An Estimate of the Global Impact of Commercial Aviation Noise

by

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Abstract

This study estimates the impacts of commercial aviation noise at 181 airports around the world. These airports are located in 38 countries plus Taiwan, with 95 of the airports located in the United States. They are part of the 190 Shell 1 airports in the FAA's Model for Assessing Global Exposure to the Noise of Transport Aircraft (MAGENTA), which comprise an estimated 91% of total global aviation noise exposure [FAA 2008]. The model calculates both physical and monetary impacts of aviation noise. The physical metrics are the number of people exposed to 55 dB or more noise, and the number of people highly annoyed. The model uses a noise depreciation index developed from hedonic pricing studies of housing transactions to monetize the effects on property owners in terms of housing value loss and rent changes.

Due to data collection difficulties the impacts are only approximately consistent chronologically. Population data are from the years 2000 and 2001 depending on the country, while house prices and rents are 2006 estimates, and noise levels are for the year 2005. Based on there data, we calculated that around the 181 airports more than 14 million people are exposed to at least 55 dB of commercial aviation noise. Of these individuals, approximately 2.3 million are highly annoyed. We found that the noise resulted in a total of $21 billion of housing value depreciation, which is equivalent to about $1.1 billion per year using a 30-year life of the house and a 3% discount rate, and an additional $800 million of lost rent each year.

The impacts are spread over all parts of the world. Although most of the airports included in this study are located in the US and Europe, each continent with an airport in the study had airports with greater than $100 million in housing value loss and greater than 200,000 exposed people. Furthermore, North America, Europe, and Asia each had examples of airports with an estimated $80 million in annualized housing value loss ($1 billion total), 400,000 people exposed to 55 dB, and $25 million in yearly lost rent.

We also examined potential changes to these impacts in the future for a scenario with no technological or operational advances to reduce noise (with the exception of retirement of older aircraft in the fleet). Based on an assumption of 2-3% annual growth rates in operations at these airports between 2005 and 2035 with no noise-technology improvements, we found that the undiscounted housing value and rent loss could approximately double by 2035 while the population exposed to 55 dB and highly annoyed could increase by about 70%. These results demonstrate the potential gains from further advances in aircraft technology and operations to mitigate community noise.

Thesis Supervisor: Ian A. Waitz
Title: Jerome C. Hunsaker Professor and Department Head of Aeronautics and Astronautics

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I must also thank my friends and family, particularly Katya for helping me maintain some sanity throughout this whole process, as well as my parents and other friends who helped me or put up with me after every time GIS failed for the fourth time in a row.

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List of Acronyms

%HA	Percent highly annoyed
AEDT	Aviation Environmental Design Tool
ANN	Artificial neural network
APMT	Aviation Environmental Portfolio Management Tool
CV	Contingent valuation
DENL	Day-evening-night average sound level
DNL	Day-night average sound level
EDS	the Environmental Design Space
EEA	European Environmental Agency
FESG	Forecast and Economic Sub-Group
GRUMP	Gridded Rural-Urban Mapping Project
ICAO/CAEP	International Civil Aviation Organization's Committee on Aviation Environmental Protection
INM	Integrated Noise Module
L_{eq}	Equivalent noise level
L_{max}	Maximum A-weighted noise level
MAGENTA	Model for Assessing Global Exposure to the Noise of Transport Aircraft
MCS	Monte Carlo simulation
MSA	Metropolitan Statistical Area
NDI	Noise depreciation index
SEL	Sound exposure level
WTP	Willingness-to-pay

1 Introduction

Millions of people worldwide live near airports and experience the positive and negative effects of aviation. Airports provide nearby residents with the benefits of travel and various economic opportunities. At the same time, however, airports can expose those residents to the negative effects of emissions and noise. The emissions lead to illnesses and contribute to climate change. Tens of millions of people are exposed to aviation noise on a yearly basis, which masks speech and other sounds, disturbs people's activities, causes vibrations, and disrupts quiet or calm environments. These disruptions lead to a number of deleterious effects for people. Significant evidence demonstrates that aircraft noise causes annoyance, sleep disturbance, learning or school performance impairment, and hypertension [THE PEP 2004].

Residents near airports have generally complained most about the noise of aircraft as opposed to their emissions or other environmental effects. This has often led to political action to reduce the noise often through opposition to airport expansion plans. The carbon dioxide, particulate matter, NOx, and other pollutants emitted by aircraft, however, have significant and sometimes long-lasting impacts. Assessments of potential technological, operational and policy options for addressing the environmental impacts of aviation must therefore take account of the trade-offs and interdependencies among noise, emissions, and the economic benefits of air transportation. The work presented here provides such quantification methods for noise. The intention is that these estimates would be combined with similar analyses of the effects of emissions and airline and consumer economics to create a complete picture of the impacts of different options for mitigating environmental impacts.

Previous studies have analyzed the impact of aviation noise for individual airports (e.g. [Van Praag & Baarsma 2004]), nations (e.g. [Morrison et al. 1999]), and groups of nations ([INFRAS/IWW 2004]); however, no comprehensive study estimating the effect of aviation noise on a global scale has been conducted. With the Aviation Environmental Portfolio Management Tool (APMT), we have estimated the physical and monetary impact of aircraft noise around 181 airports in 38 countries plus Taiwan on every continent except South America and Antarctica.

1.1 APMT

APMT is a part of the FAA's environmental tool suite designed to conduct cost-benefit analyses of technology, operations and policy alternatives for addressing environmental impacts. The main components of the tool suite are the Aviation Environmental Design Tool (AEDT), the Environmental Design Space (EDS), and APMT. The various modules of the tools suite estimate future passenger demand, carrier supply and ticket price, aircraft technology changes, the resulting flights with their emissions and noise, and finally the impacts on people of those changes in air quality, climate, and noise. AEDT estimates the noise and emissions produced by aircraft, and EDS models the emissions and noise characteristics of future aircraft technologies. The diagram in Figure 1 shows the different parts of the FAA tool suite and their information paths. APMT is itself composed of two different components, the Partial Equilibrium Block and the Benefits Valuation Block. For the analysis of a policy, the policy or scenario is first fed into the Partial Equilibrium Block, which estimates the future fleets and operations, the costs to airlines and manufacturers, and consumer surplus given those conditions. As part of that process

EDS creates new technology aircraft for future fleets. Alternatively fleet characteristics can be specified exogenously as was the case for the work shown in this thesis. The fleets and operations are then passed to AEDT, which simulates the flights and calculates the resulting emissions and noise. These outputs are sent to the Benefits Valuation Block, which calculates the resulting physical and monetary impacts in terms of changes the climate, local air quality, and noise.

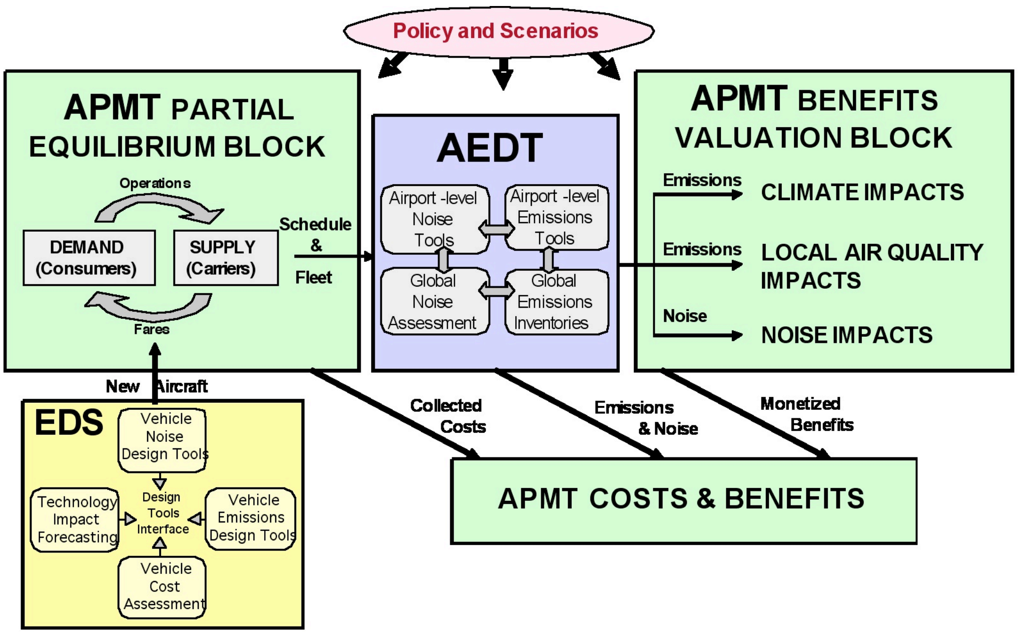


Figure 1: APMT and other FAA Environmental Tool Suite Components

Development of APMT is continuing, and thus its various benefits calculations are conducted on different geographic scales. The Climate Module in the Benefits Valuation Block estimates the globally-averaged impact of emissions on surface temperature and the monetary value of the resulting effects on health, well-being, and ecology. The Local Air Quality Module assesses the incidence of morbidity and premature mortality from primary and secondary particulate matter and their monetary valuation at the county level in the United States. It is planned for the module to eventually expand its coverage to the rest of the world. Finally, the Noise Module assesses the number of people exposed to aircraft noise, the number of people highly annoyed, and the housing value and rent loss for residents around 181 airports in the world. Work on all modules continues in an effort to improve their functionality and scope.

1.2 Organization

This section provides a description of the structure of the thesis and the sections that compose it. The remaining part of the thesis has 6 chapters that present the background and results of the main analysis. I describe the contents of each chapter in greater detail below:

Chapter 2:

Chapter 2 describes the existing state of knowledge concerning aircraft noise impacts and their assessment. It provides an overview of the major, known, physical effects of aircraft noise—annoyance, sleep disturbance, non-auditory health effects, and learning disturbance. This chapter also describes methods of providing quantified estimates of these impacts where such methods are available. I also describe various methods of valuing aircraft noise effects in monetary terms and the relative advantages of these methods.

Chapter 3:

The next chapter presents the methods and data used in APMT's Noise Module to calculate noise impacts. I describe the flow of data from the noise contours, which come from part of AEDT, to the final monetary and physical impact outputs as well as the mathematical equations we use to calculate the impacts. The source and use of the model's internal parameters are also outlined in this chapter. The monetary calculations require detailed housing value and rent data, which is not available for most of the world, so in this chapter I also present models developed with the assistance of the consulting firm ICF Consulting to estimate these values around airports.

Chapter 4:

Chapter 4 presents the main results of the study. The current physical and monetary impacts of aviation noise are calculated at 181 airports around the world. The physical metrics are the number of people exposed to at least 55 dB of noise and the number of those who are highly annoyed. The monetary valuation is in terms of housing value loss and rent reduction.

Chapter 5:

In addition to analyzing the current impacts of aviation noise we have estimated possible future impacts, which I present in the chapter 5. Based on an assumption of growth in operations between 2 and 3% from 2005 to 2035 with no noise technology changes other than those brought about by retirements of older aircraft in the fleet, we calculated the monetary and physical metrics through the year 2035. Although this analysis is not a firm prediction of future impacts, but an assessment of one possible scenario, it does indicate growth of aircraft noise and its effects in the absence of technological advances.

Chapter 6:

Finally, chapter 6 provides a discussion of the results and conclusions that can be made from them. I describe the geographic distribution of impacts. Additionally, I explain the differences among the changes in operations, contour areas, and impact metrics and the reasons behind them. In this chapter I also provide recommendations for future work, discussing ways to improve the estimate of noise impacts.

1.3 Contributions

The main goal of this work is to estimate the current effect of aircraft noise at a global scale. Significant work has been done for the US and Europe in this area, but estimates of aviation noise impacts in the rest of the world are lacking. In addition to this result, however, we have also examined possible future changes in these effects. The results of these analyses demonstrate the importance of including the effects on rental prices around most airports, which has received too little attention, particularly in studies that calculate noise depreciation indices. Additionally, in the process of conducting these analyses we have measured the correlation of the various physical and monetary metrics at each airport.

We conducted this work with the collaboration and assistance of several different groups. The entire team and associated organizations involved in the FAA's environmental tool suite work to make these analyses possible. In particular, Wyle Labs modeled the noise levels around each airport that were used in these analyses. ICF Consulting also provided significant support by assisting in the creation of a model to estimate house prices and rents around airports.

2 Literature Review

This chapter presets the current state of knowledge regarding the effects of aviation noise on the residents near airports. First I review the physical impacts of aircraft noise. Then I describe the various methods of valuing those effects in monetary terms and existing estimates of the value of noise. I end the chapter with a brief discussion of some previous efforts to calculate the impacts of noise for different geographical areas.

2.1 Noise Metrics

Due to the fact that aircraft flights are intermittent events and the resulting noise varies with time, several measures of noise exist. These measures can be broadly grouped into measures of single events and time-averages of multiple events. The type that best describes an effect of noise depends on the effect. For direct effects of a single event, such as sleep awakenings, two of the most common metrics have been L_{max}, which measures the A-weighted maximum sound level of the event, and the sound exposure level (SEL), which is the total noise energy for an event. Long term effects, such as annoyance and learning disruption, generally conform better to longer time-averages of noise levels, such as the day-night average sound level (DNL) and the equivalent sound level (L_{eq}). An L_{eq} for a period of time is the constant noise level that carries the same amount of energy in that period as the actual, time-varying sounds that occur in that length of time. DNL is the A-weighted L_{eq} for a 24-hour period with an additional 10 dB applied to nighttime events to account for the greater disturbance they are likely to cause due to lower background noise [EPA 1974]. A-weighting accounts for the different noise perception by the human ear at each frequency. Humans have a different sensitivity to noise at different frequencies. Thus, the same sound pressure (i.e. noise with the same dB level) at two different frequencies can appear to have different loudness to humans. The A-weighting of noise, which is reported in units of dBA, takes into account these different sensitivities to represent the noise levels that humans actually perceive. Another metric closely related to DNL is the day-evening-night average sound level (DENL), which is the same as DNL except that it also applies a 5 dB penalty to the events that occur in the evening.

The inclusion of the number of flights, loudness of individual events, sensitivity of the human ear to particular frequencies of sound, and the greater impact of night flights makes DNL and DENL useful for the prediction of several effects, but it also makes them problematic for public understanding of noise conditions. Residents near airports hear individual flights with peak sound levels that exceed the averaged DNL value and that can occur unexpectedly. According to the Australian Department of Transport and Regional Services [DOTARS 2000] residents generally want to know straightforward, transparent information of aircraft operations. They ask for the location of flight paths, the number of flights, their times during the day, and similar information. Therefore, DNL and most other average noise level calculations have great value for technical purposes, but are more problematic for the communication of airport noise to residents.

2.2 Physical Effects of Aircraft Noise

Aircraft noise has a number of direct effects on the residents near airports. The noise disturbs people and their activities. This disturbance leads to several different effects. The most well-known effect is general annoyance, which occurs in a relatively large portion of the population exposed to aircraft noise, but significant evidence also exists that aircraft noise disturbs sleep, hinders learning, and causes certain cardiovascular diseases. Limited evidence indicates connections between aircraft noise or environmental noise in general and hormone changes, general performance, and psychiatric disorders [Public Health Effects of Large Airports 1999]. The effects with significant evidence are described more fully in the following sections.

2.2.1 Annoyance

Annoyance is one of the most readily apparent effects of aircraft for residents living near airports. Complaints due to annoyance and its resulting damage have delayed or added costs to many airport expansions. For example, planned expansions in 2000 at Madrid airport drew a suit from 16 nearby suburbs and further protests due to the increased noise [Goodman 2000].

One of the earliest and most influential reviews of transportation noise annoyance studies was conducted by Schultz [Schultz 1978]. Since then many additional studies have analyzed the existing surveys of noise annoyance and developed exposure-response functions (e.g. [Miedema & Oudshoorn 2001], [Miedema & Vos 1998], [Fidell et al. 1991], [Finegold et al. 1994]). Schultz's curve grouped all forms of transportation noise together. More recent studies by Finegold et al. (1994) and Miedema & Vos (1998), which combined use virtually all the available noise attitudinal data from the last 50 years, both show that aircraft noise causes more annoyance at a given DNL than road traffic and railroad noise [Schomer 2001]. Finegold and his fellow authors, though, cautioned against separating the curves due to a lack of data for transport modes other than aircraft, and Finegold's more recent paper [Finegold & Finegold 2002] argues against such a separation. The 95% confidence intervals, however, of Miedema & Oudshoorn's percent highly annoyed equations do not overlap at higher exposure levels [Miedema 2007].

In the APMT Noise Module we currently use the curve of the percent of people highly annoyed by aircraft noise developed by Miedema & Oudshoorn. This curve utilized one of the largest databases of annoyance surveys. Additionally, the authors developed 95%-confidence intervals, which are relatively small, and the curve has gained significant international recognition. It was, for example, recommended for use by a working group of the European Commission [EU 2002]. The relationship that the authors found between the percent of people highly annoyed (%HA), which they define as an annoyance level of 72 or higher out of 100, and the DNL of aircraft noise is:

$$\%HA = -1.395\cdot 10^{-4}\left(DNL-42\right)^3 + 4.081\cdot 10^{-2}\left(DNL-42\right)^2 + 0.342\left(DNL-42\right) \qquad (1)$$

This relationship along with the 95% confidence intervals is shown in Figure 2.

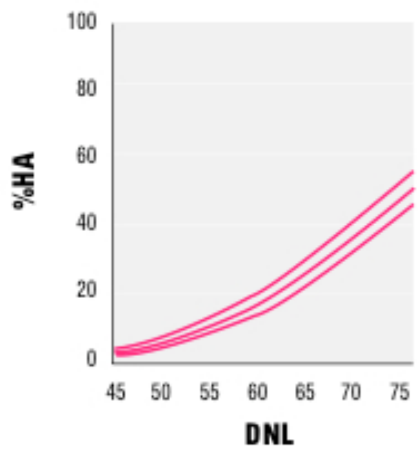


Figure 2: Percent highly annoyed by aircraft noise and the 95%-confidence interval. Source: Miedema & Oudshoorn (2001).

All of these exposure-response functions are suitable for predicting only a community-wide response to noise. The scatter of results for individual studies is quite high, and individuals' own sensitivity to noise varies greatly. Figure 3, for example, shows the results of studies of annoyance from aircraft noise collected by Fidell & Silvati [Fidell & Silvati 2004]. Despite the large variability in the data, the 95% confidence intervals of Miedema & Oudshoorn's curves are quite small [Miedema & Oudshoorn 2001]. Therefore, their curves predict the normal, population-wide response quite well. Responses at individual airports, however, will often deviate significantly from these conditions because of local conditions.

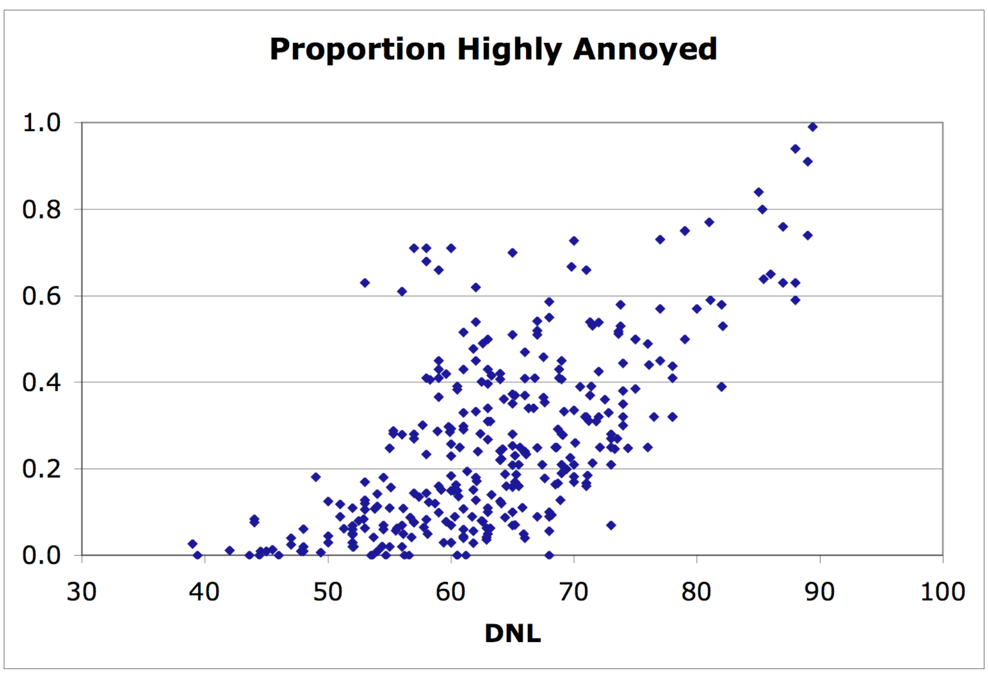


Figure 3: Aircraft noise annoyance data. Data source: [Fidell & Silvati 2004]

The scatter is due in part to the fact that the level of individuals' annoyance depends on non-acoustical factors as well as just the noise level. Fear, for example, has a very significant effect on the level of annoyance. A high level of fear related to aircraft can result in an increase in annoyance equivalent to an increase of up to 19 dBA in noise [Miedema 2007]. Additionally age and the number of people in a household show small effects on the level of annoyance [Miedema 2007].

