Integrating Air Transportation System Demand Predictions in Preliminary Aircraft Design

Antonio A. Trani*, Hojong Baik†, Nicolas Hinze‡, Senanu Ashiabor§
Virginia Tech, Blacksburg, Virginia

Jeffrey K. Viken**, Stuart Cooke††
NASA Langley Research Center, City, Hampton, Virginia

This paper describes a methodology to integrate air transportation demand estimates in the preliminary aircraft design process. The paper describes the adaptation of the Transportation Systems Analysis Model (TSAM) developed by the Air Transportation Systems Laboratory at Virginia Tech for NASA Langley Research Center to predict potential demand of aerospace vehicle concepts. TSAM uses traditional air transportation systems engineering techniques to: 1) predict the number of intercity trips generated in the country based on socio-economic factors, 2) distribute these trips across the country, 3) predict the most likely modes of transportation used to execute these trips, 4) predict flights and trajectories associated with air transportation trips, and 5) predict impacts of the intercity trips generated in the National Airspace System (NAS). The paper includes a case study to estimate the potential demand for advanced tilt-rotor aircraft technology operating in the Northeast Corridor in the United States.

1. Introduction

Traditional aircraft design analysis requires clear aircraft mission requirements and estimates of the number of vehicles to be produced in the program’s life cycle. Mission requirements are traditionally setup by the aircraft design team in consultation with the customer (typically airlines for commercial vehicle development). The determination of the potential market for the vehicle to be designed is more challenging to define. Airlines and aircraft manufacturers continuously revise their estimates of vehicle demand based on historical market outlooks. This uncertainty is perhaps best epitomized in the current battle between Airbus and Boeing about the potential demand for long-range commercial transport aircraft. Airbus justifies the design of very-large capacity aircraft such as the A380 on the grounds of mature origin-destination market consolidation and capacity constraints at existing hub airports. Boeing justifies the development of the 787 and 777-200LR aircraft on the grounds of market fragmentation across long-haul markets. This illustrates that existing techniques to predict market demand for new aerospace vehicles is a difficult task requiring an understanding of the interactions between social and technological factors.

Very few models seem to exist to predict the potential demand of novel aerospace technologies. This is the main trust of this effort. NASA’s Systems Analysis Branch (SAB) is responsible for the evaluation of new aerospace vehicle concepts and thus has a vested interest at improving the modeling capabilities to predict vehicle demand.

* Associate Professor, Department of Civil and Environmental Engineering, Patton Hall 200, Virginia Tech, Virginia, 24061, AIAA Senior Member.
† Research Assistant Professor, Department of Civil and Environmental Engineering, Patton Hall 200, Virginia Tech, Virginia, 24061.
‡ Research Associate, Department of Civil and Environmental Engineering, Patton Hall 200, Virginia Tech, Virginia, 24061.
§ Graduate Research Assistant, Department of Civil and Environmental Engineering, Patton Hall 200, Virginia Tech, Virginia, 24061.
** Senior Research Engineer, Systems Analysis Branch, NASA Langley Research Center, Hampton, Virginia.
†† Senior Research Engineer, TSAA Program Lead, NASA Langley Research Center, Hampton, Virginia.
The Virginia Tech Air Transportation Systems Laboratory developed a national Decision Support Model (TSAM) to estimate the potential demand for the Small Aircraft Transportation System Program (SATS). The TSAM model uses traditional air transportation systems engineering techniques to: 1) predict the number of intercity trips generated in the country based on socio-economic factors, 2) distribute these trips across the country, 3) predict the most likely modes of transportation used to execute these trips, 4) predict flights and trajectories associated with air transportation trips, and 5) predict impacts of the intercity trips generated in the National Airspace System (NAS). The TSAM model is illustrated graphically in Figure 1. The model uses aircraft performance and aircraft operational cost estimates to predict potential air transportation demand of new aerospace technology. The model employs socio-economic activity information (currently the Woods and Poole data set\(^1\)) and historical trends of trip makers to generate intercity trips. Trip distribution of intercity trips is executed using a gravity-type formulation calibrated using the American Travel Survey\(^2\) (ATS) and the Bureau of Transportation Statistics (BTS) state-to-state travel flow records modeled by Baik and Tran\(^3\). A multinomial logit model is used to quantify the number of passengers selecting a mode of transportation when presented with multiple trip mode alternatives\(^4,5\).

