage. The advantage remains if

$$\alpha_1 T_1 + \alpha_5 C_1 \geq \alpha_1 T_2 + \alpha_5 C_2$$

$$\alpha_1 (T_1 - T_2) \geq 0.5\alpha_5$$

$$T_1 \leq \frac{0.5\alpha_5}{\alpha_1} + T_2 = 0.868 + T_2$$

Therefore, the online connection flight can have 0.868 hrs extra transfer time to reach equal market share with indirect connection. If alternative 2 has transfer time of 1 hr, that of alternative 2 may reach up to 1.868 hrs.

6.2   Physical integration

This refers to the degree of geographic, instrumental and structural involvement between stations, and may as well lies in the architectural design. Physical integration can also provide the sense of "*inside the system*", however, not on an easily quantifiable base. For

example, user walking on a linking bridge with direction sign may consider him/herself inside the system. But the conventional metrics cannot capture the improvement on the level of service; as the difference in terms of travel cost is limited, neither does it imply long-term cooperation relationship between the modes. Even within the same terminal, there can be multiple types of physical integration. Here we use the case of JFK (John F. Kennedy International Airport New York) to illustrate different levels of physical integration.
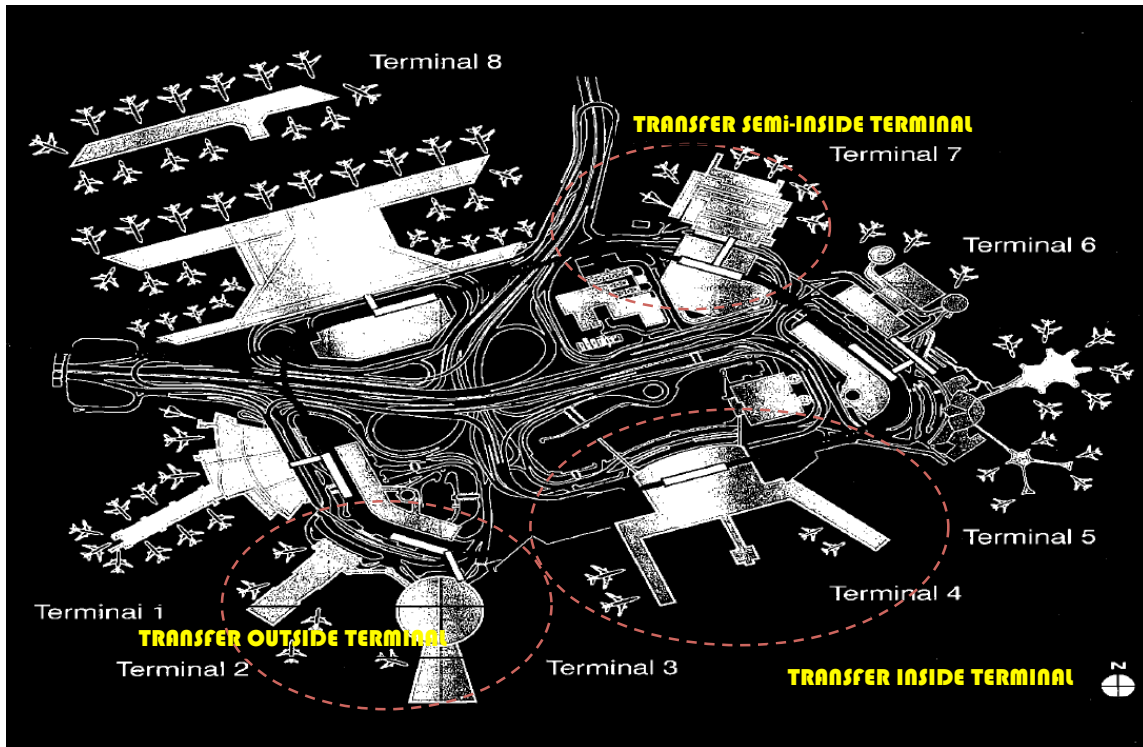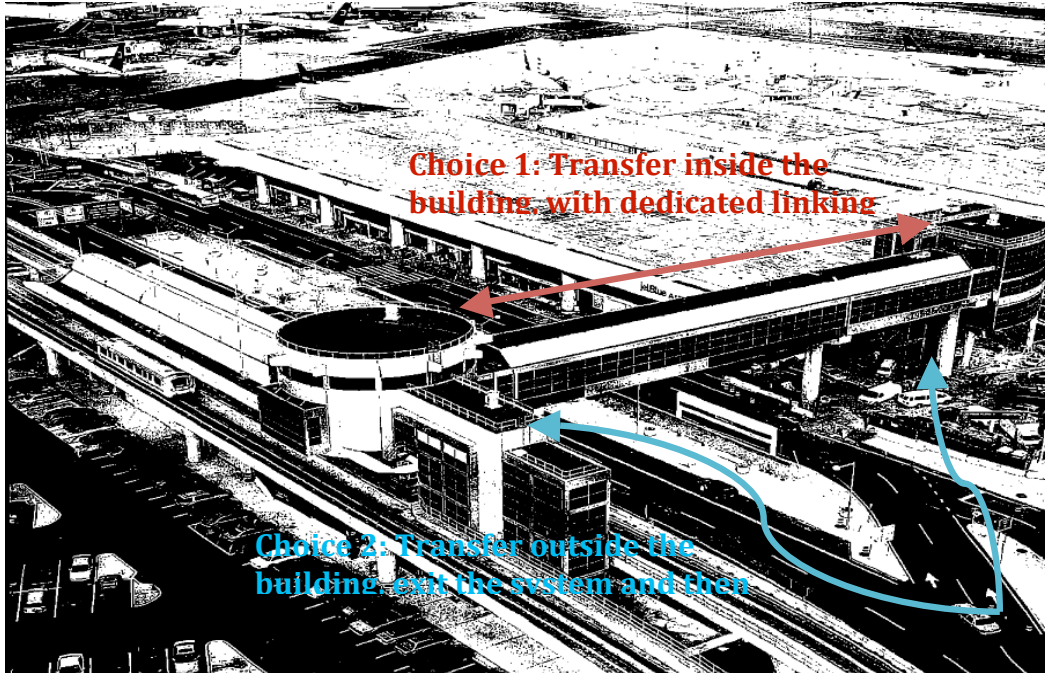