This data scatter makes any functional fit problematic. Neither Miedema & Vos [Miedema & Vos 1998], nor the updated version of their results presented in Miedema & Oudshoorn [Miedema & Oudshoorn 2002] provide an R^2 value for the fit of their exposure-response functions, but Fidell & Silvati [Fidell & Silvati 2004] state that Miedema & Vos's curve for the percent of people highly annoyed by aircraft noise accounts for less than half of the variance of the data. Using the data surveys provided in Fidell & Silvati [Fidell & Silvati 2004], which is not the same database as those used in the following studies, the R^2 values for the percent of people highly annoyed by aircraft noise (or transportation noise in general if equations for different modes of transportations are not given) for several studies are shown in Table 1.

Table 1: Variance of annoyance data accounted for by various exposure-response functions

Study	**R^2**
Miedema & Vos 1998	0.43
Miedema & Oudshoorn 2002	0.40
FICON 1992	0.17
Schultz 1978	0.26
Fidel et al. 1991	0.37

Due to this scatter, the assumptions that go into any specific function form, and the substantial underestimation of the average annoyance rate at moderately high noise levels (i.e. about 55 dB to 70 dB) by the FICON 1992 curve, Fidell & Silvati [Fidell & Silvati 2004] advocate using the weighted mean of the percent highly annoyed for 5-dB intervals. Figure 4 shows the curves from these studies and the values recommended by Fidell & Silvati with points at the center of each interval. The graph shows that the two Miedema curves estimate the average annoyance at moderately-high noise levels much better than the FICON curve and match Fidell & Silvati's points fairly closely.

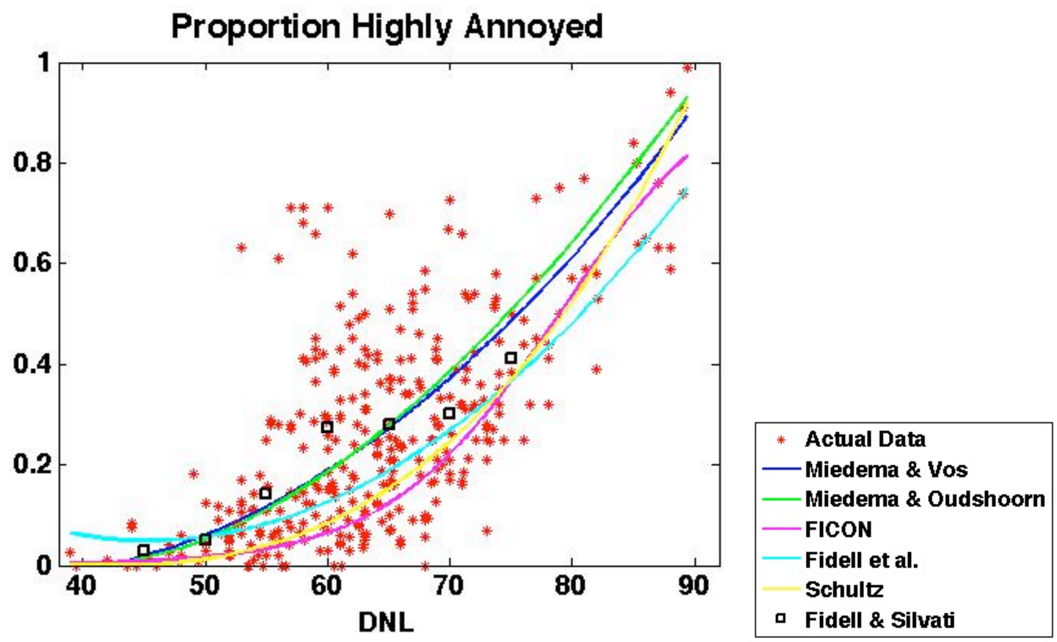


Figure 4: Annoyance exposure-response functions

Several other factors beyond the statistical fit of an exposure-response function affect the function's application for predicting annoyance levels. One possible issue is the change in people's reaction over time. Many people have theorized that the noise patterns from current flights, which generally occur more often but are quieter than older airplanes, cause a different amount of annoyance than did those flights with the same DNL in the past. Much more work is needed to determine the validity of this idea and to quantify the actual shift, but Guski [Guski 2004] has provided some evidence indicating that it does exist.

Another issue is that the exposure-response functions are designed to estimate the long-term response of a community. A significant change in the noise profile around an airport can create a large increase in annoyance in the short-term, which will generally decrease with time as people acclimate to the new conditions. Fidell & Silvati [Fidell & Silvati 2002] examined the response around one airport before and after a new runway opened and attributed a large portion of the resulting increase in annoyance to non-acoustical factors.

Further, annoyance data is lacking for a large portion of the world. The data for Miedema & Oudshoorn's analysis as well as the other analyses mentioned above are from North America, Europe, and Australia. Very few studies have measured the annoyance due to aircraft noise in other parts of the world, and most of those studies were conducted in one country, Japan [Fields 2001]. Thus, the validity of the Miedema & Oudshoorn function or any other curve developed with this data for predicting annoyance in other parts of the world is still unknown.

2.2.2 Sleep Disturbance

Aircraft noise affects sleep in a number of ways. It awakens people, but it also increases motility, alters sleep stages or patterns, and possibly affects hormone levels [THE PEP 2004]. Furthermore, these changes in sleep quantity or quality could potentially affect performance the next day, although more work is necessary to determine such an effect. Awakening is one of the most researched areas of noise sleep disturbance, and the effect with the most thoroughly developed exposure-response relationships.

The relationship between the noise level of individual events and resulting awakenings has been studied fairly extensively. Several studies have analyzed collections of individual studies and created exposure-response functions (e.g. [FICAN 1997], [Finegold & Elias 2002], and [Passchier-Vermeer 2003]).

Despite the well-developed research of awakenings from single events, however, the more important concern for policy makers and residents near airports is the awakenings from a full night of aircraft noise, not just a single event. Much less research has been conducted for this topic. Recently two groups of researchers have developed methods to estimate the effect of a full night's set of flights. One method, developed by Anderson & Miller [Anderson & Miller 2007], combines the probabilities of awakening for single events to find the probability of awakening at least once for a number of flights in a single night. They base their analysis on the assumption that awakenings from different events are independent. The authors do not provide evidence for this assumption except that their validation dataset indicates that their model overall predicts awakenings well. Based on this assumption, the probability of not waking up from multiple noise events is the product of the probabilities of not waking up from each individual event. Therefore, the probability of waking at least once during a night is

$$P_{awake,multiple} = 1 - P_{sleep,multiple} = 1 - \prod_{i=1}^{N}\left(1 - P_{awake,single,i}\right) \qquad (2)$$

where: $P_{awake,multiple}$ = Probability of awakening from multiple events
$P_{sleep,multiple}$ = Probability of sleeping through multiple events
$P_{awake,single,i}$ = Probability of awakening from the single event i
N = Number of events

Their approach also accounts for different sensitivities of individuals and the different likelihood of awakening based on the time since retiring for the night that the event occurs. By examining sleep studies around 3 airports they found both that individuals varied significantly in their likelihood to awaken for a given event and that as the amount of time since a person retired increased, the likelihood that a flight of a given SEL level would wake that person also increased. This method results in a large set of exposure-response functions based on the number of flights, their individual SELs, the times at which they occur, and the sensitivity of the person. For a single flight and a single person, the probability of awakening is given by:

$$P_{\text{awake,single}} = \frac{1}{1+e^{-Z}} \qquad (3)$$

$$Z = -10.723 + 0.0861 SEL\_i + 0.00402 T_{retire} + \beta$$

where: SEL_i = Indoor SEL
T_{retire} = Time since retiring
β = Individual's sensitivity, which ranges from -4 to 4

Passchier-Vermeer [Passchier-Vermeer 2003] developed a different method that uses a multi-event, time-averaged metric to predict the worst-case, total number of awakenings per person in a night. The metric, L_{night}_i, is the indoor equivalent sound level during the night. This method also assumes that noise-induced awakenings from separate events are to be independent, which means that the number of noise-induced awakenings in a night is equal to the sum of the probabilities of the individual events. Additionally, if the number of awakenings as a function of SEL is concave down for an argument of the form $10\log(x)$, which is the case for Passchier-Vermeer's method, then the maximum number of awakenings occurs when all flights have the same SEL [Passchier-Vermeer 2003]. The resulting exposure-response function is:

$$\#\,Awakenings = N \cdot 0.96 \cdot 10^{-3} = 0.96 \cdot 10^{\frac{L_{night\_}i - 44.2}{10}} \tag{4}$$

where N = the number of flights

A plot of this equation is shown in Figure 5.

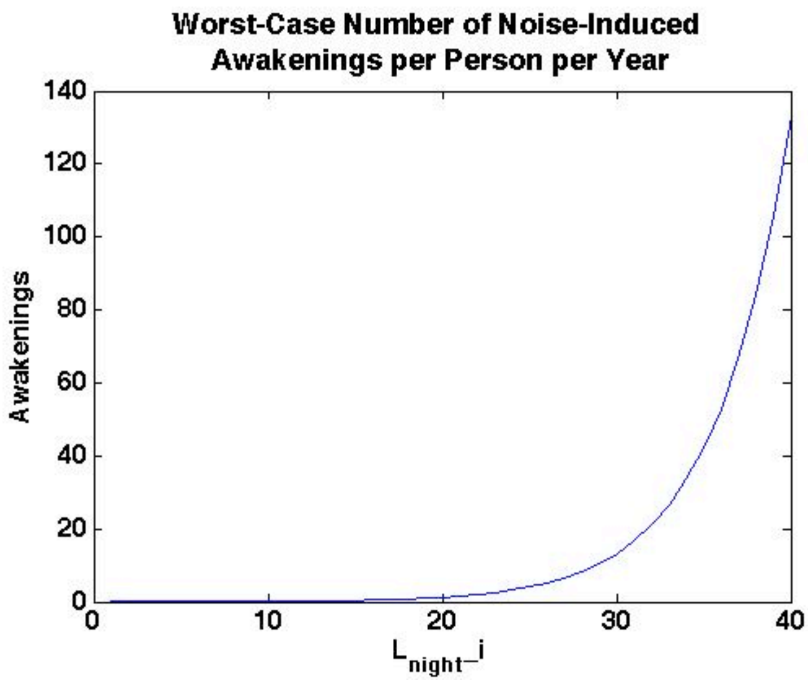


Figure 5: Passchier-Vermeer's noise awakenings curve

The number of awakenings in this situation is quite sensitive to the number of flights that occur. Figure 6 shows, for example, that 14 flights per night cause approximately 153 awakenings for the average person in a year, but 28 flights a night cause almost 5 times as much (approximately 753 awakenings in a year).

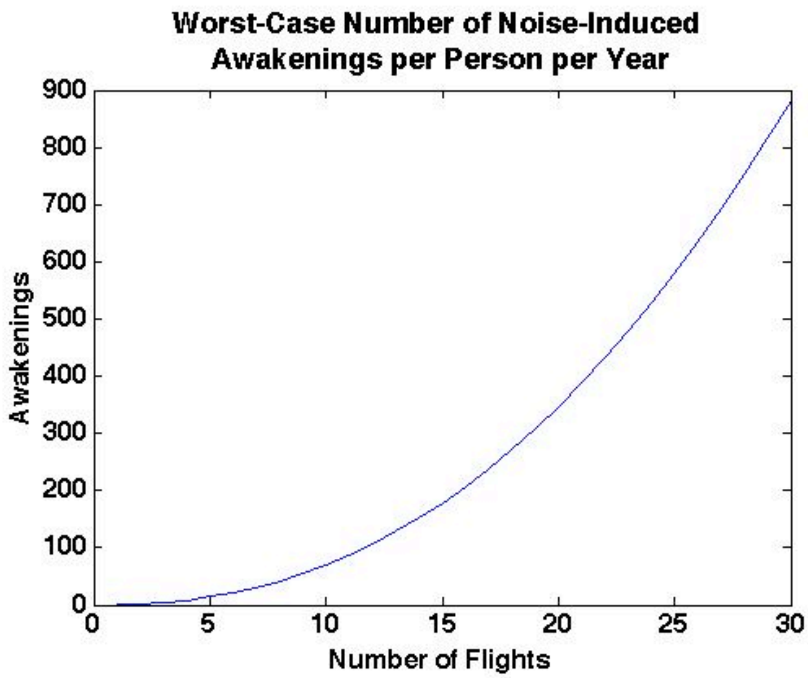


Figure 6: Passchier-Vermeer's awakening curve as a function of the number of flights

The use of a single, nightlong noise level in Passchier-Vermeer's method is attractive from a policy and computational standpoint. The usefulness of such metrics for actually predicting awakenings is questionable, however. Fidell et al. [Fidell et al. 1994] found that full-night measures of noise level accounted for no more than 1% of the variance in their self-reported and behavioral awakenings data.

One of the weak points of both Anderson & Miller's and Passchier-Vermeer's approaches is that they assume all awakening events are independent without providing sufficient evidence for this assumption. Anderson & Miller do, however, use a validation set of data that indicates, at least for the flight timings in that data, that their assumption is sufficiently accurate. Currently, limited research has been conducted on the nature of individuals' awakening patterns. Several factors, such as age and personal sensitivity to noise, have been shown to cause differences in the responses of different individuals to noise while they sleep [Miedema, Passchier-Vermeer & Vos 2003], but much less work has been conducted on the different ways each individual responds under different conditions. The important assumption of independence between noise event awakenings, however, has not been significantly studied.

2.2.3 Learning Impairment

Aircraft noise affects the performance of students through several mechanisms. Most fundamentally, aircraft noise can drown out the speech of teachers and students [Eagan 2007]. It has also been linked to decreases in the motivation of children and can interfere with children's discrimination of other meaningful auditory information from background noise [Evans & Lepore 1993].

A number of studies have found links between aircraft noise and cognitive abilities. Studies around Heathrow airport found that levels of aircraft noise were associated with lower reading comprehension or performance on reading and math standardized tests [Stansfeld & Matheson 2003]. A recent cross-national study of 89 schools similarly found that higher aircraft noise was associated with reduced reading comprehension after controlling for socioeconomic factors [Clark et al. 2006]. A Munich study that examined students before and after one airport closed and a new airport opened in a different location indicates a causal link between aircraft noise and the reduced reading comprehension and long-term episodic memory that the study found [Hygge et al. 2002].

Strong evidence exists for the effects of aircraft noise on learning and school performance, but exposure-response functions that could be used for policy analysis are still needed. Many studies report results in terms of performance on a test or given activity as opposed to a broader metric. One of the most useful relationships is given by Stansfeld et al. [Stansfeld et al. 2005], who report that in their study a 5 dB increase in aircraft noise resulted in lower reading comprehension equivalent to a 2-month delay in the UK and a 1-month delay in the Netherlands.

2.2.4 Health Effects

The health impairments that are most strongly linked to aircraft noise are cardiovascular diseases. Other health issues to which noise has been linked, such as psychological well-being and biochemical effects [THE PEP 2004, Public Health Impact of Large Airports 1999], have only limited and insufficient evidence. The cardiovascular disease with the strongest link to aircraft noise is hypertension [Babisch 2006]. Babisch [Babisch 2006] conducted a review of studies of transportation noise and cardiovascular health and found consistently higher risks of hypertension in areas exposed to higher aircraft noise. Four studies that had statistically significant results showed relative risks between 1.4 and 2.1 for individuals living in areas exposed to daytime noise levels of approximately 60-70 dBA or more, and one study found a relative risk of 1.6 at noise levels beginning at 55 dBA. Since Babisch's review, results of the HYENA study conducted near 6 major European airports have been published, which showed an increase in hypertension with an odds ratio of 1.14 for every increase of 10 dB of average nighttime noise [Jarup et al. 2008].

The evidence for a connection between aircraft noise and ischaemic heart disease is more mixed. Reviews by Babisch [Babisch 2006] and van Kempen et al. [van Kempen et al. 2002] find studies with contradictory results. The analysis by van Kempen et al. found links between aircraft noise and increases in angina pectoris, the use of cardiovascular medicines, and consultations with a doctor, but the relationships were not statistically significant.

2.3 Monetary Valuation of Aircraft Noise

The physical effects of aircraft noise can be valued in monetary terms as a way of aggregating the various effects. No market exists for reducing noise, so one cannot simply look at the prevailing amount that individuals are willing to pay to make their surroundings quieter. Therefore, researchers generally take one of two routes in valuing noise. One method, called hedonic pricing, examines the prices of complimentary, market goods that are related to noise and, therefore, reveal individuals' value of noise. The second approach, stated preference methods, utilizes surveys to elicit respondent's value of noise. Regardless of the method, however, the monetary value of noise is not a separate effect that occurs in addition to the physical impacts. Instead, it is a different way to account for them. Existing residents who experience a drop in their house price due to an increase in the noise level experience the real effect of lost wealth, but the total value of the effects of the noise is not the lost housing value plus the value of the annoyance and health effects. It is only the lost housing value (assuming that the housing market conforms to the assumptions described in the hedonic pricing section below) because with that money the person can move to an equivalent house in a quieter area and return to his or her original level of well-being. A WTP is more straightforward because it is explicitly the amount of money that a person equates to a given change in noise level. Each method has advantages and disadvantages compared to the other, but both face the challenge of requiring fully-informed individuals and generally look at only residential costs, as opposed to, for example, losses from delayed airport expansion.

2.3.1 Hedonic Pricing

Hedonic pricing (HP), which uses reductions in house prices, is the most common method of valuing aircraft noise [Navrud, 2002]. In this process researchers examine actual housing transactions and attempt to isolate the effect of aircraft noise on the differences in prices. The level of noise at a home is one of many characteristics that individuals will generally include in their decision process, and since most people find aircraft noise annoying, they will not pay as much for a house that experiences loud noise as they will for an identical one exposed to less noise. Researchers attempt to measure this difference in price a person would pay for a house based on the noise level it experiences, but one cannot practically examine sales of houses that are identical except for the noise level. Therefore, to determine the effect of noise the study must control for as many characteristics of the houses that affect the price as possible. These traits include characteristics of the structure or property (e.g. size of the house, presence of a balcony) and of the location (e.g. distance to work, parks or other amenities and environmental conditions). Several studies have shown that easier access to the airport is a desirable trait that results in higher house prices (e.g. [Tomkins et al. 1998], [Pope 2007]), while others have shown that it has no effect (e.g. Burns et al. 2001). Nelson (2004) conducted a meta-analysis of aircraft noise valuation studies and found no statistically significant systematic effect of accounting for accessibility, but given that individual studies have found an effect and that accessibility and noise generally affect housing prices in opposite ways (i.e. as a house is located closer to the airport, increasing the value due to accessibility, the noise level generally increases, lowering the price) HP studies should control for this characteristic, particularly since it is relatively easy to estimate. The researchers fit the sales prices to a function of the noise level and all of the house and neighborhood characteristics. Although this function can theoretically be of any form, a semi-log equation of the following type is common:

$$\ln(P) = c_0 + \sum_i c_i \ln(Z_i) + c_N N + u \qquad (5)$$

where P is the house price, the c terms are constants, Z_i is one of the house's characteristics other than noise, N is the noise level, and u is an error term [Nelson 2004].

This function describes how changes in noise translate into changes in house prices. The price of a house as a function of the noise level is called the hedonic price schedule and is generally conveyed as a noise depreciation index (NDI), which is the percent drop in price that results from each 1 dB increase in noise. With this semi-log equation, the NDI is then:

$$NDI = \left(\frac{\partial P}{\partial N} \bullet \frac{1}{P} \right) \times 100 = c_N \times 100 \qquad (6)$$

In general, however, the implicit price function cannot give the WTP for a change in noise level. The total WTP is the sum of the areas under each individual's marginal WTP for the change [Freeman 2003]. The implicit price function, however, is only the locus of buyer and seller equilibrium points for each quantity of noise [Palmquist 1984], as indicated in Figure 7. To determine the individuals' demand functions we need additional information beyond the implicit price function about their demand of the good at various prices. Two general methods exist for finding the demand curve. One method is to measure individuals' demand for the good in one market where prices vary over time [Bateman et al. 2001], although that situation requires that the supply or demand itself is not changing in that period. The second method requires looking at the demand of similar individuals in separate markets that have different prices [Freeman 2003].