In the past, air transportation systems analysis models have been used to predict impacts of new concepts of operation in the NAS. However, seldom have these models been directly coupled with aerospace design analyses to close the loop between the demand function and the "supply attributes" offered by new aerospace vehicle concepts. This is the main thrust of this paper. Figure 2 illustrates the relationship between aerospace design and air transportation systems analysis models. The figure illustrates two important feedback loops required to execute credible demand estimation of aerospace technologies: 1) a feedback loop between the initial design and trade-studies and the customer requirements and 2) a feedback loop between the air transportation systems analysis model (such as the TSAM model presented in this paper) and the customer requirements. We believe the enhanced TSAM model presented in this paper attempts to reconcile the later feedback loop which is seldom pursued in practice.

The objectives of the paper are: 1) to develop a framework to relate aircraft design and transportation systems analysis models, and 2) to demonstrate the use of such framework using two well-understood computer model to quantify the demand for new vehicle technology.

II. Modeling Approach

The approach taken in this project is to modify the existing Transportation Systems Analysis Model (TSAM) developed at Virginia Tech for the National Consortium for Aerospace Mobility (NCAM) and NASA\(^5\). This model was developed under the Small Aircraft Transportation System (SATS) Program to predict the potential demand of SATS aircraft operations in the National Airspace System (NAS). The model, uses a multinomial logit model to estimate traveler’s preferences and has been calibrated using both American Travel Survey data and surveys collected by Virginia Tech researchers. To accomplish the objectives of the paper we introduced several important changes to the original TSAM model: a) modifications to accept user specified landing sites required by new aerospace technology, and b) modifications to TSAM vehicle performance module to accept generic input to allow for new vehicle technology.

A. Modifications to the Air Transportation Systems Analysis Model (TSAM)

The first modification to the TSAM model requires a new landing facility pre-processor to handle user defined landing facility sets. A new custom landing facility (or airport) pre-processor reads a comma delimited file (.csv) containing information about the landing facilities used by the new aerospace technology. The information fields required in this file are: landing facility ID, landing facility name, associated city name, state, longitude (degrees) and latitude (degrees). Three tasks are performed internally in the model to generate the appropriate distances between county population centroids and the custom airport set chosen by the user. A shape file with the new airport set information is also generated as part of the internal process of importing an airport set. This shape file is used to display graphically the position of the new landing facilities in the TSAM maps. Microsoft Mapppoint software\(^6\) is required to import an airport set.

A second modification to the original TSAM model entails changes to the vehicle performance module to accept new vehicle technology performance information. This task required minor modifications to the existing TSAM model by adding a pre-processor to read generic aircraft information related to the aircraft performance and the cost
components of the vehicle. The model accepts typical inputs about vehicle performance in the form of a BADA 3.5 compliant file. This file provides basic information about the vehicle performance in three flight regimes: a) climb, b) cruise and c) descent.

The analysis presented in this paper examines the performance and cost estimates of a new generation tilt-rotor operated in the Northeast corridor using the TSAM model. In practice, the analysis of aerospace vehicle performance and cost estimates is the result of numerous iterations and evaluations using aircraft design programs. Our analysis demonstrates that intercity transportation models like TSAM can complement the traditional work done by aerospace engineers and help them predict the potential demand impacts of aerospace technology. Figure 3 illustrates the relationship between aerospace design using the aircraft design program FLOPS and air transportation systems analysis modeling using the enhanced TSAM Model described in this paper.

FLOPS is a conceptual aircraft design software developed by L. McCullers at Swales Aerospace. Nine design and analysis modules comprise FLOPS: weights, aerodynamics, engine cycle, propulsion, mission performance, takeoff and landing, noise footprint, cost analysis and function control. FLOPS provides numerous options to run aircraft design modules independently. FLOPS produces all necessary aerodynamic, propulsion and mission performance information for a new aircraft design. This information can be manipulated to generate: 1) a BADA equivalent coefficient file, and 2) a generic mission summary profile similar to a .PTF file in BADA.

B. Integration of Aircraft Design and Air Transportation Systems Analysis Models

The cost analysis module in FLOPS provides an initial guess of the life-cycle cost per seat-mile for the vehicle. This cost can be used as an initial solution in the enhanced TSAM model to study the effects of supply cost in the level of service and demand for air transportation services. It is possible then to relate the outputs of an aircraft design model like FLOPS and the inputs needed in the TSAM model to predict demand. Two methods have been studied to use FLOPS output as an input to the enhanced TSAM Model.