Figure 6-2: JFK Plan View

Figure 6-3: Transfer Choices

The impact of physical integration on user's behavior is rather abstract, and difficult to evaluate. As is illustrated in the previous example, part of the impact can be psychological, but the understanding of user's reaction to it can be essential, because it reflects the mechanism of multimodal level of service integration, and user's reluctance to transfer. On the other hand, better demand forecasting will better justify the investment cost, and help supplier making planning decision. Physical integration can incur different level of investment cost, but less operating cost comparing with scheduling coordination. As a result, it is a challenging and rewarding task to estimate the marginal benefit with improving physical integration. Due to all the reasons above, the primary goal of this session is to identify the elements in user's reaction, and mapping them to different levels of physical integration.

Scheduling coordination and physical integration cannot be completely separated. The two methods are always utilized in accordance, as it exists in most transportation facilities. But because in this report we want to emphasize on marginal benefit, we analyzed the impact by elements. It is still important to keep in mind that, as the transportation alternative is an integrated process, no attribute can be completely separated with another.

There are different types and levels of physical integration. In this report, the utility resultant from physical integration are classified into two categories: 1) structural utility: the basic level of utility due to the sheltering effect of physical integration, which can be considered as constant with respect to level of integration; 2) facility utility: the utility due to the facilities involved in the transfer (people mover, moving walks, shuttle bus, etc). Therefore, the facility utility is variable with change of integration methods. The overall utility of physical integration is the sum of the two.

6.2.1 Structural Utility

Studies on transfer environment tend to focus on the either pedestrian environment in open space and on the impact of facility assistance, such as the presence of escalator. The impact of the presence of a dedicated link alone is not well analyzed. For example, while users are choosing a route of transfer between stations, it makes a difference whether one needs to enter the open space and cross the street and access the following terminal, or whether there is a dedicated linking structure for transfer. We refer to this part of utility as "*structural utility*". Structural utility is critical in terms of passenger utility. The impact of structural utility on user perception is subtle and includes elements such as the sense of security, orientation, and the perception that one is being cared for *inside the system.*

IMPROVED LEVEL OF SECURITY

Physical integration offers user the coverage from the elements and gives a sense of safety and security. But as discussed earlier, the evaluation of level of security is too complicated to be realized analytically. But we still have reason to believe that physical integration offers a measurable attribute of level of service in an intermodal environment.

REDUCED RISK OF CONFUSION

The transfer terminal can serve as guidance to the user, and eliminate much of the uncertainty and confusion during transfer. This effect may be different on first time traveler and regular travelers. But it, too should have a measurable impact on the utility as perceived by passengers in an intermodal system. Although not commonly done, attributes such as physical integration shouldn't be neglected in user's mode choice modeling.

PERCEIVED INTEGRATION OF SERVICE

Physical integration conveys the additional, positively perceived attribute, of integrated services. The sense of being inside the system detracts from the disutility of a connection activity. Coordinated schedules and "online" transfers often go hand in hand with physical integration since they are often offered by the same provider.

6.2.2 Information Assistance

The definition of information assistance is relatively vague. It starts from the basic orientation function and range up to all the information that helps improve the level of service. Form of information assistance includes graphics, signing, IT systems, on-line information availability, and etc. For example, when a traveler is entering an airport from a train station, he/she needs direction sign to find the terminal building location, which also provides the feeling that he/she is inside the system. It will further soothe the traveler's anxiety if there is flight information available inside the connector. On-line information availability about the train station, the airport, the scheduling, and the bundling scheme (if bundle ticket is available) will further improve the level of service. In our definition, not all of the information availability mentioned above should be necessarily integrated as part of structural utility. Part of the assistance is also counted as scheduling coordination, on-line information about transfer, for instance. But it should be noted that structural utility couldn't be guaranteed without adequate information assistance, such that certain level of

information assistance is an inseparable part of physical integration. For instance, as discussed in the previous session, we have presumed that the linking structure includes signs and graphics that provide the orientation to the terminal building.