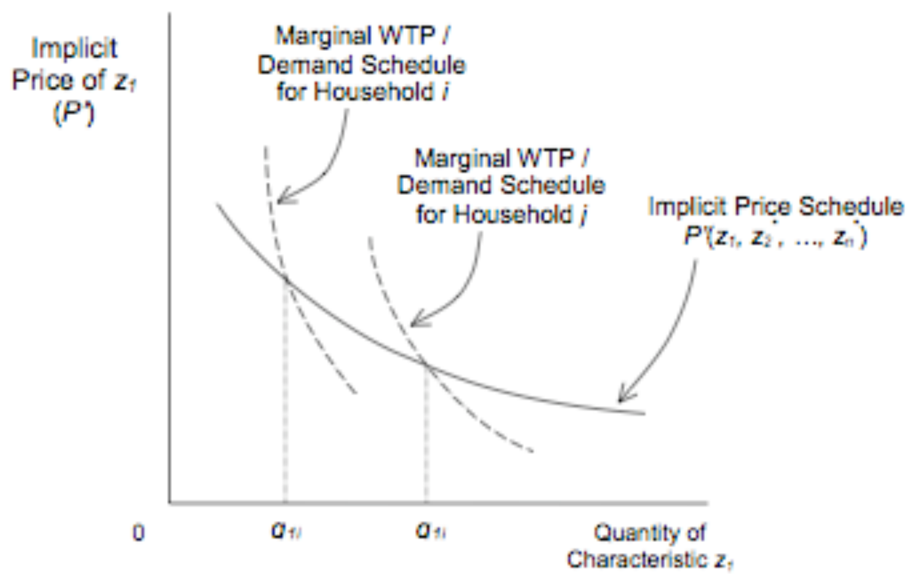


Figure 7: Implicit Price Function and Individual Demand Curves. Source: [Bateman et al. 2001]

When, however, noise affects a localized area, meaning only a small portion of the overall housing market is affected, Palmquist [Palmquist 1992] argues that the welfare change, that is the WTP, of dwelling owners is given by the area under the hedonic price schedule for noise. A sufficiently small affected area will not reduce the overall supply of housing, so the change in noise would not change the implicit price function itself, which would happen with a larger impact. Owners, therefore, can change housing and return to their original position on the implicit price function at only the cost of the difference in prices at the two noise levels, assuming no transaction costs exist. Palmquist further argues that tenants face no damages when moving costs are zero because they can simply move to an equivalent dwelling unaffected by the noise. When moving costs exists, he states that they place an upper bound on the damages for current tenants. Moving costs, however, are often more than simply the out-of-pocket expenses and opportunity costs of time associated with finding a new home and moving and can include psychological factors, such as distress of moving away from one's home, neighborhood, or neighbors. Moving expenses can be particularly high when rent controls exist and make market prices much higher than prices for individuals' existing rent.

2.3.2 Stated Preference Methods

The second major set of noise valuation methods are stated preference studies. These studies use surveys to directly ascertain the respondents' willingness to pay for or accept a given change in noise. Stated preference studies have been conducted for many fewer cities than hedonic pricing methods, particularly in the United States [Navrud 2002], but offer an alternative or complement to them. The most common type of stated preference study conducted for aircraft noise is contingent valuation (CV). The exact format of CV surveys can vary significantly depending on the audience and the type of information the researchers want to elicit. Most surveys, however, have 7 common sections: (1) an introductory section that describes the general context of the decision the respondent is going to make; (2) a detailed description of the good that will be offered to the respondent; (3) a description of the setting in which the good will be provided; (4) a description of the manner of payment for the good; (5) a method to elicit the respondent's preferences for the good; (6) debriefing questions asking why the respondent answered the way he or she did; and (7) a section to collect a set of the respondent's characteristics, including his or her attitudes, debriefing questions, and demographic information [Carson et al. 2001].

2.3.3 Relative Advantages of Hedonic Pricing and Stated Preference Methods

Each valuation method has advantages and disadvantages compared to the other. Hedonic pricing uses actual transactions, so it does not capture strategic, unrealistic behavior. The disadvantages of using actual markets, however, are that the markets must be competitive and in equilibrium, which means prices or rents must not be controlled, buyers must be fully informed of the noise level, and transaction costs must not exist. The extent to which buyers are informed of the noise level before they purchase a house is particularly important because if they are generally not aware of the noise, hedonic pricing could underestimate the value people place on quiet conditions. Limited empirical evidence exists concerning the extent to which buyers know about noise levels before they move, but one study conducted around Raleigh-Durham International Airport indicated that a requirement for sellers to disclose the level of noise at their home decreased housing prices at the most heavily impacted areas by an extra 37% beyond the earlier implicit price of noise when the disclosure requirement did not exist [Pope 2008]. Additionally, the number of factors that people consider in their choice of housing, from its layout to the quality of nearby schools, makes controlling for all such factors extremely difficult. Hedonic studies also require a prior assumption in the form of the price function, and, for example, Nelson's [Nelson 2004] meta-analysis showed that the use of a linear model had a statistically significant effect on the value of the NDI.

Stated-preference methods avoid the problems of imperfect markets but have their own problems. One feature of stated-preference studies that can be considered as either an advantage or a disadvantage based on one's viewpoint is that the studies capture non-use value of noise as well as use value. Non-use values take several different forms, but they are all values that people place on an entity for reasons besides their interaction or expected interaction with that good. A common example is the money people would pay to protect an endangered species that they will never experience, or to maintain a national park they will never visit. Little or no research has been conducted examining the non-use value of noise, but one form that may be particularly relevant is option value. People in some areas may be willing to pay some amount to reduce noise at a location where they do not live in order to maintain the option of purchasing a house in that area that does not experience loud noise.

Stated-preference methods have several unequivocal disadvantages due to the difficulties of eliciting people's opinions. One such issue is their susceptibility to strategic behavior. Respondents may, for example, say that they would pay no money for an improvement because they believe that someone else should be the one to pay for it or they may state an inflated value if they believe it will convince policy-makers to act but that they will not bear the cost. Well-conducted surveys reduce the extent of strategic behavior, but the general effect of such bias on the computed WTP has not been extensively studied [Venkatachalam 2004]. Additionally, the results of stated-preference methods can differ based on the type of survey and question formats that are employed [Carson et al. 2001].

Both methods have common problems as well. One issue is that both methods require that individuals be fully informed about the noise level and its effects. Some of the effects of noise, particularly the health effects, are not well known and, therefore, people may not take them into account when they purchase a house or decide their willingness to pay to reduce noise. A lack of fully-informed individuals biases the resulting valuation of noise, however, only if the individuals systematically under- or overestimate the noise impacts. For example, a group of people may be unaware of the long-term health effects of aircraft noise and not include them in their valuations while another group may believe that a given noise level is more annoying or causes more incidences of illness than it actually does. The two groups, therefore, could compensate for each other and add only to the variance of the measured valuation, not its mean. Additionally, both methods measure only personal values of noise. Economic losses of delayed or canceled airport expansion due to complaints of noise cannot be measured by examining housing prices or surveying residents. These losses have not been thoroughly studied, but they may prove to be significant. Difficulties exist, however, in determining how much of the calculated losses would actually be losses to the economy and how much would be transfers from aviation to other industries, such as those for other modes of transportation, or simply other airports. Another shortcoming that is the result of the scope of most existing studies as opposed to a fundamental problem with the methods is that most studies do not examine effects on properties or land other than homes. Uyeno et al. [Uyeno et al. 1993], for example, included vacant land in their hedonic pricing study and found the NDI for that land was greater than the NDI for both detached homes and multi-unit residential buildings.

2.3.4 Other monetary Valuation Methods

A few additional methods exist to measure the monetary impact of aircraft noise on people. One method is "happiness" surveys, which serve as a compliment to hedonic price methods. With these surveys researchers measure the general well-being of individuals who live near airports and create an equation for well-being or happiness as a function of income, noise level, and other factors. If the local housing market is in complete equilibrium and no cost exists for people to move, then the noise level should have no effect on well-being. In this case the differences in housing prices due to noise would completely describe the costs of noise (at least to the extent that people are conscious of them). If those assumptions are not correct, however, noise level will affect well-being and an increase in income will be necessary to balance the happiness of individuals who live in areas with more noise. For an example of a study using this type of survey see van Praag & Baarsma [van Praag & Baarsma 2004].

Another recent method to measure the impact of noise on property values is artificial neural networks (ANN). Collins & Evans [Collins & Evans 1994] provide an explanation of ANNs and an example of their application to determine the effect of aircraft noise on property values. ANNs are black boxes, to which inputs are given and a complex network of inter-connected "neurons" produce a set of outputs. Each neuron takes numerical inputs either from outside the network or from other neurons. It adds these inputs together with a bias level and conducts a mathematical transformation to produce an output value. The outputs of the individual neurons are multiplied by weights in the connections between neurons. Before the network can be used to analyze a new set of data it is first trained by giving it a set of inputs with known results. The output will usually differ greatly from the actual results and this difference between the two is sent backwards through the network from the outputs to the inputs as an error function to change the connection weights and neuron bias levels in order to reduce the error. This process is repeated thousands of times on the same data until the network has learned the underlying pattern in the data. An important advantage of ANNs over regression analyses is that a regression relies on a pre-defined function form out of the thousands or millions of possible mathematical functions, whereas an ANN does not require any sort of prior knowledge or assumptions [Collins & Evans 1994]. The black-box nature of ANNs, however, could be considered problematic for use as part of public policies as opposed to a transparent method.

2.4 NDI

The APMT Noise Module uses an NDI distribution developed for the US by Nelson [Nelson 2004]. He examined 20 studies with 33 NDI estimates at 23 different airports in the US and Canada. For a list of these studies see the appendix. The NDI estimates had an unweighted mean of 0.75, a median of 0.67, and a fixed-effects weighted-mean of 0.58. Statistical tests indicated that the sample values did not represent estimates of the same value. Therefore, he developed 6 regressions with constant values from 0.5069 to 0.8316. In the Noise Module we use Nelson's regression (6), which has a constant of 0.6651 with a standard error of 0.2043. This regression has one of the higher statistical significances based on the J-B test and uses the least statistically insignificant regressors. We use a normal distribution of NDI values with a mean value of this constant and a standard deviation of its 95%-confidence interval, i.e. 0.1042.

Relatively few hedonic price studies have been conducted for aviation noise in other parts of the world and no extensive meta-analysis of non-US values has been conducted. Bateman et al. (2001) [Bateman et al. 2001] conducted a review of hedonic pricing studies and gathered the follow values for cities outside of the US and Canada:

Table 2: Foreign NDI Values from [Batemant et al. 2001]

Source Study	Study Year	Study Area	NDI
Abelson, 1979*	1972-3	Marrickville, Sydney, Australia	0.4
Abelson, 1979*	1972-3	Rockdale, Sydney, Australia	0.5
Gautrin, 1975	1968-69	London Heathrow, UK	0.62
Pennington et al., 1990	1985	Manchester, UK	0.47
Yamaguchi, 1996	1996	London Heathrow, UK	1.51
Yamaguchi, 1996	1996	London Gatwick, UK	2.3

*Reviewed in Nelson (1980)

A few additional studies have measured the effect of aircraft noise on housing properties since the Bateman et al. review, including that study itself. Some of these studies are summarized here:

Figure 8: Additional Foreign NDI Values

Source Study	Study Year	Study Area	NDI	Noise Metric
Baranzini & Ramirez 2005	2003	Geneva, Switzerland	1.17 (on rents)	DENL
Bateman 2001	1986	Glasgow, Scotland	0.25	NNI
Pommerehne 1988	1983	Basle, Switzerland	0.20	NNI
Salvi 2007	1995-2007	Zurich, Switzerland	0.93	Leq16
Tomkins et al. 1998	1992-3	Manchester, UK	0.78	Leq

Although a more thorough analysis is necessary to truly compare these values with US ones, the unweighted mean of these values, 0.83, and particularly the unweighted mean without the two outliers from the Yamaguchi study, 0.59, indicate that NDI values in Europe and Australia are similar to those in the US.

Rental properties compose a significant portion of the total number of homes around many airports, so the effect on the residents and owners of those buildings must be considered as part of a noise impact assessment. Palmquist [Palmquist 1992] argues that the welfare loss to landlords is the capital loss of the building, but tenants will pay less rent for a noisy dwelling than an equivalent quiet one, so the capital loss is equivalent to a recurring loss in rent payments. In equilibrium markets rents are proportional to building prices [Freeman 2003], so a percentage change in the building price should produce the same percentage change in the rent. Therefore, the NDI of the sale price of a rented property and the NDI of the rent itself will be the same in equilibrium. Whether aircraft noise affects rental prices the same amount as owner-occupied housing prices is not known, however. The studies used in Nelson's analysis are almost all for owner-occupied housing. Only one study used rental properties, which found an NDI greater than the mean of all the NDI values, and few other studies in North America or other parts of the world have looked at the effect of noise on rent prices. In one of the few studies to look at both housing prices and rents, Feitelson et al. [Feitelson et al. 1996] found a smaller reduction per dB for rent than house prices around one major hub airport, but studies need to be conducted in more areas. Therefore, in the APMT Noise Module we assume that the NDI developed by Nelson applies to rent prices as well as housing prices.

2.5 NDI and WTP Values

We collected a series of NDI and WTP values for transportation noise for entire nations or groups of nations, which were either used in cost-benefit analyses or developed by researchers or political bodies. A review of several of these studies produced 13 NDI values and 15 values of WTP that could be stated in units of Euros/dB/household/year for European nations, the European Union as a whole, and Japan. For any study that provided a range of values for the NDI or WTP the mean value was taken. An assumption of 2.2 people per household was used to convert a WTP per person to a WTP per household. Comparisons of these noise valuations and the US valuation used in the noise module are shown in Table 3, Figure 9, and Figure 10. To convert the US NDI into a WTP a 3% discount rate, r, and 30-year useful life, n, were used. These values create an inverse annuity factor defined as:

$$f = \frac{r}{1 - \frac{1}{(1+r)^n}} = 0.051 \tag{7}$$

where f is the inverse annuity factor, r is the discount rate, and n is the useful life.

Table 3: Comparison of International and APMT US Noise Valuations

	International Values	APMT US Value
Mean NDI	0.59%	0.665%
Mean WTP (€/dB/household/year)	56	76

The equivalent WTP of the US NDI appears relatively large compared to the international WTP values (which have a mean of €56); however, the distribution of foreign NDIs is also on average greater than the mean WTP. The mean of the equivalent WTP from the international NDIs using the average US housing price is €68. This disparity between the equivalent WTP computed from the NDI values and the actual WTP values may be caused by the different methods in calculating the WTP and NDI because WTP is generally computed by surveying individuals while NDI generally uses actual housing prices. Alternatively, part of the disparity may result from the difference in average housing values in the US and Europe. As shown in Figure 9, the US NDI value used as the default within APMT is slightly higher than the mean of the international values; however, it lies well within the range of the studies.

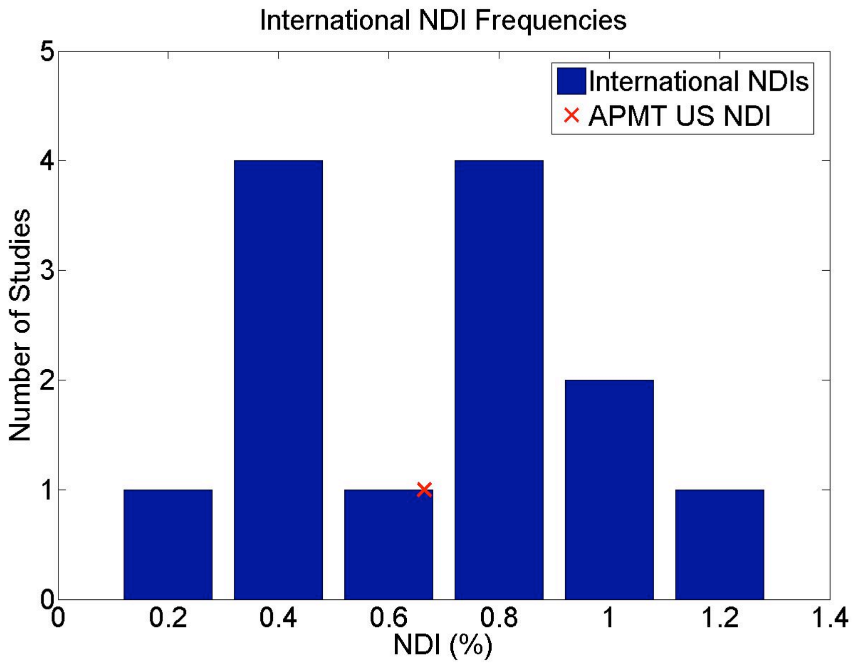


Figure 9: NDI Values

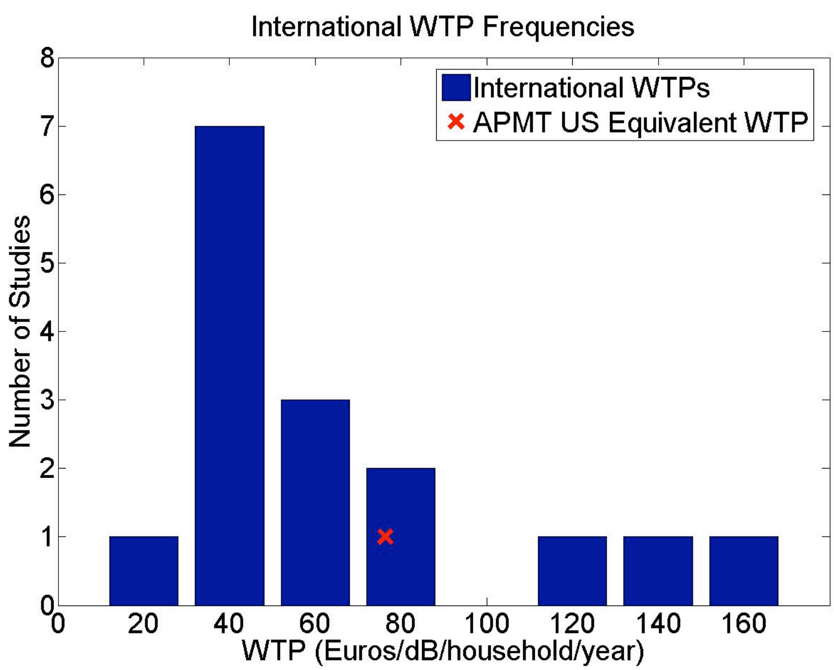


Figure 10: WTP Values

Studies that have compared NDI values from hedonic pricing methods and WTP values from state-preference surveys for the noise in a single city have found mixed results. Some studies found a greater value by examining housing transactions, while others found a greater value from the surveys [Nelson 2007]. In a more general analysis of studies that compared valuations from the contingent valuation type of stated-preference method and valuations from revealed preference methods Carson et al. [Carson et al. 1996] found that on average the contingent valuation results were less than the revealed preference results by 8-23% depending on which data was used and how it was treated.

2.6 Noise Impact Assessment

Several studies have calculated aviation noise impacts for regions [Gillen & Levinson 1999], countries [Morrison et al. 1999], and Europe [INFRAS/IWW 2004]. These studies have generally taken one of two approaches. One method takes noise contours and detailed population data around individual airports and calculates the number of people or corresponding monetary loss within each contour (see, for example [Morrison et al. 1999]). In the second method researchers derive or use an average cost for an aircraft event or passenger-kilometer and calculate the total cost based on the number of such events (e.g. [Gillen & Levinson 1999]). The INFRAS/IWW study is one of the most comprehensive studies and looked at the EU17 countries. Using a WTP of 0.11% of per capita income per dB reduction for all transport noise sources and a threshold of 55 dB for aircraft, this study calculates a total cost of noise of 2.9 billion Euros per year in 2000, which amounts to a value of $2.72 billion (in 2000 dollars) per year. These methods are somewhat questionable because the authors added the value of health risks and medical costs to the result from the WTP studies. In theory, fully-informed individuals would include their valuation of all effects of noise in their WTP to reduce that noise (unless the study is a survey and asks specifically for the person's valuation of reducing his/her annoyance, not the noise level). Individuals may be uninformed about the health risks of noise and systematically underestimate the value of those effects, but the study does not provide data to support the validity for this assumption.

3 Noise Impact Calculations in APMT

The previous chapter outlined the physical and monetary effects of aircraft noise on residents living near airports. The APMT Noise Module currently calculates the number of people exposed to noise, the number of those that are highly annoyed, and the monetized value of the effects in terms of housing value depreciation and rent reduction.

The process for calculating these impacts in APMT's Noise Module is outlined in Figure 11. The noise module receives contours from AEDT. Those contours are placed over population data to calculate the number of people exposed to the noise. An uncertainty is applied to the contour levels to calculate the number of people highly annoyed, but not the population exposed to 55 dB due to the fact that 55 dB is the lowest contours we have. The calculated population would be reduced when the contour uncertainty made the 55 dB contour below 55 dB, but no lower contour exists that would increase the calculated population when the contour uncertainty increased the noise levels. Therefore, the population calculation would be artificially underestimated.

To calculate the monetary impacts, an NDI links the number of decibels above the level at which people begin to reduce their prices for a home, called the quiet level here, to the percentage drop in house prices. Therefore, the contour uncertainty is added to the existing contours and the difference between that and the quiet level is computed. These noise levels are laid on top of maps of the aggregate house value and rent around each airport, and the percentage drop in house price at a given location is multiplied by the house value or rent at that location. When we calculate future scenarios and want to include housing price growth, we apply those growth rates to the initial house prices, but for the current study, which is based on 2005 noise levels, we use housing price changes only for the US to convert the values from the 2000 Census to the year 2006 to match the foreign prices from 2006. The calculations for each point around an airport are then added together to compute the total loss of each type for the airport. The APMT Noise Module also has the capability of restricting the calculation of monetary impacts to those exceeding a certain level, called the significance level, if a policy is concerned with only certain levels of noise that are higher than the quiet level. For the purpose of this study, however, the significance level was not used, and the full impacts were calculated.