1. Method 1
   Use FLOPS aerodynamic module which includes drag polar information (a function of Mach number), and the engine cycle analysis module to generate thrust and fuel flow data tables as a function of Mach number. The combination of these two modules provides the necessary information needed to create a BADA equivalent file required as input to the enhanced TSAM model.

2. Method 2
   Use the FLOPS mission performance module to generate climb, cruise and descent fuel flows and speed tables. This generates a BADA PTF file, a required input in the TSAM model.

Both methods are complemented with the use of FLOPS aircraft cost module to predict aircraft cost estimates and thus quantify the cost of air transportation supply per seat-mile. This is the current parameter needed in the TSAM to execute mode split analysis (see Figure 1). Figure 3 illustrates in graphical form the procedure to integrate FLOPS outputs and TSAM inputs. It is important to emphasize the direct causality between demand and supply variables in air transportation systems analysis. Estimating air transportation demand and its balance with air transportation supply is an iterative problem. Without an accurate aircraft cost model the enhanced TSAM cannot predict vehicle demand. Without assessing the demand function using the TSAM model, we cannot determine an accurate aircraft cost model in FLOPS (or any other aircraft design software). Iteration is technically the only way to address the problem. The integration of the aircraft cost model in TSAM needs to be aligned with the cost components calculated in FLOPS. It is important to realize that FLOPS offers several cost estimate printing options: life cycle cost, acquisition cost, Direct Operating Cost (DOC), Indirect Operating Cost (IOC), total operation cost without depreciation, fare given a Return On Investment (ROI), and ROI given a fare.

C. Estimating Demand for New Aerospace Vehicle Technologies

The enhanced TSAM model predicts the potential demand function of various aerospace vehicle technologies using the calibrated logit model employed in the original TSAM model developed for the SATS program. A multinomial logit model is used to quantify the number of passengers selecting a mode of transportation when
presented with multiple trip mode alternatives. The logit model requires the evaluation of a trip utility function for each passenger traveling between two areas of interest (e.g., two counties within the continental U.S.). The evaluation of this utility function considers travel time (including egress and access intermodal times), travel cost using each mode of transportation, flight frequency for the commercial airline mode and for aerospace modes operating in a regular schedule, and the value of time of the traveler. More information about the methodology employed in the multinomial logit model can be found in Trani et al.\textsuperscript{5} The enhanced version of the TSAM model uses the same multinomial logit formulation employed in the TSAM model developed for the SATS program except that we replace the SATS mode variables in the model with a new vehicle technology. This makes the new version of the TSAM model more extensible and able to quantify potential demands for various types of aerospace vehicles. For example, the tilt-rotor technology vehicle presented in subsequent sections of this paper is capable of operating from vertiports near downtown areas and thus offers convenience attributes to the passenger compared to the traditional commercial airline mode. This implies that any new technology in the enhanced TSAM model is studied as a separate mode of transportation and thus modeled in the first nest structure of the logit model\textsuperscript{5} (e.g., at the same level as commercial air and automobile).

III. Application of the Modeling Framework

This section provides describes a case study used to demonstrate the technical capabilities of the TSAM used in conjunction with aircraft design methods. The case study considers the deployment of tilt-rotor technology across three heavily traveled markets in the Northeast Corridor of the U.S. Boston, New York, and Washington DC, are selected to illustrate the capabilities of the TSAM model to execute a regional analysis.

The vehicle used in this analysis is representative of tilt-rotor technology to provide fast and reliable air transportation between city centers in the U.S. The Nimbus tilt-rotor represents a third-generation vehicle with a gross takeoff mass of 15,930 kg. The performance characteristics of the vehicle are presented in detail in Figure 4. It is assumed that each node of the network is a vertiport with infinite capacity. The data presented in Figure 4 is representative of a new tilt-rotor aircraft capable of carrying 24 passengers. This aircraft is designated NimbusTR in the BADA\textsuperscript{8} 3.5 compliant file (.PTF file). As illustrated in Figure 4, the aircraft has a basic operating weight of 9,000 kilograms and a maximum operational takeoff weight of 15,930 kilograms. The maximum service ceiling of the Nimbus is expected to be 8,841 m. (29,000 ft). A maximum cruise speed of 275 knots at flight level 220 yields comparable performance to the Bell/Augusta 609 tilt rotor but with more than twice the passenger capacity. Based on the aircraft performance file shown in Figure 4, the Nimbus tilt-rotor is expected to have a range of 600 nautical miles with 24 passengers and 3,700 kg. of fuel for the mission (including 45 minute fuel reserves) flying at 5,500 meters (FL 180).