To clarify the concept, here we define information other than direction sign is considered as facility utility, because fundamental level of information is indispensible. Of course, the definition of "fundamental" is still abstract, and scenario-specific. The concept is, as long as physical integration is concerned, it is the supplier's responsibility to provide orientation, cleaning, security and etc, to maintain the basic level of service.

6.2.3 Facility Utility

The facility utility depends on the level of equipment and technological support, and thus may vary rapidly with the design and also the investment. The utility is in forms of comfort, as the user perceives it. Facility that is concerned commonly includes escalator, elevator, people mover, moving walks, shuttle bus, and etc. The evaluation of facility can be categorical. From experience, the facilities are usually offered in a combined fashion. The facility utility also differentiates across modes. For example, the transfer between buses usually doesn't involve any of the pre-mentioned equipment (though there can be technological support during boarding and unboarding, it is not considered as part of the transfer process), and the impact of facility support during the transfer is not easily perceived; whereas, in the case of entrance to the airport, due to the burden of baggage and anxiety caused by the schedule, users are more sensitive to facility utility. The task of accounting for facility utility is challenging, but there are abundant empirical resources on this issue. But few generalized results across all modes can be achieved, as the utility perception varies with transfer scenario (baggage, first-time traveler, etc).

In addition, bundling also implies the requirement of facility. Because the bundling increases the complexity of service, without adequate guidance, it may cause user's confusion. However, the complexity and confusion can be meditated by information assistance, as discussed previously.

6.3 The last Mile: Integration

In this section, we identified the importance of the "last mile", the concept of which is consistent with that of " the weakest link", as the last mile of mode interface is always a critical issue that requires integrated planning and service. The challenges in the last mile issue not only lie in that it requires integrated design, but are also due to the fact that its impact on user's perception is subtle, and to a large extent, psychological. So we developed a comprehensive framework that provides a conceptual illustration of the decision-making process, from the supplier and the user perspectives. The user's response to the issue is in terms of sense of security, being *inside* the system, orientation etc; the supplier can resolve these issues by providing schedule coordination and physical integration.

There are differences in investment and operating mechanism between the two measures. In transportation systems requiring higher level of services, the suppliers usually provide an integrated version of the two. As discussed before, information assistance is overlapping with multiple aspects of the level of service, and thus is an element that links all these measures of performances. Or more generally, we can say that information is an essential element when it comes to interfaces between or integration of transportation modes. When a certain service is provided passengers may or may not be aware of it. We suggest that when physical integration is provided, the supplier is responsible for the

fundamental level of information assistance, such as signage. This level of assistance is considered so fundamental that it will not be counted as extra facility utility. When it comes to a larger picture, such as integrated scheduling and physical coordination, then issue of information assistance is even more critical, and requires larger scale of planning. Factors such as operational skills are also indispensible. There is also the issue of "structural utility", which determines primary impact of physical integration. How all of this enters into the evaluation of intermodal services requires much more research than is currently available.

7   Conclusion and Future Work

In this report, we identified the attributes and their role in multimodal transportation, both from the demand and supply perspectives. From the supply side we focused on public transportation agencies, although a similar analysis could be done from the perspective of a private provider. But multimodal transportation tends to be the domain of public agencies given its multiplicity of infrastructures involved. This study demonstrated that both the process and the result of multimodal transportation could be quite different from the summation of results across each mode. The intermodal integration is a challenging process that requires additional research. In order to get a better understanding of this problem, we started out with a conceptual framework, in which the integration methodology of each attributes in the measure of performance is identified. This formed the basis for an analytical framework for quantitative modeling. We developed an indirect utility function that quantifies the user's perception of level of service. With also developed a set of metrics to quantify the measures of performance from the supplier's perspective. The main conclusions of this work can be summarized as follows:

1. Measuring the performance of multimodal transportation systems requires a far more complex integration than the simple addition of metrics across elements of these systems.

2. The appropriate method of integration of metrics is itself a function of the context of evaluation, the perspective taken and the role of each stakeholder. In particular, the integration of measures of performance as perceived by users is quite different when seen from the perspective of the supplier or the public agency. Externalities and other "publicly" valued attributed enter into the latter but not necessarily the former.

3. Many attributes exhibit discontinuities in their impact and the way they are perceived. This requires careful modeling to arrive at an appropriate measure of performance.

4. A major element of multimodal transportation is the intermodal interface between two or more modes. The contribution of this element to the overall performance of a multimodal system is complex and challenging to model. More than in the context of line-haul operation, intermodal systems are subject to perceptions that are rather subjective in nature and that are influences by the degree of operational coordination between modes, as well as the extent of actual physical integration that is provided in the intermodal terminals.

Finally we identify four topics that are in need of further research:

    a. The threshold value of attributes in demand modeling,

    b. The reliability problem in multimodal transportation,

    c. Externalities and the disutility of non-users.

    d. The Problem of the "last mile" and the impact of structural integration on the perception of the level of service of intermodal connections.

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