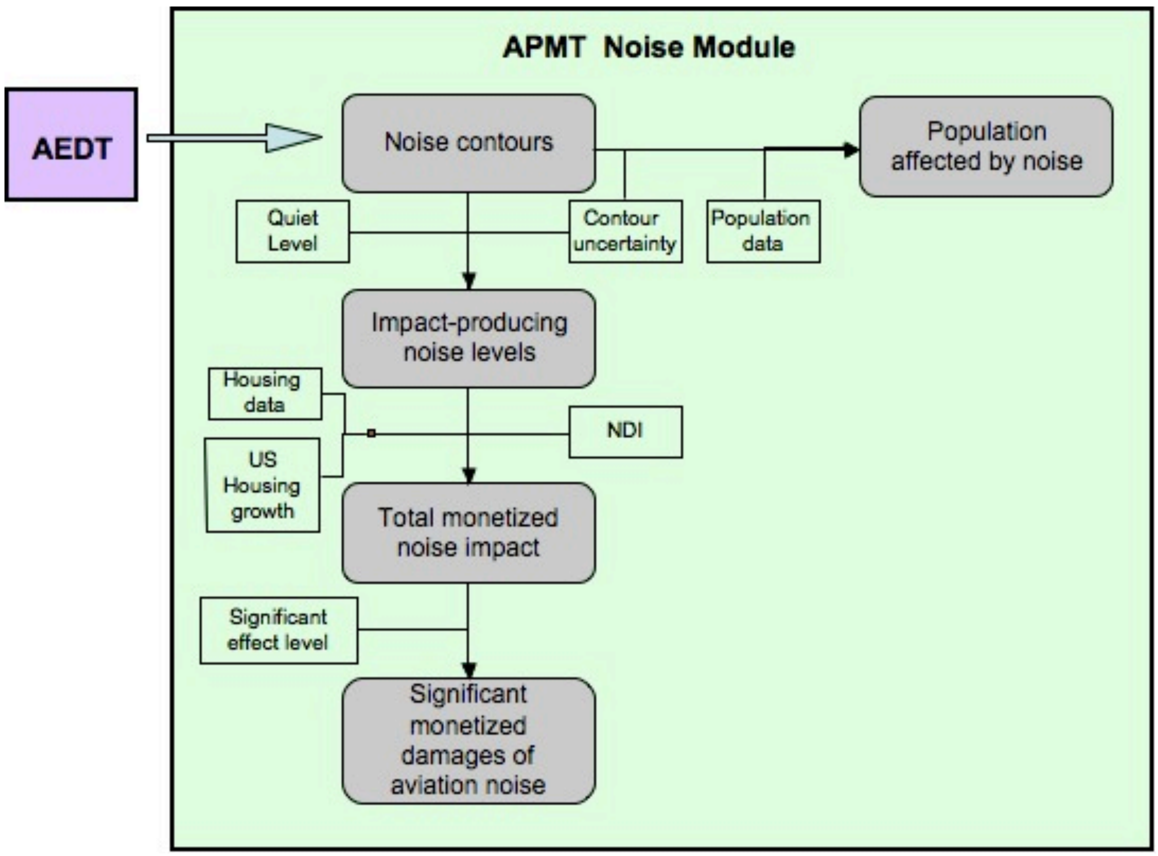


Figure 11: Monetary Loss Calculation in APMT

We calculate the number of people that are highly annoyed using Miedema & Oudshoorn's [Miedema & Oudshoorn 2001] equation, which is discussed in section 2.2.1. The calculation of monetary values is described in the following sections.

3.1 Housing Value & Rent Loss Calculation

The effects of aircraft noise are detrimental to residents' physical or emotional well-being. Monetization is a common way to group all these effects together into a single value, and as described in the previous chapter, the two main methods of monetization are calculating losses in housing values and using WTPs from stated-preference surveys. In APMT we currently use the housing value method to value noise. Due to the detrimental effects of noise individuals will generally pay less for a house that experiences a given level of noise than for an otherwise identical house that experiences less noise. Therefore, an individual who sells a dwelling affected by aircraft noise will, in general, receive a monetary loss in comparison to the situation in which the aircraft noise was not present. This loss, however, is a one-time occurrence. If, for example, a house experiences noise that results in a 5% decrease in the house's value, and the noise remains constant for 20 years, the house does not become worthless at the end of that period. The house will still have a reduction in value of only 5% assuming all factors are constant. The loss is realized only when the owner sells the property, but at any given moment the property's value is reduced a certain amount due to noise. This picture is somewhat complicated by the fact that the value of a house to a household at a given time is the present discounted value of the expected benefits from the house [Bateman et al. 2002]. Therefore, a given noise level that is expected to last for 1 year would reduce the price of a house less than the same noise level that is expected to last for 10 years. With the APMT Noise Module we assume that the same expectations that gave rise to the NDI values examined by Nelson [Nelson 2004] will apply to the scenarios we analyze.

The calculation of the housing capital loss caused by aircraft noise is easiest explained by starting with its impact on a single dwelling. Thus, let P_{NA} be the value of this dwelling in the case that it experiences no aircraft noise, and let P be the true price at which the owner could currently sell the unit with the aircraft noise to which it is actually exposed. Due to the negative effects of noise $P \leq P_{NA}$. Regardless of the fact that this person will not necessarily sell this house today, the capital loss due to noise for this person is $\left(P_{NA} - P\right)$. The NDI links housing values and noise levels to this monetary loss. Aircraft noise, however, has an effect on housing prices only beginning at a certain level, which in the APMT Noise Module we call the quiet level and designate here as DNL_{quiet}. The housing value loss, L, under these conditions for a given day-night average sound level (DNL) is then:

$$L = P_{NA} - P = NDI \cdot (DNL - DNL_{quiet}) \cdot P_{NA} \tag{8}$$

In each future year both the actual price of the property and the price if no aircraft noise was present will theoretically change. In the i-th future year, let $P(i)$ be the actual price and $P_{NA}(i)$ be the price with no noise. The equation for the loss in value in the future year is the same as equation (8) except that the prices and DNL level are replaced with their values in the i-th year. To calculate the total impact over multiple years we add the difference in value loss for each year compared to the loss the year before and discount that value to the present, or the net present value of the total noise impact, NPV, with a discount rate r, is:

$$NPV = L(0) + \sum_{i=1}^{T} \frac{L(i) - L(i-1)}{(1+r)^{i}} \tag{9}$$

To calculate the total impact around an airport, the prices P and P_{NA} are simply replaced with the sum of the prices of all homes that experience the given DNL level. We, therefore, take contours of DNL levels around each airport and overlay them onto housing value data in order to calculate the total loss for that airport, as demonstrated in Figure 12.

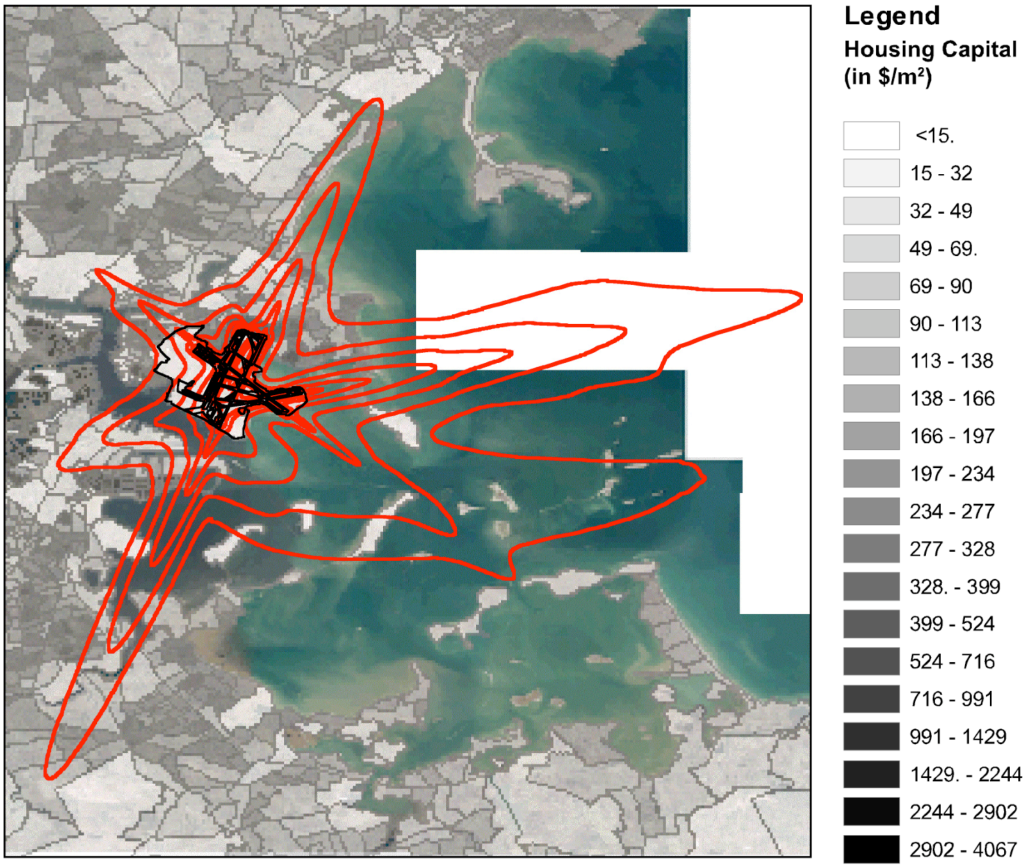


Figure 12: Noise Contours over Housing Value Data. Note: these are not actual contours for this study and are for demonstrative purposes only

Rent loss at a given time is calculated using Equation (8) as well. For the same reasons as the reduction in house prices, when people choose a dwelling to rent they will generally pay less for a unit that experiences more noise than an otherwise identical unit. The resident of the rented dwelling then has no WTP for a reduction in noise because the lower rent compensates for the detrimental effects of noise. The dwelling owner, however, receives less money because of the noise, and, correspondingly, if he or she were to sell the unit instead of rent it, the owner would receive a lower price. The loss to the landlord, therefore, can be calculated either in terms of the one-time loss associated with capital depreciation of the dwelling or in terms of the reduction in the recurring stream of rent. In APMT we currently use the reduction in rent because the US census provides detailed data of the amount of rent that residents pay but not the value of those dwellings.

In theory the NDI value for rent can differ from the NDI for owner-occupied house prices, but insufficient data exists to determine how the two are related, so we have used the same NDI for both types of housing in this study. Unlike housing loss, however, rent is a yearly stream, so the loss from reduced rent recurs every year. Therefore, Equation (7) is not used to calculate the present value of the effects of multiple years of aircraft noise. Instead, the equation for the present value, PV, of yearly monetary streams with a discount rate r is used, which is:

$$PV = L(0) + \frac{L(1)}{(1+r)} + \ldots + \frac{L(i)}{(1+r)^i} \quad (10)$$

3.2 Data & Models

The calculation of noise impacts requires the geographic layout of noise levels, population, housing units, and housing prices. The APMT Noise Module uses the noise contours produced by the FAA's Model for Assessing Global Exposure to the Noise of Transport Aircraft (MAGENTA). MAGENTA currently can calculate the noise levels around 181 airports, 95 of which are in the United States. A table of the number of airports used in this study in each region of the world is found in the appendix. These airports are part of the 190 Shell 1 airports, which together comprise an estimated 91% of total global aviation noise exposure [FAA 2008]. The other 9 airports have outdated or missing location data.

3.2.1 Noise Contours

The contours represent the DNL of noise in dBA, computed as a yearly average. For this study contours were made for 2005 based on the operations conducted on 18 October 2005, which comprised 65,235 flights. They were created by the FAA's MAGENTA, which is effectively a batch processor of the Integrated Noise Module (INM). INM calculates the single-event noise levels created by a single airplane flying a specific trajectory arriving to or departing from an airport. The program uses industry-supplied functions that give the noise level from a specified engine and airframe combination at a specified distance and thrust setting. The dimensions of the runway are entered into the program, and then it uses these noise-power-distance curves to calculate the noise level at grid points around the runway from discrete points of the inputted trajectory and interpolates the results for the sections of the trajectory between those points. MAGENTA calculates the total noise from multiple airplanes at each airport by inputting the airport data and then running INM for each airplane in the fleet mix with its corresponding trajectory. The resulting single-event noise level contours are added together to calculate the desired cumulative noise level, which in this case is DNL. INM does not contain all aircraft in the world's fleet, so the noise from these planes is estimated by a flying a similar plane with an adjusted the number of operations to make the noise contours of the two planes' operations match. In cases when the full noise and performance data are not available, MAGENTA uses certification noise levels to run the correct number of operations (for more description of this process see [ECAC Doc 29 1997]).

Thus, to create the noise contours for this study first the fleet mix and number of operations for each aircraft type was determined. The 65,235 flights that occurred on 18 October 2005 were used for this. MAGENTA was then used to run the aircraft arrivals and departures for each airport through INM. The resulting contours of all the flights into or out of each airport were then combined to calculate the DNL contours for each airport. To calculate the population, for example, within a given contour we would multiply the population density of each exposed geographic division by the area of it that the contour covers and add the results for all the exposed divisions.

3.2.2 Population and Housing Data

Population data come from a variety of sources. We use block group-level 2000 Census data for the US, the European Environmental Agency's (EEA) population density map for most of Europe, and the Gridded Rural-Urban Mapping Project (GRUMP) map for most of the rest of the world. Where more detailed data were available from local statistics agencies, namely the United Kingdom, South Africa, Canada, and Australia, we used those data.

To calculate the total monetary loss from housing we need the total value of all dwellings around the airports. We gathered data for the number of owner-occupied and renter-occupied housing units in each country. For locations where we have population data at a finer resolution than housing data we applied the ratio of housing units per person in the larger geographic area to the population data to estimate the number of housing units at the finer resolution. Additionally, not all housing data was divided into owner-occupied and renter-occupied units. For areas where this data did not exist, we applied the average ratio of owner-occupied units to renter-occupied units for all the airports for which we had data, which came to a ratio of approximately 3/2, and assumed that all tabulated dwellings for which tenure was not known were either owner-occupied or renter-occupied.

We currently have detailed housing value data only for the United States and England. The US data is from the 2000 census, which provides the aggregate value of owner-occupied houses and the aggregate rent paid for renter-occupied dwellings in each block-group. We use the OFHEO's [OFHEO 2008] distribution of housing price growth for metropolitan statistical areas from 2000 to 2006 to convert the prices to 2006 levels. We assume that rent prices increased at the same rate. The England population data is from the 2001 census and the housing price data is for postcode sectors in 2001. We use the housing price indices for London and Manchester from 2001 to 2006 to increase these prices to 2006 levels. Both the UK house values and the UK house price indices were obtained from the UK Land Registry.

3.2.3 House Price and Rent Models

For countries where we do not have detailed house price or rent we must estimate the variation in these values with models developed by the firm ICF International based on data around US airports. The company developed a model to estimate the house price at a given distance from an airport and a model to estimate the rent at a given distance based on the house price at the same location. Each of these models, however, requires the average respective value, either house price or rent, for the entire city in which the airport is located. Even these values, though, are not available for many locations. Therefore, we also developed models to estimate the average house price and rent for an entire city. Each of these 4 models is described in greater detail in the remainder of this section.

The house price model estimates variations in house prices with distance from an airport. The model starts with the average house price in the area in which the airport is located, which takes the form of a coefficient for a dummy variable in the case of the US airports, and estimates the price as a function of distance using the population density, per capita GDP, and the number of passengers that use the airport in a year as additional parameters. The resulting equation is of the form:

$$\begin{aligned}\ln(P) = c_0 + c_1 \cdot \text{distance} + c_2 \cdot \text{distance}^2 + c_3 \cdot \text{pop\_density} + c_4 \cdot \text{gdp\_pcap} \\ + c_5 \cdot \text{passengers} + c_6 \cdot \text{dummy}_1 + \ldots + c_{n+5} \cdot \text{dummy}_n\end{aligned} \tag{11}$$

where: P = house price in dollars

distance = distance between the point and the airport in miles

gpd_pcap = GDP per capita in thousands of dollars

passengers = the airport's number of enplaned passengers in a year in thousands

dummy_i = dummy variable for airport i

c_i = a coefficient

The model was created using average house prices around US airports, and the results, excluding the dummy variables for US airports, are shown in Table 4. When the model is applied to a foreign airport, a local constant is used in place of the constant, c_0, and the coefficient of the dummy variable derived from the US airports. To calculate this constant, equation (11) is solved for c_0 using the city's average house price for P and 20.3 miles for the distance. The value 20.3 mi is the average distance for which the average house price was obtained with the regression equation for several US cities.

Table 4: Results of Housing Price Model

Variable	Coefficient	t-statistic	95% Confidence Interval
Constant	11.4817000	791.56	11.45327 - 11.51013
Distance	0.0265700	28.73	0.02476 - 0.02839
Distance squared	-0.0006708	-19.88	-0.00073691 - -0.00060466
Population density	0.0000037	22.53	0.00000338 - 0.00000403
GDP per capita	0.0005854	2.26	0.00007877 - 0.00109
Passengers	0.0000101	27.65	0.00000938 - 0.00001082
No. of obs.	170,020		
R-squared	0.4177		
Adjusted R-squared	0.4169		

The housing price model was developed with US data, and UK airports were the only foreign locations where we had detailed house price data. Therefore, we could test the model against the housing prices around only Heathrow, Gatwick, and Manchester airports. We compared the estimated values to the 2001 average sales price by postcode sector for all the areas within 25 miles of the airport. Hundreds of postcode sectors lie within that distance, so we also averaged the prices of all the areas within each 0.5 mi or 0.75 mil band from the airport to create a cleaner trend of prices to compare to the model. Figure 13, Figure 14, and Figure 15 show these values for the three airports. The estimated prices around Heathrow and Gatwick were within 47% of the actual 0.5-mi or 0.75-mi averaged prices. The model estimated the prices near Manchester airport more poorly, differing from the 0.75-mi averaged prices by up to 70%.

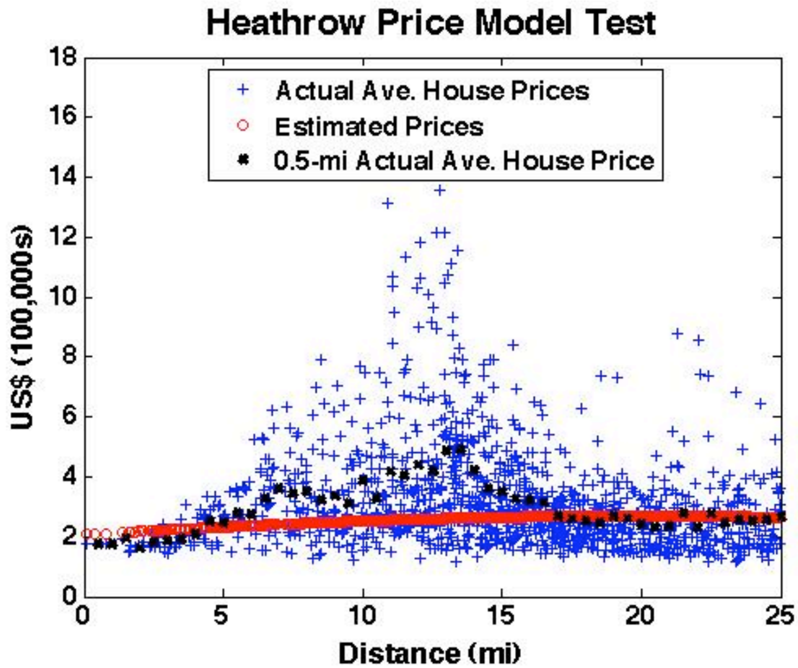


Figure 13: House Price Model Test around Heathrow

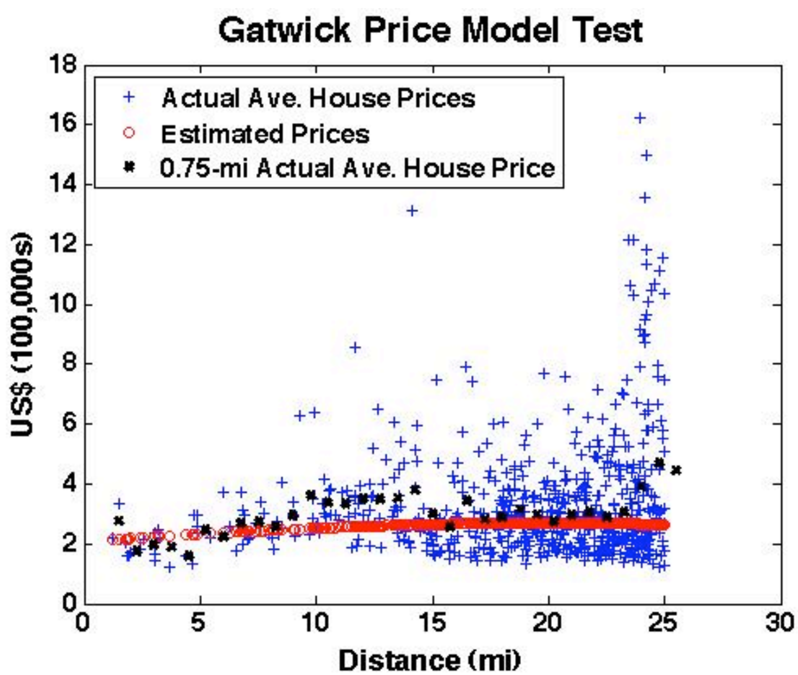


Figure 14: House Price Model Test around Gatwick

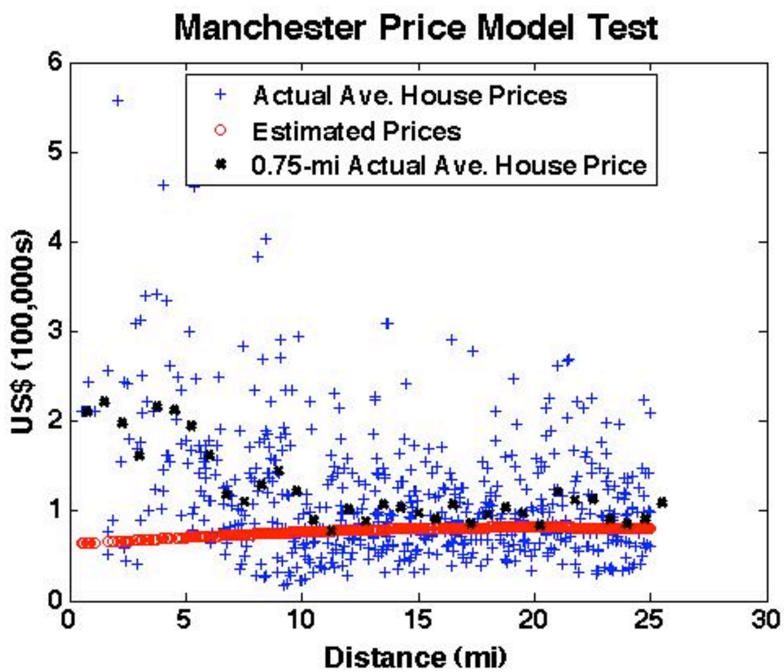


Figure 15: House Price Model Test around Manchester

As part of the Noise Module's analysis we also measure the impact on rental prices. For most of the world, detailed rent data was not available. Thus, with the help of ICF International we also developed a regression for estimating the average monthly rental price at a given location as a function of the average house price at that location with the equation for rent, R:

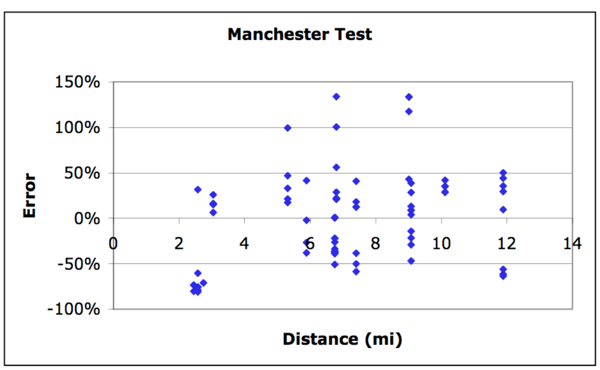
$$R = c_0 + c_H \cdot House\_price + c_1 \cdot dummy_1 + ...c_n \cdot dummy_n \quad (12)$$

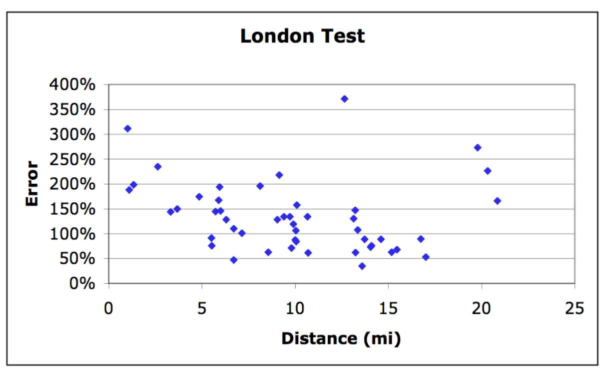
Table 5 shows the results of this regression for the US data on which it was based. The variables named d_JFK, d_LGA, etc., are the coefficients dummy variables for the given airport. When it is applied to foreign airports, a local constant is derived to replace the constant and dummy variable coefficients shown in the table. The local constant is calculated by solving the equation for c_0 with House_price replaced by e raised to the local constant from the house price equation.

Table 5: Results of the rent price regression

Variable	Coefficient	95% Confidence Interval
c_H	0.00116	0.00115 - 0.00116
c_0	407.052	404.25802 - 409.84625
d_JFK	55.522	50.02020 - 61.02341
d_LGA	71.190	65.87979 - 76.50052
d_LAX	54.328	47.54025 - 61.11519
d_SFO	145.009	134.78770 - 155.22940
d_BOS	28.161	18.56037 - 37.76242
d_PHX	81.502	70.30788 - 92.69609
d_DAY	-128.306	-145.11223 - -111.49888
d_DET	-26.658	-35.66507 - -17.65123
Adjusted R^2	0.430	

We could not obtain detailed rent data around any foreign airports, so to test the rent model we and IC Consulting gathered individual asking rents for approximately 50-150 apartments at various locations near 6 different airports (London; Manchester, UK; Sydney; Melbourne; Mumbai; and Singapore). The errors for the estimated rents are shown in Figure 16, and the average error for each city is given in Table 6. The individual errors, at least, are exaggerated due to the limited number of apartments used and due to the fact that individual apartments are used. This model is meant to estimate rents in locations where little to no housing data is available, so it relies on distance and the local house prices, which for many of these cities will also be an estimate based on distance and a few large-area or airport statistics. The size and other traits of individual apartments will make their prices vary significantly at a given location. Figure 17 shows the error of the estimated rent in comparison to the average of the actual rents in each 1-mi distance band from the airport.





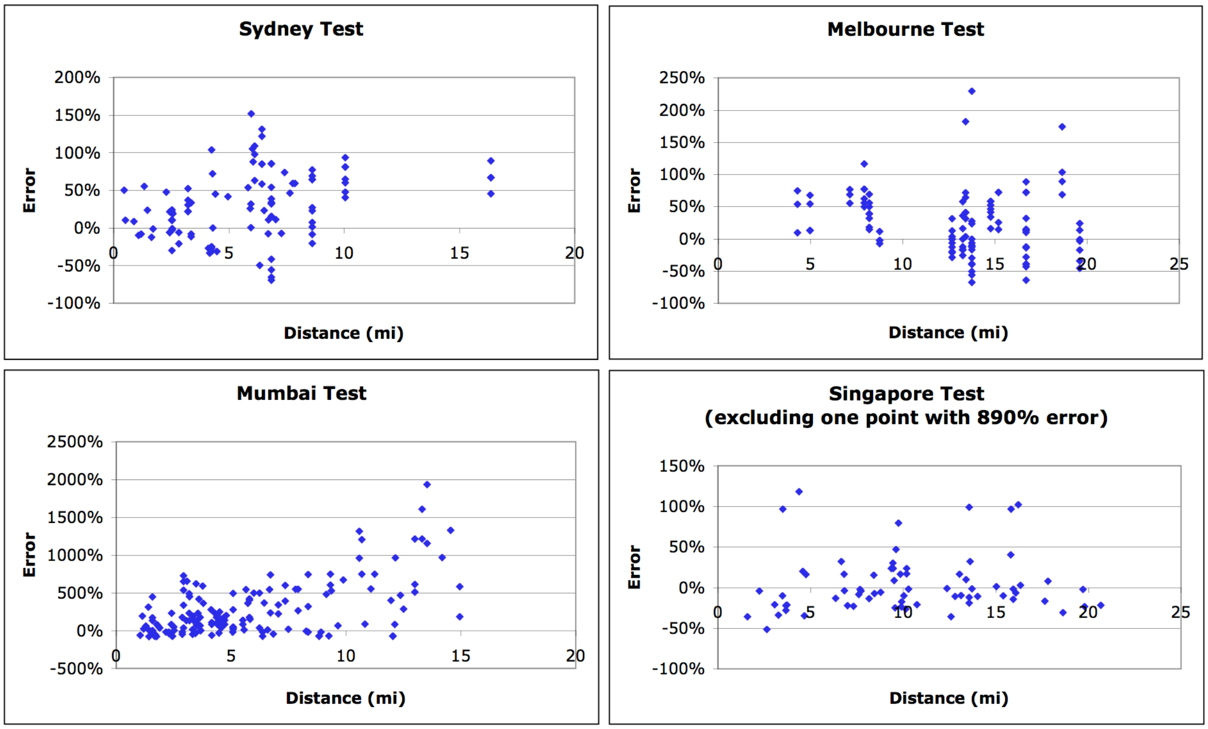


Figure 16: Rent Model Tests

Table 6: Rent Model Errors

City	Average Error
Manchester	3%
London	134%
Sydney	31%
Melbourne	24%
Mumbai	287%
Singapore	17%

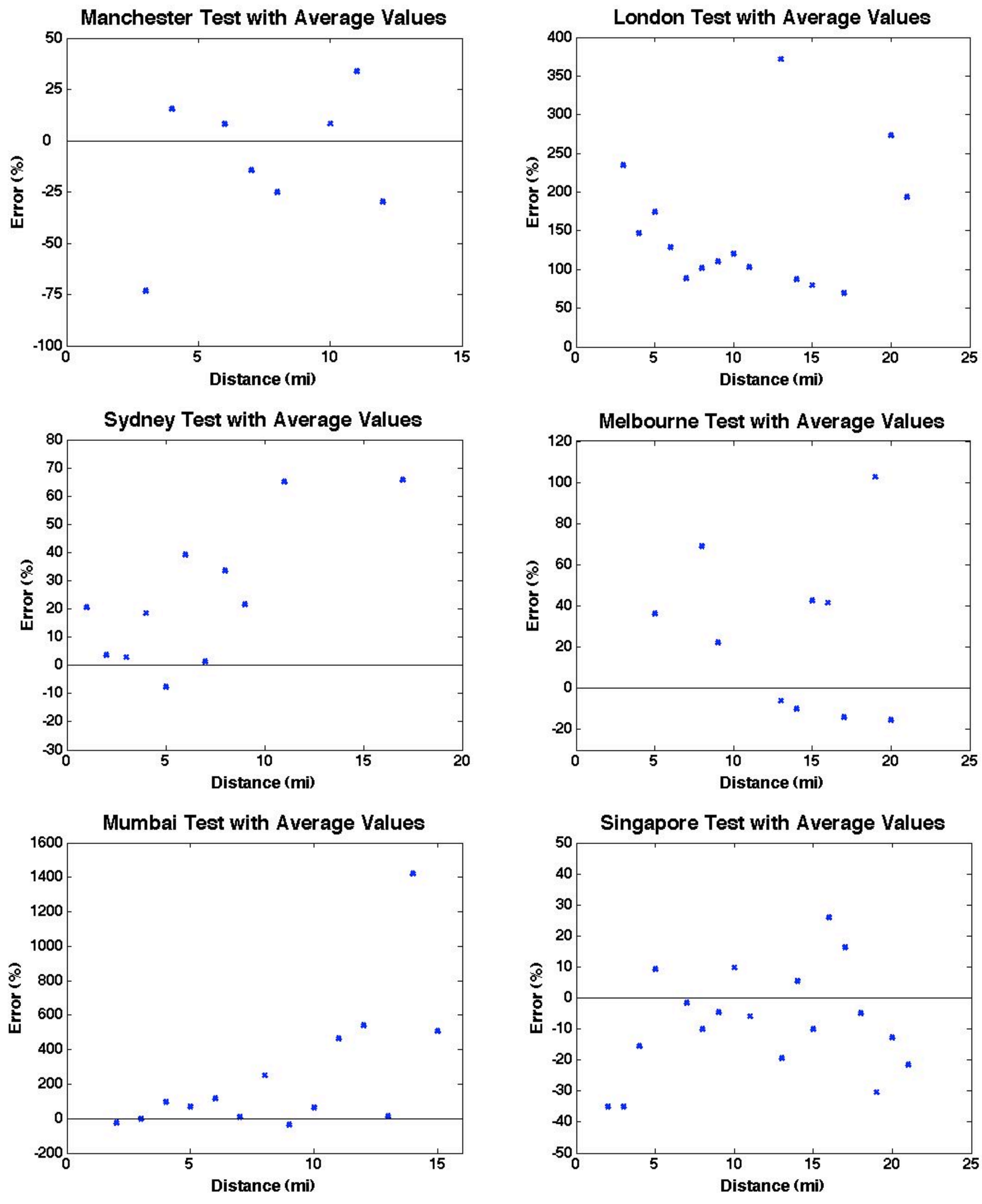


Figure 17: Rent Model Errors using Averaged Rents

Average house prices or rents were not available for many of the cities in our database. We obtained average house values for 20 cities from various sources, mainly news stories, and the average rent for 34 cities from a UBS report [UBS 2006]. Values in other cities, therefore, had to be estimated. Based on the medium, unfurnished 3-room rent provided by UBS we developed a model to estimate rents using the lodging per diems provided by the US State Department to civilian employees traveling abroad as well as the country's GDP per capita in terms of purchasing power parity and average income. The resulting equation is:

$$\ln(R) = c_0 + c_1 \cdot Lodge\_rate + c_2 \cdot GDP\_per\_cap + c_3 \cdot Average\_income \quad (13)$$

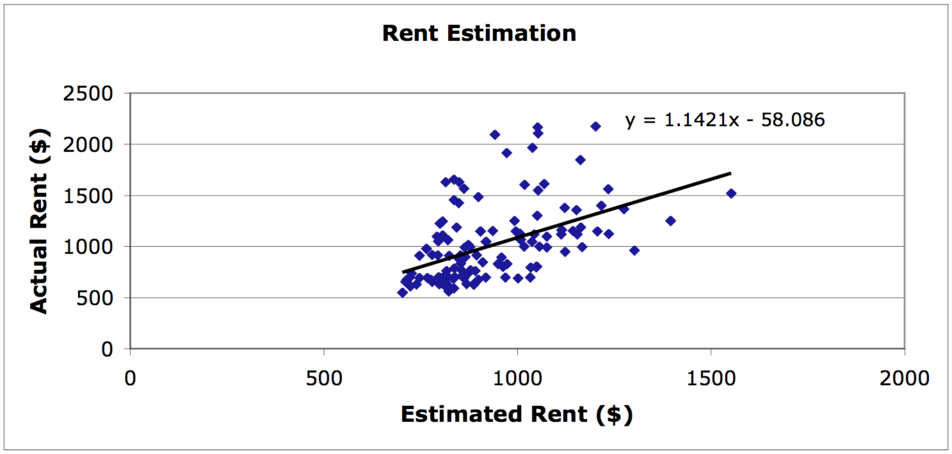
where: R = average rent
c_i is a constant

The values of the constants and their significance are shown in Table 7.

Table 7: Average Rent Estimation Coefficients

Coefficient	Value	p-value
c_0	5.74	< 0.0001
c_1	0.00459	< 0.0001
c_2	1.65E-05	< 0.0001
c_3	7.84E-08	0.001
Adjusted R^2	0.50	

We tested the regression with the average rents in several US metropolitan statistical areas using the 2000 median rent for 2-bedroom apartments from the census provided by HUD [HUD 2005] converted to year 2006 values using the housing price index change of the corresponding area from 2000 to 2006, which is the method that HUD uses for estimating rents. Figure 18 shows the results of this test. The ordered change in the error indicates that the regression is failing to account for some factor; however, the scarcity of more local data makes improving the regression difficult. Additionally, the US rental market may be peculiar with respect to the global average market or the U.S. General Services Administration, which sets the domestic per diem rates, may determine those rates differently than the way that foreign rates are determined.



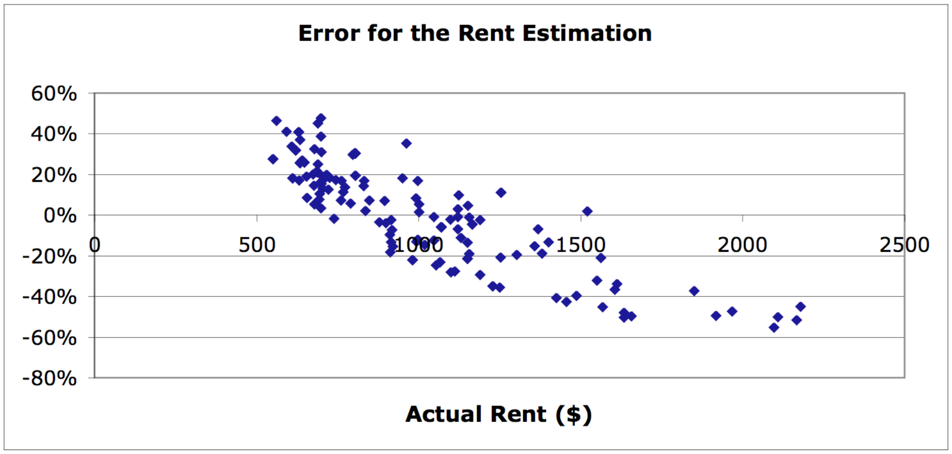
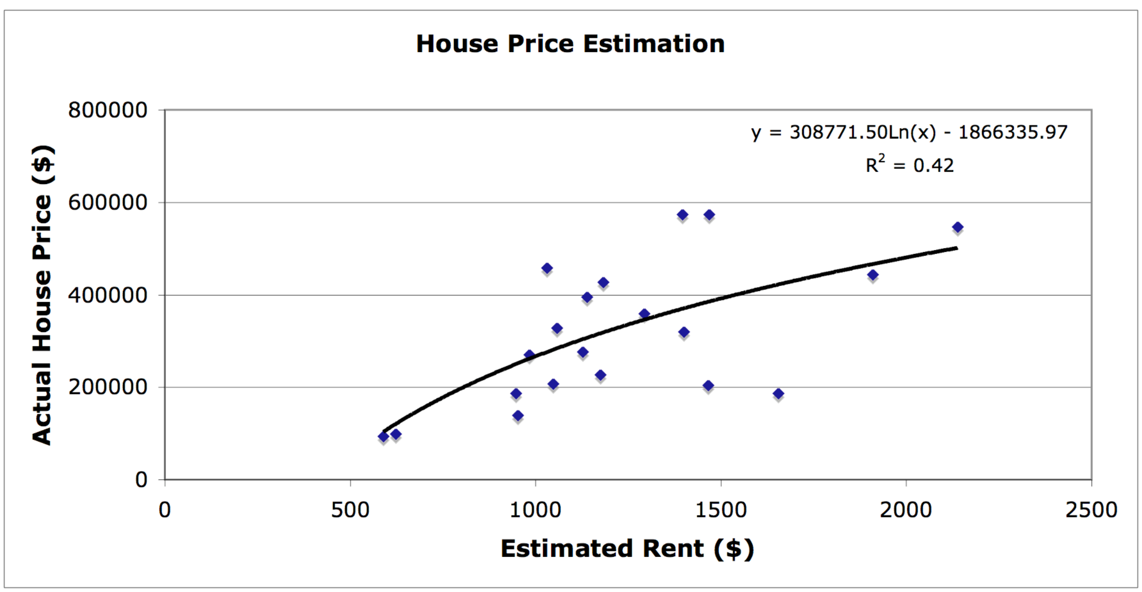


Figure 18: Rent Estimate Test Results

With the estimated rents we then created a regression to estimate the average house price in each city using the prices we obtained for 20 foreign cities. The data, shown in Figure 19, shows significant scatter, but we used a logarithmic fit because it provides a slightly better fit and it produces very similar results to the linear fit except at very low rents, where the linear fit overestimates the two data points at $590 and $620 by approximately 50%. Several airports, most notably Manila and Tehran, have low estimated rents and large exposed populations that could lead to significant overestimates of the noise impact if the house values are overestimated by similar amounts as the data points used in the regression. Furthermore, the lowest estimated rent was $535, so we did not have to worry about extremely low or even negative house prices that would result from estimated rents below $500.



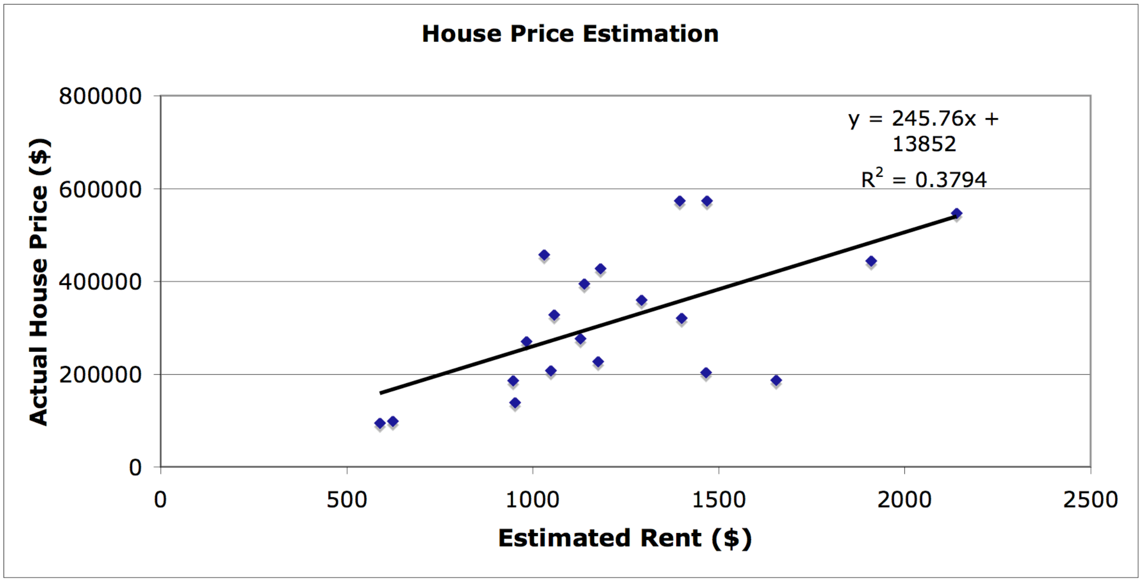


Figure 19: Average House Price Regression

We tested the regression equation on US data. We applied the average house price equation to the average rent in US metropolitan regions from the 2000 Census converted to 2006 US$. We compared the calculated average house price to the actual average house price for the same region. The error is again skewed slightly, and overall underestimates the average house prices, as shown in Figure 20. A factor may well be missing in the regression, therefore, but the extent to which peculiarities in the US housing market explain the error is unknown.