Aircraft speeds, rates of climb and descent, and fuel flows are shown in Figure 4 for three vehicle weight configurations (labeled as "lo", "nom" and "hi" and corresponding to low, nominal and high weight configurations). The performance of the Nimbus is illustrated graphically in Figure 4. Because the TSAM model is a national-level decision support model, the estimation of vehicle speed and distance performance profile is executed for all possible continental U.S. trips (up to 3,000 statute miles). Figure 5 illustrates graphically the three regions served by tilt-rotor landing sites. These vertiports are assumed to be located at the population centroid of three counties associated with each city center. The diagram shows the total annual intercity trips in the Northeast corridor of the U.S. For this study we selected Middlesex County (MA), Queens County, and Washington, D.C. as the three county centroids where vertiports are located. By selecting county centroids we are portraying the benefit of tilt-rotor operations as they would occur from landing sites located in highly populated areas.

The baseline demand analysis for the tilt-rotor system assumes a cost per seat-mile of $0.75 (statute mile). This cost seems arbitrary at this point. In practice, the cost is derived using historical trends contained in aircraft design code such as FLOPS. Past tilt-rotor studies conducted by Boeing have used similar cost parameters\textsuperscript{9}. Processing times at vertiports are 0.58 hours of processing time at the origin vertiport and 0.17 hours at the destination vertiport have been assumed in the baseline demand estimation. These processing times are small compared to commercial airline processing times of up to 1.5 hours for domestic flights. One of the main advantages of using smaller vehicles such as tilt-rotors would be faster security checks. The ramifications of changes to these assumptions can be easily studied in the model through sensitivity runs. Figure 6 illustrates the potential demand for tilt-rotor services using
the baseline conditions ($0.75 per seat-mile). This map illustrates the "catchment" areas for each one of the three markets around the vertiports.

Figure 6 illustrates the potential market demand by county for a 275 knot vehicle with short vertiport processing times and short intermodal connection times. Several counties in the vicinity of the counties where vertiports are located generate more than 10,000 person-trips per year. The white color in the map represents no trips generated using the tilt-rotor aircraft. Mode choice results at the national level are summarized in Table 2. According to this figure, the tilt-rotor system could capture 1.0 million person-trips per year (in all three markets) using year 2005 socio-economic characteristics. According to TSAM, business auto intercity trips nationwide account for 155.8 million person trips. commercial airline mode accounts for another 82.7 million person trips. The small percent of tilt-rotor trips is explained by the small number of vertiports in system (only three in a highly populated areas). The tilt-rotor trips average 253 statute miles whereas automobile trips average 223 statute miles. Commercial airline trips average 994 statute miles.

The TSAM model estimates individual mode trip demands for every county of interest. Figure 7 illustrates the total business trips via automobile originating in Middlesex County (MA). Dark areas represent counties with more automobile trips originating from Middlesex county. Light colors represent counties with smaller annual demands. The TSAM model does not estimate intercity trips less than 100 statute miles of route distance. For this reason, several counties around Middlesex are colored white (no trips).

Figures 8 and 9 illustrate the commercial airline and tilt-rotor demand maps for trips originating from Middlesex County, respectively. Figure 8 clearly illustrates the far reach of commercial airline mode. The figure demonstrates two clear effects of the gravity model used in the trip distribution step of the TSAM model: 1) large cities attract more trips than smaller towns, and 2) distance plays a role in the attractiveness of the trips. For example, there are more trips originating from Middlesex county and ending in Queens, NY (253 miles away) than the number of trips originating from Middlesex to Roanoke County, Virginia (small city and farther away). Figure 9 shows the counties served by the tilt-rotor technology with three vertiports. As expected, the demand function across three vertiports is not equally distributed.

Figure 10 shows the market share solution for the tilt-rotor technology as a function of distance for four household income levels. The figure indicates that tilt-rotor trips (door-to-door) are executed in the range from 150 to 600 statute miles (door-to-door route distance). Note that tilt-rotor market share peaks at 230 miles. A second smaller peak is observed at a distance of 440 statute miles consistent with the route distance between Washington (DC) and Boston (MA).

Figure 11 presents the one-to-one county analysis mode choice window. This window allows a user to select two counties and perform a quick assessment of the mode split between several modes of transportation available in the model. The information presented in Figure 11 indicates that a trip from Queens, (New York) to Falls Church (Virginia) has been selected. The business trip analysis is carried using automobile and tilt-rotor costs of $0.30 and $0.75 per seat-mile, respectively (shown in Sections 4 and 5 of the mode choice window). The Nimbus tilt-rotor BADA file is used in this context with a vehicle range of 600 statute miles (Section 5 of the window). The custom airport set (e.g., three vertiports) is used in this analysis. The model outputs are summarized in the table shown in Section 8 of the mode choice window (Figure 10).

The summary table presented in Section 8 in Figure 11 demonstrates the potential travel time benefits of the tilt-rotor over automobile and commercial airline modes. The tilt-rotor is at least 2.1 hours faster than the nearest competing mode of transportation for travel between the selected county pair. At a cost for service of $0.75 per passenger-mile, a tilt-rotor aircraft competes very well in price ($334) with commercial airline fares between La Guardia (LGA) and Reagan National (DCA) airports ($213 and $284 for coach and business fares, respectively). Fares in TSAM are derived from the Department of Transportation Databank 1 dataset. Airline schedules are synthesized using the Official Airline Guide (OAG). Table 1 presents a sensitivity analysis using the enhanced TSAM Model for three tilt-rotor cost levels ranging from $0.50 per seat-mile to $1.00 per passenger-mile. It is important to note that demand elasticity with price is not linear. For example, increasing the tilt-rotor fare from $0.50 per seat-mile to $0.75 per seat-mile decreases the total demand from 1.2 to 1.0 million annual person trips.
However, if the fare is further increased to $1.00 per seat-mile the drop is from 1.0 million at $0.75 to 0.9 annual person trips (a more gradual change).

### Table 1. Tilt-rotor Demand Elasticity with Cost for Service at Three Vertiports.

<table>
<thead>
<tr>
<th>Scenario ($ per passenger mile)</th>
<th>Tilt-rotor Technology Annual Person Trips (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>1.2</td>
</tr>
<tr>
<td>0.75</td>
<td>1.0</td>
</tr>
<tr>
<td>1.00</td>
<td>0.9</td>
</tr>
</tbody>
</table>

### IV. Conclusion

A framework to connect aircraft design and air transportation system model has been proposed in the paper. The original TSAM model developed for the SATS program has been successfully modified to: 1) accept user specified landing sites, 2) accept generic input to allow the evaluation of new vehicle technologies, and 3) quantify the demand for new vehicle technologies including connections to aircraft design models. The model has been tested using the performance characteristics of tilt-rotor technology in the Northeast corridor. Three vertiports located at three high-density population centroids were used in this study. The analysis presented in this report demonstrates that generic landing sites can be easily incorporated into the enhanced TSAM model. This adds flexibility to the model and allows NASA and aircraft manufacturers to estimate the potential demand of new aerospace vehicles. The results obtained in this study demonstrate the effects of technology, cost and spatial location of landing facilities in the demand function for air transportation services. The tilt-rotor system modeled in this report represents one of many types of aerospace technologies to be considered as alternative capacity multipliers for NAS. The potential demand for tilt-rotor trips between three high-density markets in the Northeast corridor was quantified using classical transportation methods and indicates potential demand for the service at the nominal cost of $0.75 per passenger-mile. This is only true if the short processing times assumed in the model using tilt-rotor technology are achieved. Moreover, technology drivers are today needed to bring the cost for service down to the $0.75 per passenger mile.

The following recommendations are postulated at the end of this study:

1) A more direct integration between the enhanced TSAM model and traditional aircraft design programs should be pursued. This integration could allow aircraft design programs like FLOPS to write direct BADA files and estimate aircraft operating cost components allowing the TSAM to read these values as input. This approach would close the loop between aircraft design and air transportation systems modeling.

2) The current TSAM model does not have the capability to study trips where two or more air modes are used as part of a traveler’s trip solution. This would prove to important for new aerospace technology concepts to bring passenger to hub airports.