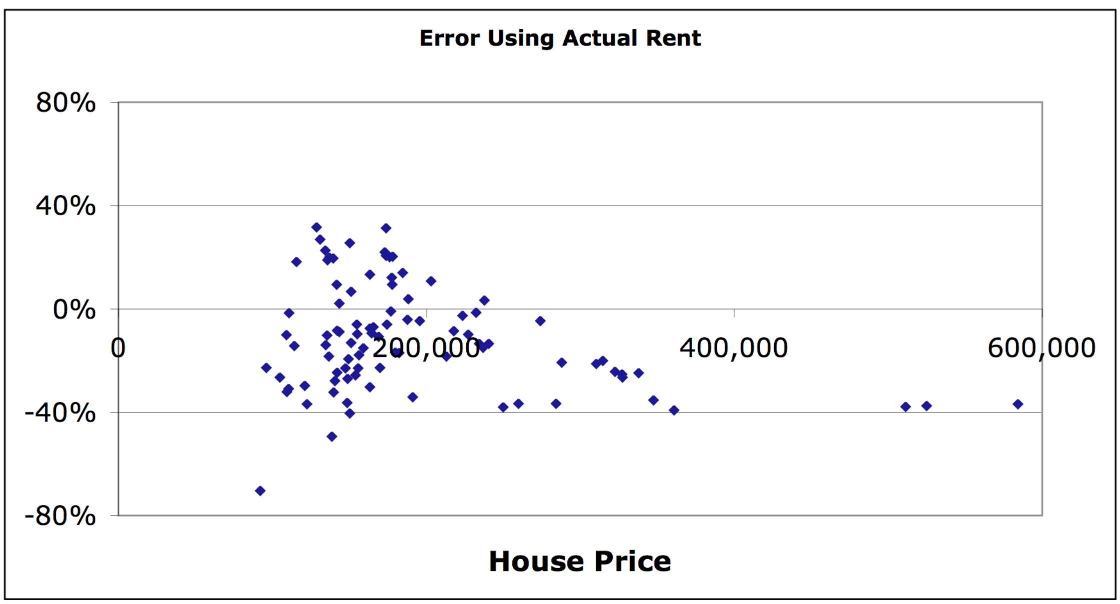


Figure 20: House Price Regression Test with US Data

3.3 Monte Carlo Method

The factors in the equation for future housing loss all have uncertainties associated with them. These uncertainties will propagate through the calculation and create uncertainty in the output. The NPV calculation is non-linear and the uncertainty distributions of the model factors are of several different types. Therefore, we perform Monte Carlo simulations (MCS) to determine the distribution of the output. For each MCS we make thousands of runs in which each model factor is given a random value from its distribution and the resulting NPV is calculated. The MCS, therefore, results in thousands of individual NPV calculations, which together estimate the total distribution of the NPV that results from the uncertainties in the model factors.

3.3.1 Inputs & Model Factors and Their Uncertainties

The APMT Noise Module includes a total of 2 inputs and 6 model factors. The values and other characteristics of these inputs and model factors are summarized in Table 8. The two inputs are the noise contours from INM and housing capital data from the US Census Bureau. The inputs currently have no uncertainty distributions from their source, but one of the model factors is a distribution that we apply to the noise contours as an uncertainty. Of the 6 model factors 3 have uncertainty distributions. Two other model factors, the discount rate and the level of significance, are sets of discrete values because they are the result of value judgments rather than values that cannot be exactly determined for reasons of scientific uncertainty or a lack of predictability. The level of significance is unique because it does not affect the value of the computed noise impact. Instead, it determines which of the computed noise impacts are significant and will be included in the reported NPV output.

Table 8: Module inputs and model factors

	Source	Approach to Uncertainty	Values
Model Inputs			
Noise Contours	INM		
Population & Housing Data	Various sources		
Model Factors			
Discount Rate	User specified	Discrete values	3%, 7% by default
Housing Growth Rate	OFHEO, UK Land Registry	No uncertainty used	Historical distribution of housing price increases, housing price indices
Quiet Level	User specified	Triangular distribution	50 dB to 55 dB with a mean value of 52.5 dB
Noise Contour Uncertainty	User specified	Triangular distribution	-2 to 2 dB with a mean value of 0 dB
NDI	Nelson (2004)	Variation about the mean as developed by Nelson (2004)	Mean value of 0.006651 and a standard deviation of 0.0010423
Significance Level	User Specified	No Uncertainty	Quiet level, 60 dB, 65 dB by default

These uncertainties arise for various reasons. For relatively short periods, such as those used in this analysis, the discount rate is uncertain because of the imperfect knowledge of future economic conditions. The quiet level, NDI, and noise contours have scientific uncertainties due to measuring or modeling difficulties. The noise contours generated for the future also have uncertainty due to the fact that they predict future scenarios. The model factors and their distributions are further described in the sections that follow, except for the significance level, which was not used in this study, and the discount rate.

3.3.1.1 Quiet Level

The quiet level, which is the noise level below which aviation noise is defined to have no effect on housing prices, is implemented as a triangular distribution between 50dB and 55dB. This range for the quiet level is fairly common in noise cost-benefit analyses. Navrud [Navrud 2002] recommends a DENL level of 50 dB for aircraft noise. He notes that people are annoyed at noise levels below this value; however, few studies provide estimates of the economic value of the annoyance at lower levels. His report also cites numerous studies that use quiet levels of either 50 or 55 dB. Lambert [Lambert 2005] reports that Germany, France, the Netherlands, and Switzerland have recommended or official valuations of noise that use 55 dB as a cut off during the day and Sweden has a cut off of 50 dB. Furthermore, the typical background noise in an urban area is approximately 50-60dB during the day and 40dB at night [Nelson 2004] (i.e. 50 dBA at night accounting for the night penalty included in the DNL calculation). Most US and international regulatory bodies also recommend DNL values of 55 dB or lower as the onset of impact. The US EPA recommends a 55 dB DNL for the "level requisite to protect health and welfare with an adequate margin of safety" [EPA 1974]. The National Research Council Committee on Hearing, Bioacoustics and Biomechanics similarly sets DNL 55 dB for the level of noise impact and sets further requirements for certain situations for DNL values as low as 40 dB. The ANSI also uses DNL 55 dB for housing and other noise sensitive land uses [Schomer 2001]. The WHO recommends L_{eq} values of 55 dB to prevent "serious annoyance" and L_{eq} of 50 dB to prevent annoyance [WHO 1999]. A few US federal agencies, however, use a DNL value of 65 dB instead. These agencies are the FAA, DOD, and HUD, which use 65 dB instead [Schomer 2001].

3.3.1.2 NDI

The noise depreciation index (NDI) is the percentage decrease in housing value for each decibel increase in the noise level. The uncertainty in the NDI is implemented as a normal distribution with a mean value of 0.6651 and a standard deviation of 0.10423. This uncertainty was derived using the regression presented in Nelson [Nelson 2004]. The concept of NDI and the choice of Nelson's regression is discussed further in section 2.4.

3.3.1.3 Contour Uncertainty

The noise contours from MAGENTA are fixed values, so we add a contour uncertainty to these values in order to take into account the uncertainty associated with them. Assessment of the uncertainty in the MAGENTA contours has not been completed. Therefore, we currently assume all the INM contours have an uncertainty with a triangular distribution between +/- 2dB with 0 dB as its mean as an estimate. This value is relatively arbitrary, and will be updated once a greater understanding of the contour uncertainty is developed through the AEDT assessment activities. Currently, the MAGENTA capabilities allow us to apply an uncertainty only to the level of the noise and not the area of the contours themselves. A previous study showed that a relatively small change in contour area can create a large increase in the monetary value of the impact [Tam et al. 2007], so the methods for calculating the contours are currently being updated to provide the ability to scale the area of the contours.

3.3.1.4 Housing Value Growth Rates

The US housing data, which serves as an input to the noise module, is from the year 2000. The housing values in future years are needed in order to calculate the noise impact in those years. Therefore, a housing growth rate must be used to project the 2000 data to future years. In this test we used 2006 house prices, so we calculated the average change in prices between those years for 381 Metropolitan Statistical Areas (MSA) in the US as compiled by the Office of

Federal Housing Enterprise Oversight [OFHEO 2008]. Since the housing price indices that the OFHEO create are based on actual transactions, we do not assume any uncertainty in the distribution. Instead, we use the distribution of values for the 381 MSAs and randomly assign a value to each US airport in each Monte Carlo run. The range of this distribution is from 1.7% to 18.2% increase per year and the mean value is 7.6% increase per year.

The UK is the only other country for which we do not estimate house prices. We obtained average prices for postcode sectors in 2001 and changed the prices to 2006 levels using the house price indices for the respective city given by the UK Land Registry between the years 2001 and 2006.

For all other countries, we estimated prices for the year 2006. When we assessed future impacts we did not change prices for any countries beyond the 2006 values, so these countries did not require any growth rates.

4 Results

We estimated the impact of aviation noise at 181 airports. We measured the impact using 4 different metrics: (1) owner-occupied housing value depreciation, (2) rent loss, (3) number of people exposed to at least 55 dB, and (4) the number of people highly annoyed (HA). The summary results are shown in Table 9. The uncertainty for the number of people highly annoyed presented here and in Chapter 5 underestimate the actual uncertainty because they account only for the uncertainty due to noise levels, and not the uncertainty in the exposure-response function itself. Miedema & Oudshoorn's paper [Miedema & Oudshoorn 2001] does not provide quantitative estimates of the curve's confidence intervals with which to assess the impact's uncertainty. Similarly, the uncertainties in the monetary impacts are underestimated due to the fact that reliable quantification of the uncertainty from using the various price and rent models does not exist.

The area exposed to 55 dB or more around each airport was on average 56.6 km^2 but ranged from 1.78 km^2 to a maximum of 236 km^2. Figure 21 shows the distribution of areas covered by each airport's contour of 55 dB and Figure 22 shows the distribution the 65-dB contour areas.

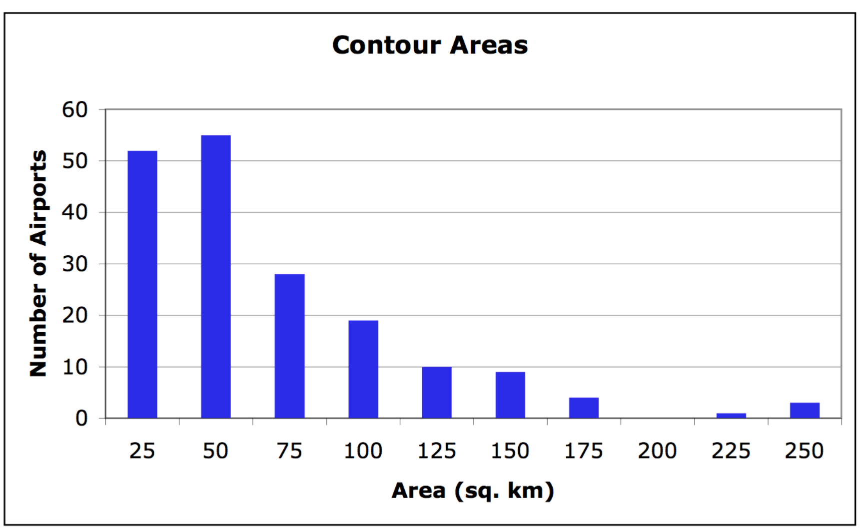


Figure 21: Histogram of 55 dB Contour Areas

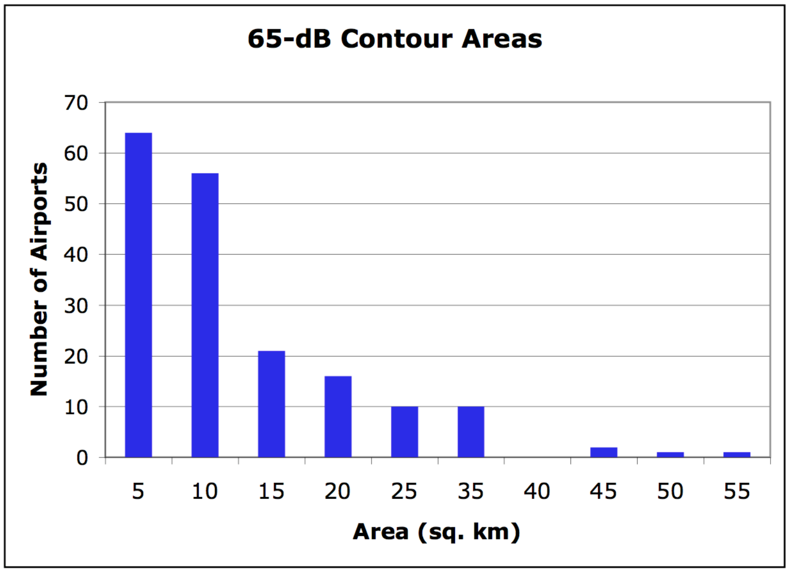


Figure 22: Histogram of 65-dB Contour Areas

The housing value depreciation is approximately 26 times as great as the lost rent (assuming the same NDI for rent and housing value). Rental loss, however, is a recurring, yearly stream while the housing value loss is a one-time occurrence, although its magnitude can change if the noise level changes in the future. To compare these values, therefore, the housing value depreciation must be amortized to an annual amount. Table 10 shows these annualized amounts for various 30-year, real discount rates. The 2.8% rate is the 2008 real interest rate on Treasury notes and bonds according to the Office of Management and Budget [Office of Budget and Management 2008]. The 3% and 7% rates are the OMB's recommended values for cost-benefit analyses [Office of Management and Budget 2003]. These values show that the loss in value of owner-occupied houses is about 60-70% of the total monetary value of the noise impact, which corresponds with the fact that 60% of the housing around the foreign airports where tenancy is known are owner-occupied.

Table 9: Global Noise Impact

Metric	Mean Impact (Millions of $ or People)	Standard Deviation (Million $ or People)
Housing Value Depreciation	$21,000	$1,100
Rent Loss	$800	$41
Population Exposed to 55 dB	14	N/A
Number of People HA	2.3	0.03

Table 10: Annualized Housing Value Depreciation

Discount Rate	Annual Value of Housing Value Depreciation (Million $)
2.8%	1,060
3%	1,090
7%	1,720

The owner-occupied housing value loss for individual airports ranged from a non-zero minimum of $267,000 to a maximum of $1.6 billion. The 95 US airports accounted for $5.88 billion or 27% of the owner-occupied housing value loss.

The reduction in total rent had a similarly large spread. The maximum amount totaled $83 million per year, while the minimum was only $2,700. The rental loss around US airports was $269 million or 34% of the total.

Due to the relatively coarse resolution of the GRUMP population data (grids with sides of length 30 arc-second) and to the fact that housing prices had to be estimated for much of the world, the exact ranking of the airports may be incorrect. Additionally, if inside each geographic area for which the population is correctly known people tend to live in the quietest parts, then our calculations would, everything else held constant, overestimate the total impact. For example, satellite images indicate that a significant portion of the land directly surrounding LED airport in St. Petersburg does not contain housing, meaning the monetary and physical impacts are likely smaller than those calculated. At the same time, however, given that the official population for, in this case, rayons is known, the populated areas the contours cover must be more densely populated than the values that GRUMP gives for those points. This difference would lead to underestimates of the impact in those locations, which would somewhat make up for overestimates in other areas.

The maximum population exposed to 55 dB was 1.2 million people while the minimum was 45 people. The 1.2 million people exposed, which occurred for a foreign airport, corresponds to over a quarter of the people exposed to 55 dB of noise from commercial aviation around all 95 US airports.

4.1 Impact Metric Correlations

The metrics of impact at each airport are all relatively highly correlated. The exposed and highly annoyed populations are the most closely related impacts with a correlation coefficient of 0.99. All other pairs of impacts had correlation coefficients between 0.59 and 0.7. Various elements that enter into the impact calculations reduce the relation between the metrics. The housing value and rent losses vary from the number of people exposed because they depend not only on the number of people exposed and noise levels but also the number of people in each dwelling, the housing prices, and the ratio of owner-occupied and renter-occupied dwellings. Thus, around one airport about 1.2 million people experienced 55 dB of noise, but the airport caused approximately half the housing value and rent loss of a second airport, which exposed only 380,000 people. The rent and housing value loss can, to a certain extent move in opposite directions, since changing the percent of dwellings that are owner-occupied or rented increases the value of one metric and reduces the other. The populations that are exposed and annoyed are much more closely related because they depend only on the population densities within and relative sizes of the various noise contours.

4.2 Model Assessment

To test the effects of each uncertain model factor's distribution on the value of the outputs we have conducted a local sensitivity analysis. In this analysis all the model parameters took values from their full probability distributions except for one parameter, which took first its lowest value and then its highest value. The NPV result from each of those cases was then compared to the case in which all the parameters vary, which is the nominal case of the results presented in Figure 23 and Table 11. With the given uncertainty distributions the contour uncertainty has the most significant effect on the mean of the housing value and rent losses by causing approximately a 50% shift in their means, and it has the largest single percent change to the variance with about a 50% reduction.

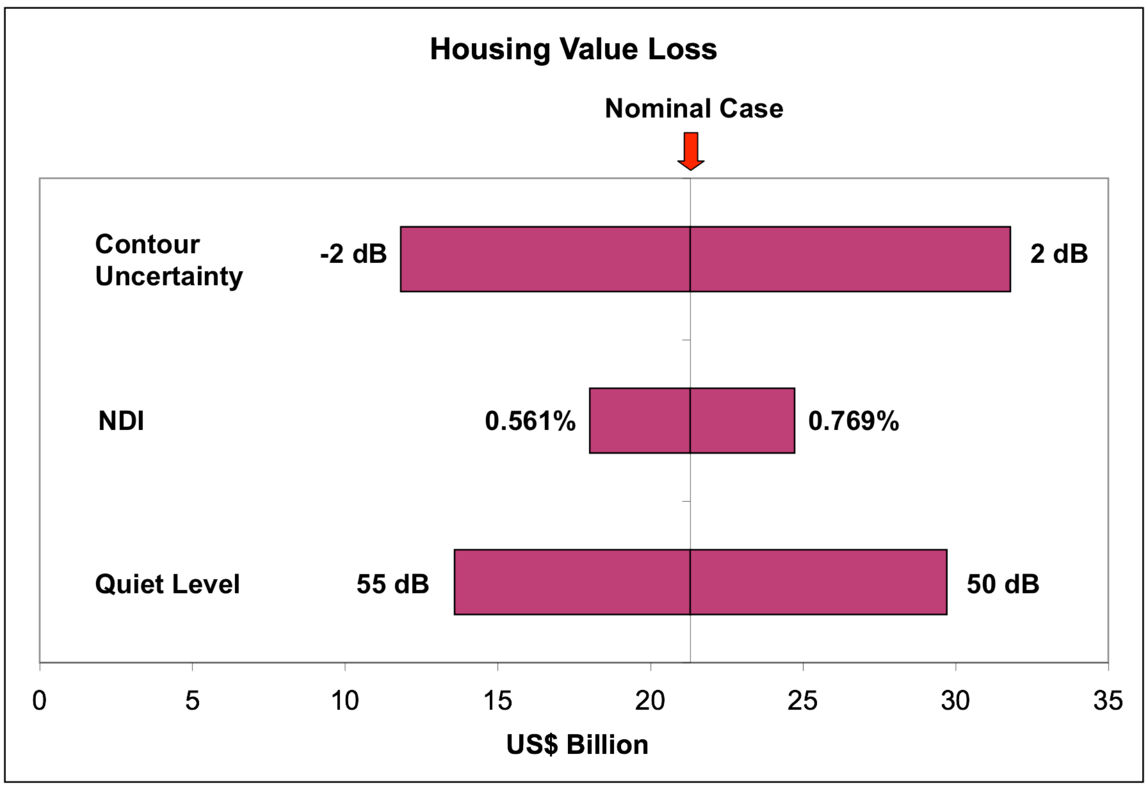


Figure 23: Probabilistic local sensitivity results

Table 11: Local sensitivity results

Model Factor	Value	Housing Value Loss (USB$2006)	% Change in NPV from Nominal Case	% Change in Variance from Nominal Case
	Nominal§	21		
Quiet Level	lower	32	49%	2%
	upper	12	-45%	-50%
Contour Uncertainty	lower	14	-36%	-34%
	upper	30	39%	5%
NDI	lower	18	-16%	-29%
	upper	25	16%	-3%

Model Factor	Value	Rent Loss (USM$2006)	% Change in NPV from Nominal Case	% Change in Variance from Nominal Case
	Nominal§	800		
Quiet Level	lower	1,200	46%	3%
	upper	450	-43%	-47%
Contour Uncertainty	lower	510	-36%	-33%
	upper	1,100	39%	5%
NDI	lower	670	-16%	-31%
	upper	920	16%	-5%

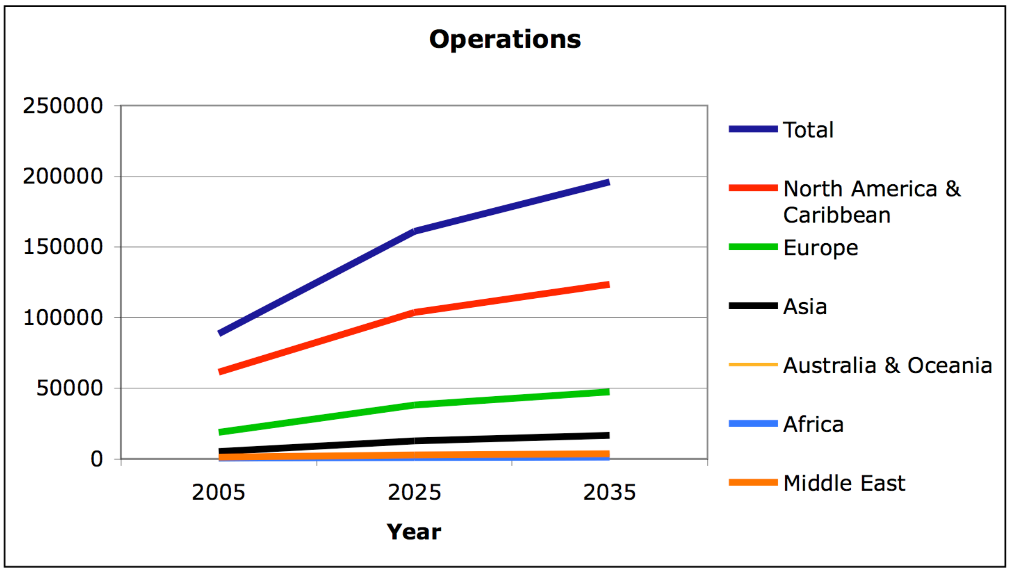
The population exposed to 55 dB is not affected by any of the model parameters because we did not use the contour uncertainty in that calculation for reasons discussed at the beginning of Chapter 3. The contour uncertainty is the only model parameter that changes the value of the number of people highly annoyed, and its effects are shown in Table 12. The change in the variance is not given because once the contour uncertainty is fixed the number of highly annoyed individuals is a single, deterministic value.