3) The future commercial airline network solution in the TSAM model is assumed to be similar in nature to the services offered in the baseline year (year 2000). This is one weakness of the TSAM that should be improved in order to make better predictions of commercial airline traffic in future years. This is a complex subject but worthwhile to be studied because many long-term planning decisions in NAS require some form of forecast of future fleet composition and airline service provided strategy.
Acknowledgments

The authors would like to thank Sam Dollyhigh and John Callery of Swales Aerospace for their continuous scrutiny of the enhanced TSAM model. Thanks to L. McCullers of Swales Aerospace for providing the FLOPS code and to the National Institute of Aerospace (NIA) for making the project possible.

References

Figure 1. SATS Program Transportation Systems Analysis Model (TSAM).
Figure 2. Relationship Between Aircraft Design and Air Transportation System Analysis Model.
Figure 3. Integration of FLOPS and TSAM Models.
**Figure 4.** Sample Aircraft Performance File in the TSAM Model (Eurocontrol BADA 3.5 style). Data for the Nimbus Tilt-rotor Aircraft. (a Hypothetical Tilt-rotor Technology Aircraft.)

<table>
<thead>
<tr>
<th>FI</th>
<th>CRUISE</th>
<th>FLIGHT</th>
<th>DESCENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TAS</td>
<td>fuel</td>
<td>TAS</td>
</tr>
<tr>
<td></td>
<td>[kts]</td>
<td>[kg/min]</td>
<td>[kts]</td>
</tr>
<tr>
<td></td>
<td>lo</td>
<td>nom</td>
<td>hi</td>
</tr>
<tr>
<td>0</td>
<td>128</td>
<td>3210</td>
<td>2050</td>
</tr>
<tr>
<td>5</td>
<td>139</td>
<td>3110</td>
<td>1980</td>
</tr>
<tr>
<td>10</td>
<td>142</td>
<td>3200</td>
<td>1960</td>
</tr>
<tr>
<td>15</td>
<td>143</td>
<td>3130</td>
<td>1930</td>
</tr>
<tr>
<td>20</td>
<td>144</td>
<td>3090</td>
<td>1910</td>
</tr>
<tr>
<td>30</td>
<td>188</td>
<td>12.4</td>
<td>12.4</td>
</tr>
<tr>
<td>40</td>
<td>191</td>
<td>12.3</td>
<td>12.3</td>
</tr>
<tr>
<td>60</td>
<td>262</td>
<td>13.9</td>
<td>14.9</td>
</tr>
<tr>
<td>80</td>
<td>269</td>
<td>13.9</td>
<td>15.0</td>
</tr>
<tr>
<td>100</td>
<td>277</td>
<td>13.9</td>
<td>15.0</td>
</tr>
<tr>
<td>120</td>
<td>251</td>
<td>10.8</td>
<td>12.2</td>
</tr>
<tr>
<td>140</td>
<td>258</td>
<td>10.8</td>
<td>12.3</td>
</tr>
<tr>
<td>160</td>
<td>266</td>
<td>10.9</td>
<td>12.3</td>
</tr>
<tr>
<td>180</td>
<td>275</td>
<td>10.9</td>
<td>12.3</td>
</tr>
<tr>
<td>200</td>
<td>276</td>
<td>10.4</td>
<td>11.9</td>
</tr>
<tr>
<td>220</td>
<td>274</td>
<td>9.7</td>
<td>11.4</td>
</tr>
</tbody>
</table>
Figure 5. Tilt-rotor Service Region. Map shows the Total Number of Intercity Trips Predicted by the TSAM Model at the County Level.
Figure 6. Intercity Business Trip Demand Map of Tilt-rotor System in the Northeast Corridor. Tilt-rotor Cost set at $0.75 per seat-mile.
Figure 7. Intercity Auto Demand Originating at Middlesex County, MA.
Figure 8. Counties with Commercial Airline Demand Originating at Middlesex County, MA.
Figure 9. Counties with Tilt-rotor Demand Originating from Middlesex County, MA.
Figure 10. Business Trip Market Share as a Function of Distance for Tilt-rotor Mode in the Northeast Corridor. Tilt-rotor Cost at $0.75 per seat-mile.
Figure 11. One-to-one County Mode Choice Analysis.