Table 12: Effect of Contour Uncertainty on the Number of People Highly Annoyed

Model Factor	Value	Number of People Highly Annoyed (Million)	% Change in NPV from Nominal Case
	Nominal§	2.3	
Contour Uncertainty	lower	1.9	-18%
	upper	2.8	20%

5 Possible Future Impacts

We have also estimated future impacts of noise using the commercial aviation growth forecasts developed by the ICAO/CAEP Forecast and Economic Sub-Group (FESG). Future operations are estimated by route group (e.g. domestic North American or between North America and Europe), aircraft seat class, and distance. The FESG growth estimates are calculated up to the year 2020, but we have extended the growth to 2035 by adding the absolute change in operations from 2015 to 2020 to each 5-year period from 2020 to 2035. Contours, however, were created only for the years 2005, 2025, and 2035. The number of operations for each region of the world by place of arrival or departure (i.e. each flight is double-counted, with one location for its departure and one for its arrival) is shown in Figure 24 and their growth rates are shown in Table 13. Overall, the operations grow by over 120% between 2005 and 2035. The biggest growth occurs in Asia with almost a 230% increase, while North America & the Caribbean had the smallest growth at only 100%.



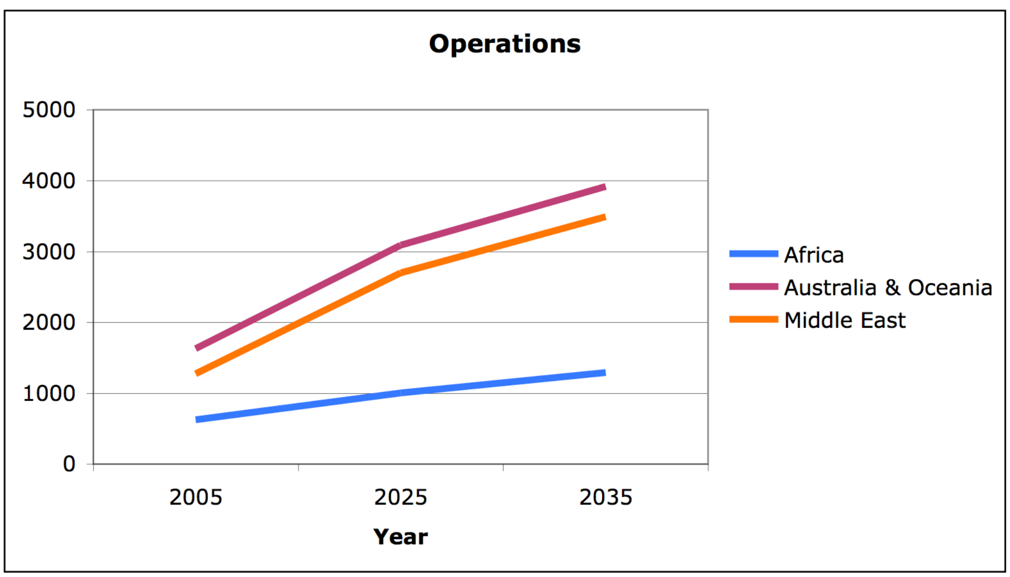


Figure 24: Operations by Region

Table 13: Average Annual Growth in Operations

Region	2005-2025 Annual Growth	2025-2035 Annual Growth	2005-2035 Total Growth
North America & Caribbean	2.7%	1.8%	101%
Europe	3.6%	2.2%	154%
Asia	4.7%	2.8%	230%
Africa	2.4%	2.5%	105%
Australia & Oceania	3.3%	2.4%	141%
Middle East	3.8%	2.6%	173%
Total	**3.0%**	**2.0%**	**122%**

The total global fleet mix (not only those operating at the 181 airports used here) remained relatively similar between 2005 and 2035, but a portion of the fleet shifted from the 100-150 seat-class aircraft to larger aircraft, as shown in Table 14.

Table 14: Global Fleet Mix

Seat Class	Percent of all Aircraft in 2005	Percent of all Aircraft in 2035
20-49	8%	8%
50-99	16%	17%
100-150	38%	19%
151-210	19%	23%
211-300	12%	18%
301-400	5%	8%
401-500	1%	2%
501-600	0%	3%
601-650	0%	3%

The scenario assumes that future aircraft have no technological improvements with respect to their creation of noise. Older aircraft were, however, retired and replaced with more modern planes. The percentage of aircraft that remain in the fleet with each age is shown in Figure 26. Over the past several decades the noise produced by commercial aircraft has decreased by about 20 dB, which is shown in Figure 25 along with the future targets of two recent research efforts. This trend, however, has slowed down in the past 10 to 20 years. Furthermore, greater attention to the effects of aircraft on air quality or the climate may direct efforts away from reducing noise to these other areas.

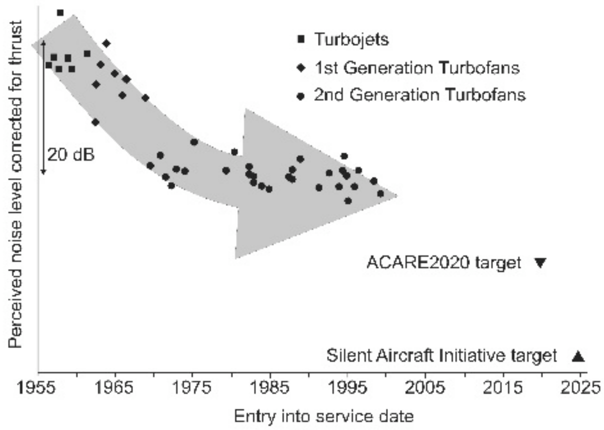


Figure 25: History of Thrust-Corrected Aircraft Noise. Source: [Crichton et al. 2007]

Another assumption of the scenario was that growth was unconstrained and resulting delays were insignificant. Due to these various assumptions the results here are not necessarily a prediction of the future but simply an indication of possible future effects.

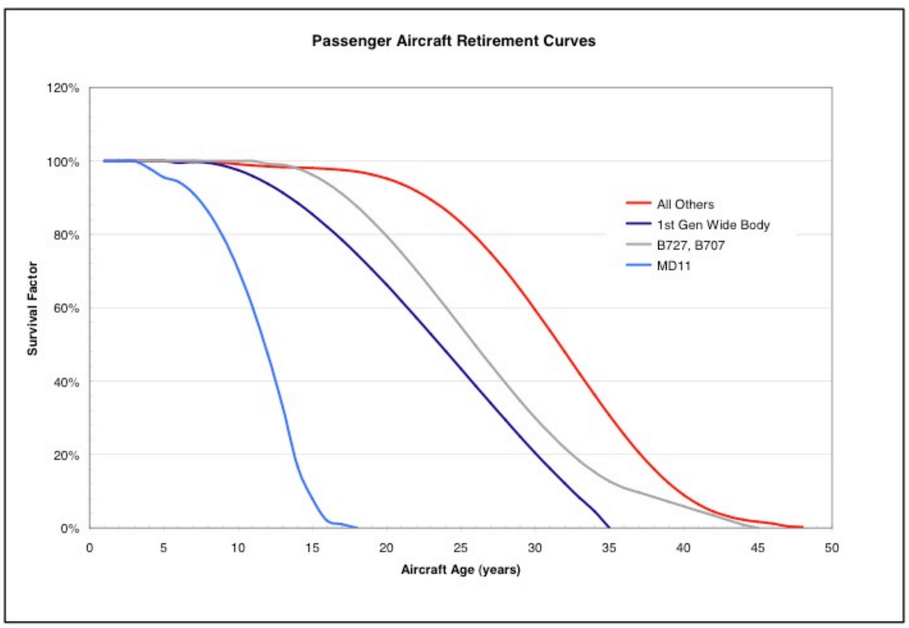


Figure 26: Aircraft Retirement Curves. Source: [CAEP_8_MODTF_3_WP10 2007]

The relative changes in the total contour area in each region between 2005 and 2035, however, are not consistent with the way that the number of operations in each region changes. The Middle East, for example, had the second highest growth in operations but the second lowest increase in contour area. Table 15 shows the change in 55-dB contour area between 2005 and 2035. All the growth rates are less than the increase in operations. One reason for this effect is that as the number of operations increases the effect of an additional operation on the noise level decreases because of the logarithmic relationship between individual noise events and DNL.

Furthermore, the type of aircraft affects how much it adds to noise level. The ranking of the regions' growth differs from the operations as well.

Table 15: 55-dB Contour Area Growth

Region	2005-2035 Total Contour Area Growth
North America & Caribbean	48%
Europe	83%
Asia	103%
Africa	-1%
Australia & Oceania	83%
Middle East	46%
Total	**60%**

For results between the datum years the impacts were interpolated with a cubic spline. Additionally, to isolate the effect of the changes in noise levels on the total impact, all populations and prices were held constant at their beginning level, (i.e. 2000 or 2001 for populations and 2006 for housing prices and rents).

A summary of the results is presented in Table 16 for discount rates of 3% and 7%, which are the OMB's recommended values for cost-benefit analyses [Office of Management and Budget 2003]. The number of people exposed and annoyed is not discounted, however, in the table.

Table 16: Possible Future Impacts

3% Discount Rate:

Metric	Mean Impact (Millions of $ or People-Years)	Standard Deviation (Millions of $ or People-Years)
Housing Value Depreciation	$ 34,000	$1,900
Rent Loss	$24,000	$1,400
Population Exposed to 55 dB	610	N/A
Number of People HA	98	1.2

7% Discount Rate:

Metric	Mean Impact (Millions of $ or People-Years)	Standard Deviation (Millions of $ or People-Years)
Housing Value Depreciation	$30,000	$1,600
Rent Loss	$15,000	$830
Population Exposed to 55 dB	610	N/A
Number of People HA	98	1.2

The discount rate has a significant effect on the monetary impacts, but Figure 27 and Figure 28 show that under this scenario the undiscounted housing value loss would grow by about 90% from 2005 to 2035. The undiscounted rent loss would grow slightly more, about 100%, in the same period.

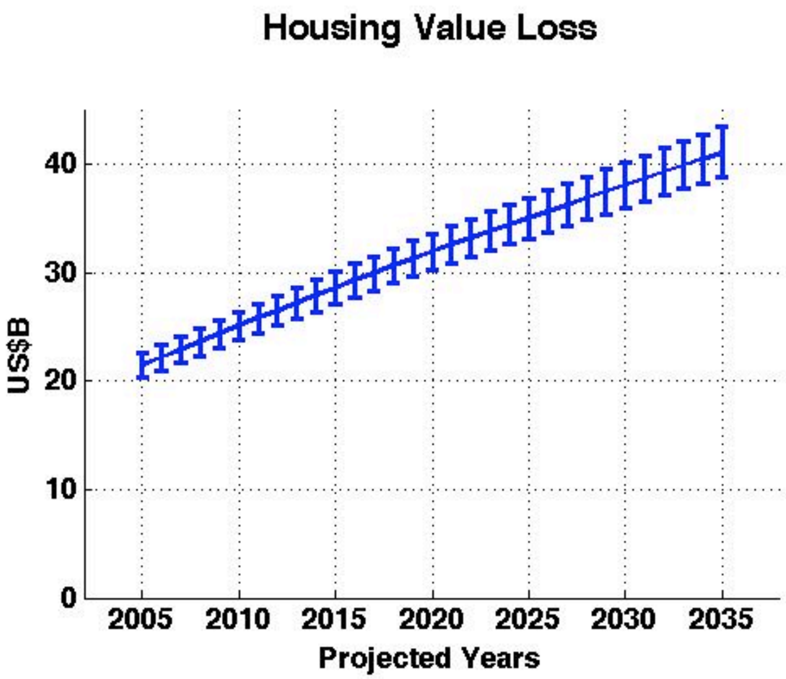


Figure 27: Undiscounted Yearly Housing Value Loss

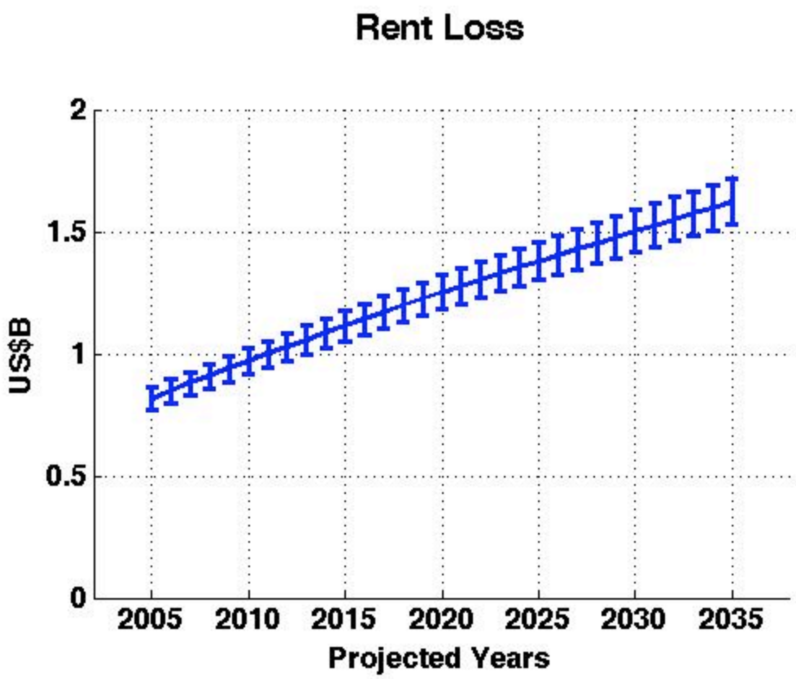


Figure 28: Undiscounted Yearly Rent Loss

The populations exposed and annoyed show a relatively steady growth from 2005 to 2035 similar to the monetary impacts, although at a slower rate, which can be seen in Figure 29 and Figure 30. Due to these trends, the housing value loss and rent loss per person exposed to 55 dB grow slightly throughout the period, about 13% and 18% respectively. The model includes no rent changes, so this difference is due to only dwellings with significantly higher rents becoming exposed, an increase in the number of rented dwellings per person becoming exposed at a given noise level compared to those in 2005, or an increase in the number of rented dwellings exposed to higher noise levels compared to those in lower noise levels.

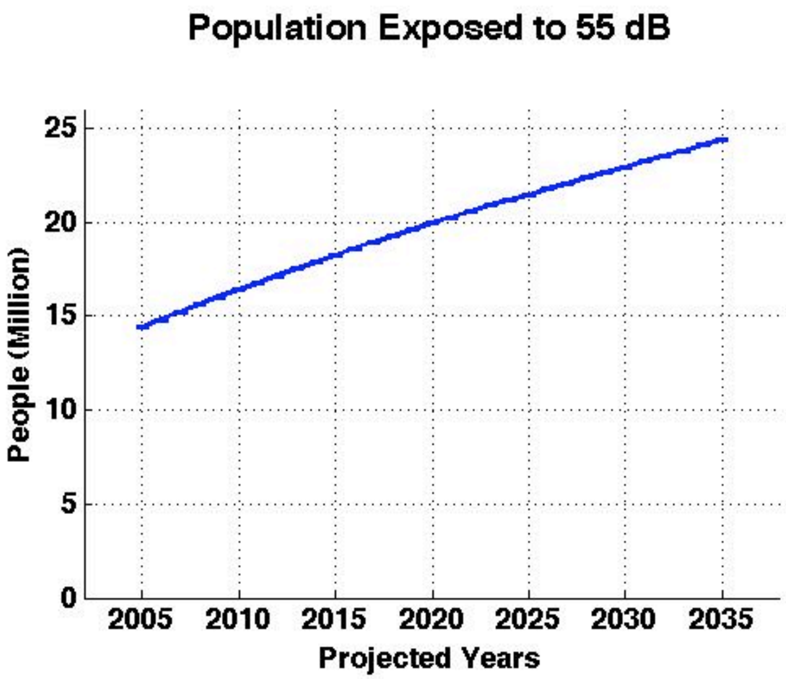


Figure 29: Undiscounted Exposed Population

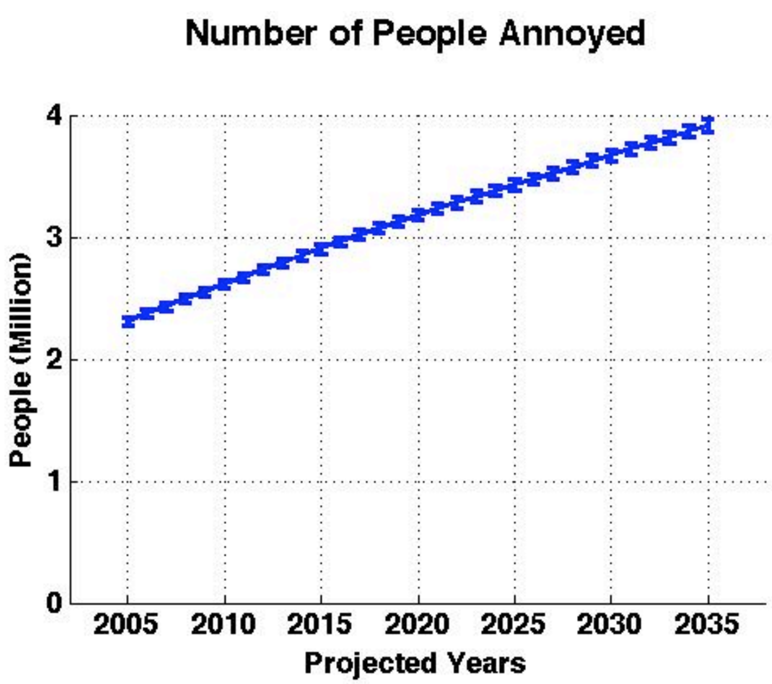


Figure 30: Undiscounted Population Highly Annoyed

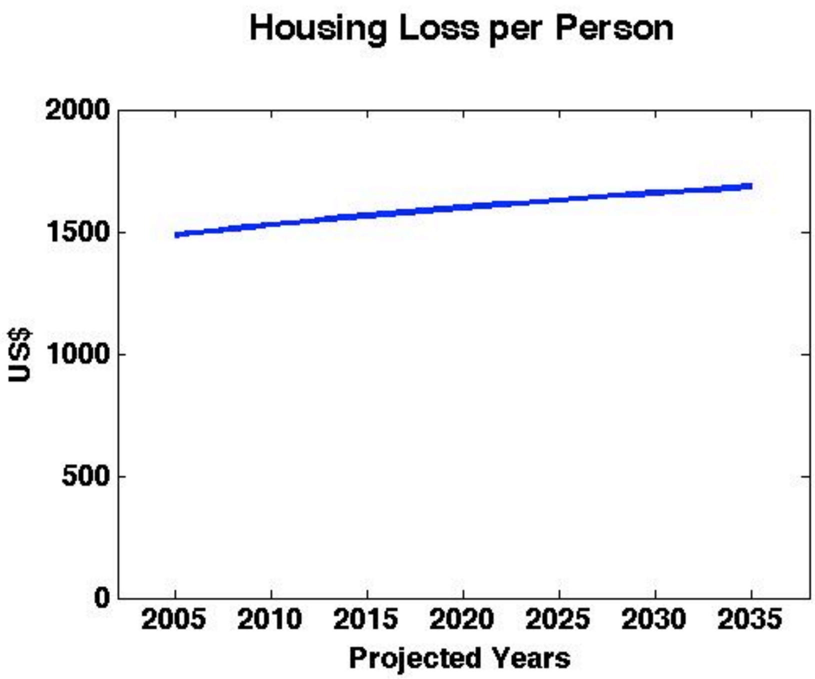


Figure 31: Housing Value Loss per Person Exposed to 55 dB

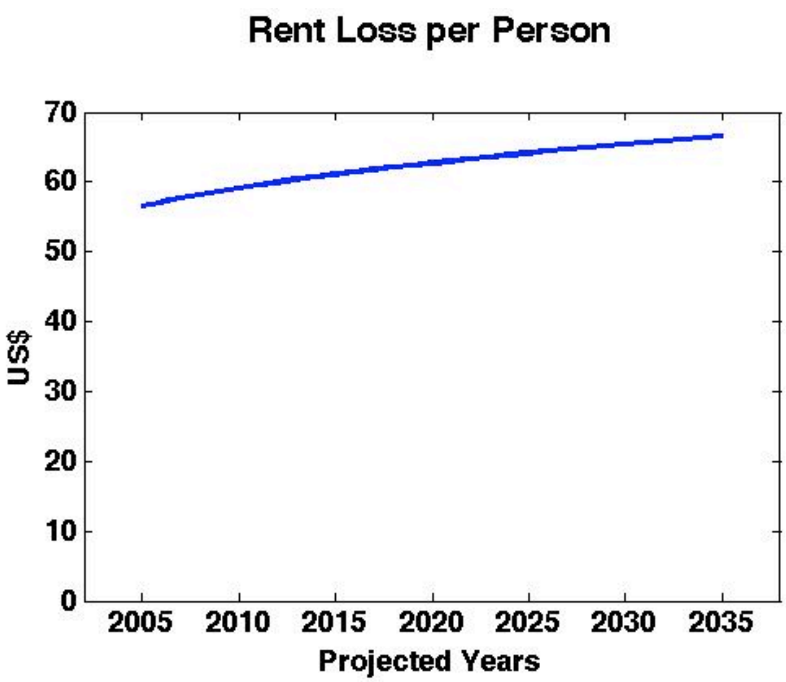


Figure 32: Rent Loss per Person Exposed to 55 dB

The regional changes in impacts were mixed and did not conform exactly to the relative differences in the regional changes of contour area or operations. As discussed earlier, the contour area is affected not only by the number of operations but also the types of airplanes and the initial level of operations. The exposed population depends not only on the area of the contours but also the population densities around the airports. Similarly, the exposed population partially determines the lost housing value and rent but so do the number of people per dwelling, the percent of dwellings that are owner-occupied or rented, and the average prices in the area. Therefore, regional differences in these factors lead to different impacts from changes in operations. Figure 33 shows how these responses differ in each region.

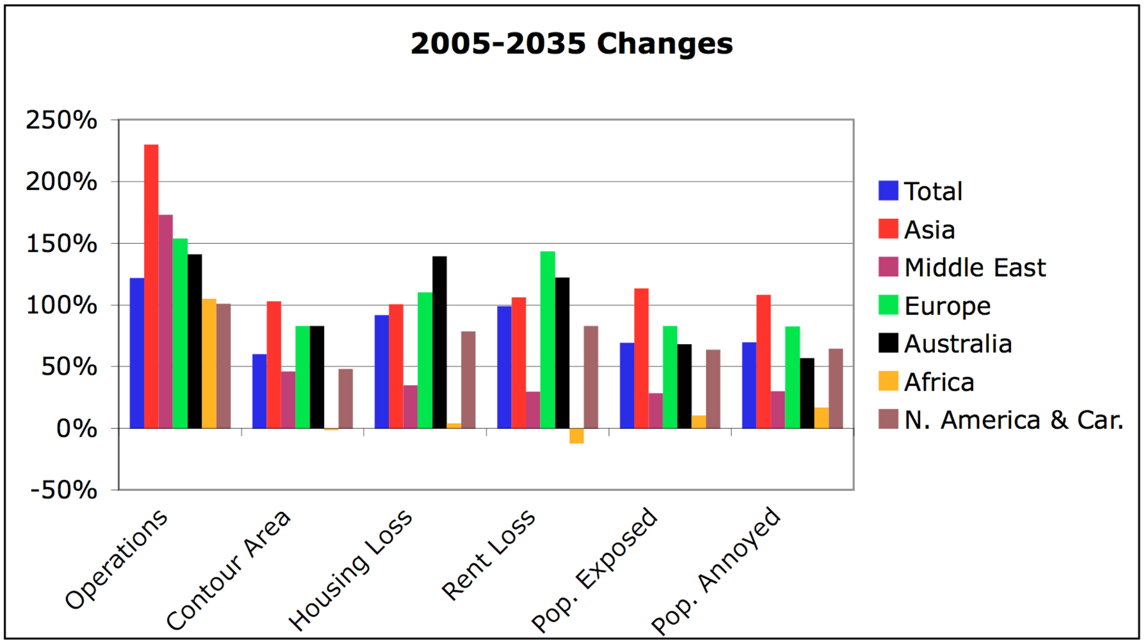


Figure 33: Changes in Operations, Noise, and Impacts 2005-2035

6 Discussion

The results demonstrate that greater work must be done concerning the effect of aircraft noise on rent prices. For the foreign airports where tenure status was known, we calculated that approximately 40% of the housing units were rentals and a similar ratio exists for the US airports. With most hedonic studies using only owner-occupied house sales, the effect on rents and, therefore, the value of the aviation noise impact at the average major airport is quite uncertain.

As discussed in previous sections, several assumptions potentially bias the estimated impacts; however, the differing or uncertain directions of these biases makes it impossible to make a statement about whether the calculations are upper or lower bounds. Most notably, the coarse population data for many countries and the need to estimate housing prices and rents add significant uncertainty to the results. If the people within the divisions in which population is known tend to live in the quieter areas, our results would overestimate the actual impacts. Alternatively, Pope's paper [Pope 2008] indicates that buyers are generally not fully informed about the state of noise at homes, which would bias the monetary estimate downward. Additionally, as discussed in the previous paragraph, the lack of noise valuation studies with rent prices possibly distorts the monetary impacts but in an unknown direction.

Despite the uncertainties in the impact assessment, the results show that aviation noise has a significant impact worldwide. Millions of people are exposed to and annoyed by aviation noise and billions of dollars of damage result from it. Additionally, the growths of these impacts that we found in our possible future scenario demonstrates the significant gains that can be accomplished with future changes in technology or operations that reduce the amount of population exposure to aircraft noise.

The effects of aircraft noise are distributed all over the world. Figure 34, Figure 35, and Figure 36 show the impacts at each airport in 2005. North America, Europe, and Asia each had airports with an estimated $1 billion in housing value loss, 400,000 people exposed to 55 dB, and $25 million in lost rent. Twenty-nine countries had an airport with at least $100 million in housing value loss, 11 countries had airports with $10 million in yearly rent loss, and 20 countries had airports with more than 100,000 people exposed to 55-dB and 17,000 people highly annoyed.

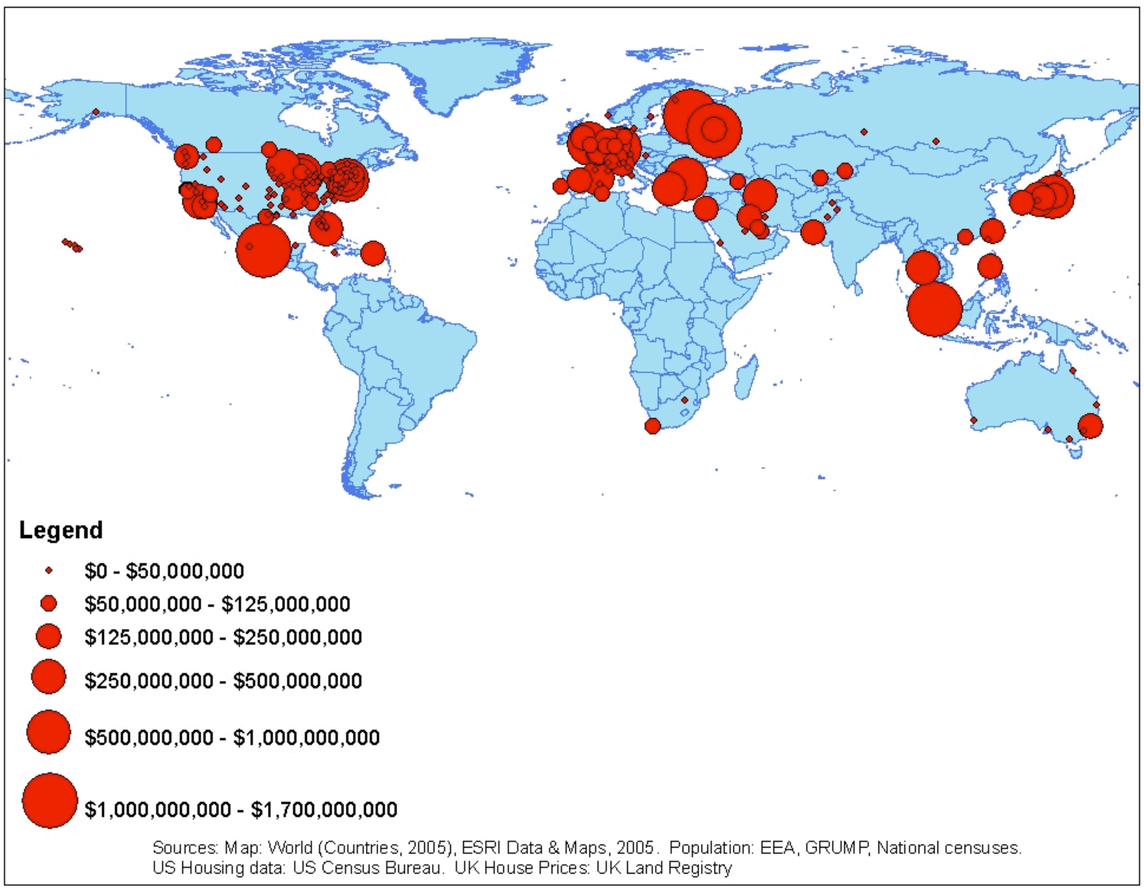


Figure 34: 2005 Global Housing Value Loss

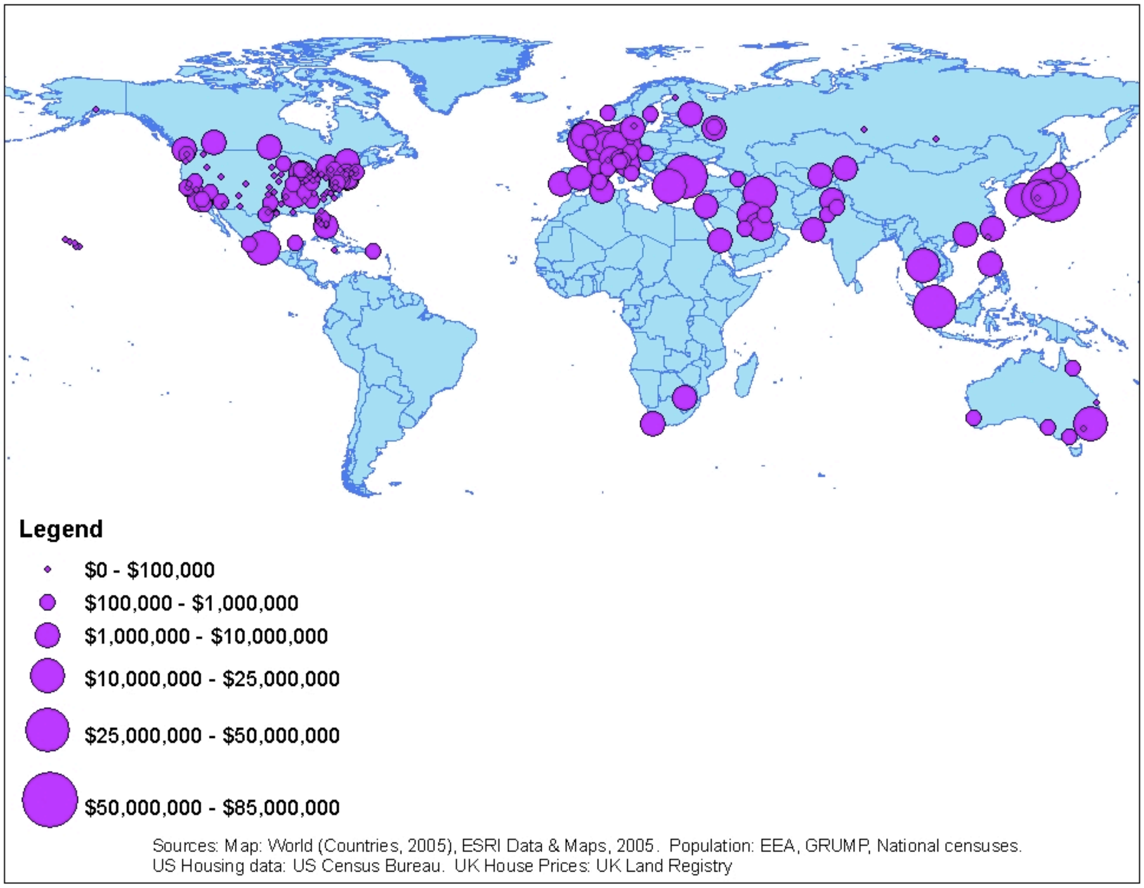


Figure 35: 2005 Global Rent Loss

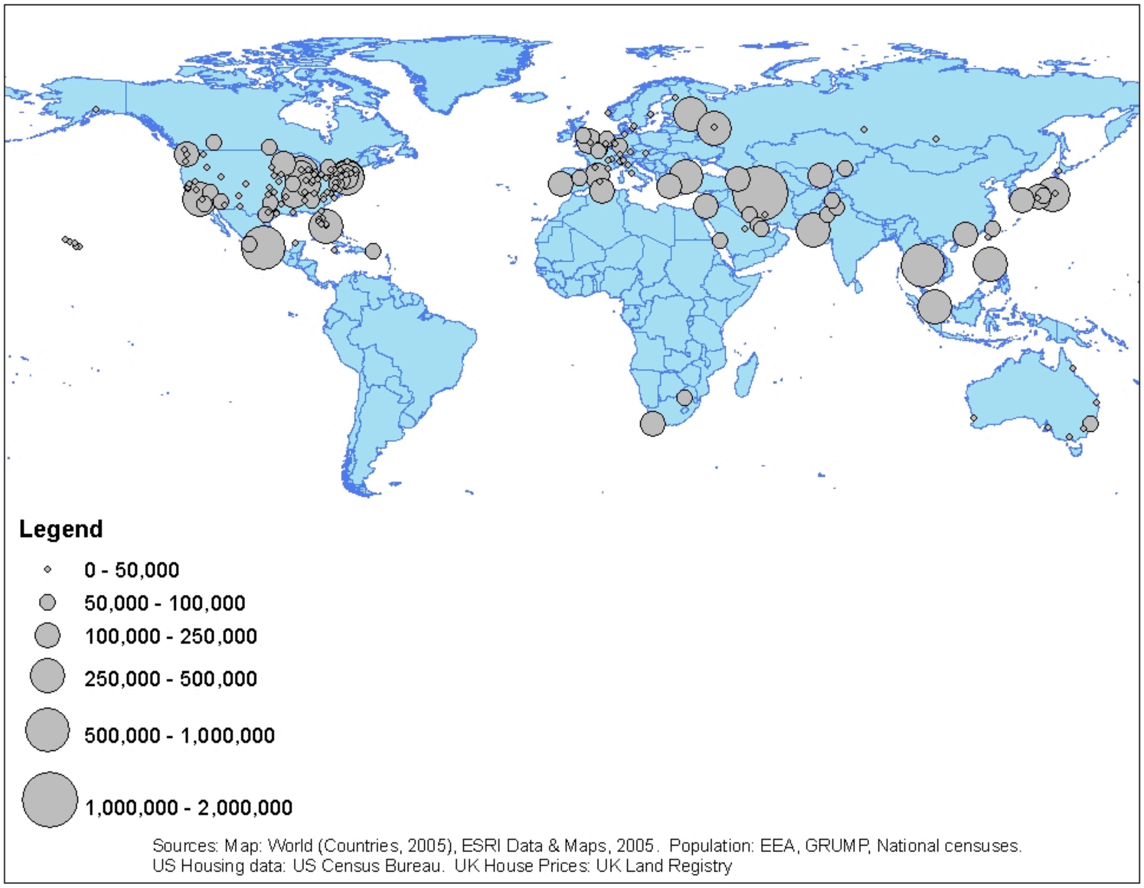


Figure 36: 2005 Global Population Exposed to 55 dB

Similar to the results found in Tam et al. [Tam et al. 2007], our results indicate the sensitivity of at least the monetary noise impact on the area of the contours at least for individual airports. Between 2005 and 2035 the area of the noise contours and the population exposed to 55 dB increased by only 70% overall, while the total housing value loss and rent loss increased by 90% and 100% respectively. The effect is not likely a result of the expansion of the higher decibel contours with respect to the lower decibel ones because the total area of the 65 dB contours for all the airports increased by only 55% between 2005 and 2035. The results around individual airports were often much more pronounced. One US airport, for example, had an 8% increase in the contour area but a 130% increase in housing value loss, and a second US airport had a 26% in contour area but a 72% increase in housing value loss and 290% increase in rent loss.

6.1 Conclusion

In this study we analyzed the impacts of aviation noise around 181 airports in 38 countries plus Taiwan. In 2005 these airports accounted for an estimated $21 billion in housing value loss, $800 million in rent loss per year, 14 million people exposed to 55 dB, and 2.3 million people highly annoyed. By 2035, without technological or operational advances, these impacts could grow to $41 billion in housing value loss, $1.6 billion in yearly rent loss, 24 million people exposed to 55 dB, and 3.9 million of them highly annoyed with current prices and population. Furthermore, these impacts are not concentrated in any geographic area. Each continent with an airport in the study had airports with $100 million in housing value loss and 200,000 exposed people.

We also examined possible future changes to these impacts under a scenario of no technological or operational advancement (with the exception of retirements of older aircraft in the fleet). In our scenario of 2-3% average annual growth between 2005 and 2035 with the biggest percentage growth at the Asian airports, the total area experiencing 55-dB of noise increased by 60% between those years. The corresponding number of people exposed and those highly annoyed increased by only a slightly larger same amount. The monetary impacts grew even faster and ended the period 90-100% higher than in 2005.

6.2 Recommended Future Work

The work presented in this paper has made a meaningful contribution towards understanding the total impact of aviation noise, but significant work is still needed. Our work could be improved with better house price and rent data. For many cities we had to estimate the average house price or rent, so obtaining actual values would not only improve the calculation of monetary impacts for those cities but also improve the regressions that estimate the average values for other cities. Furthermore, better quantification of the uncertainties associated with the various estimates and population data used in our impact assessment would improve the results and the communication of their validity. Some of the excluded MAGENTA Shell 1 airports have sizable contours, so including them in future studies would likely appreciably contribute to the total impact. Also, inclusion of South American airports would provide information about the impacts of aviation noise in a region of the world not covered in this study. Adding the Shell 2 airports would also improve the assessment, but if the FAA's estimates are correct, they would have a minor effect.

Future studies should also include estimates of additional physical effects of aircraft noise. Methods exist to quantify the number of people awakened by aircraft, and, using minimum, acceptable limits of noise in schoolrooms, allow for calculating the number of children exposed to excessive levels of noise. These metrics would better communicate the experiences of residents living near airports.

More generally, further study of the effect of aviation noise on rent would improve calculations of the monetary value of the noise. Numerous studies have been conducted to study the effect on owner-occupied sales and some have measured the WTP of residents in general, although no comprehensive meta-analysis has been done with stated-preference studies. More work, therefore, needs to be done to determine the effects on rent so that the monetary valuation of noise can be more fully calculated. Similarly, other biases in current estimates, such as from lack of informed buyers or people who do not take health effects of noise into account in their decisions, need to be better quantified.

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8 Appendix

8.1 Studies Included in Nelson 2004 Meta-Analysis

Study (publication date)	Airport (& area)	NDI %: Abs. value (std err)
BAH-FAA (1994)	Baltimore	1.07 (.823)
BAH-FAA (1994)	Los Angeles	1.26 (.788)
BAH-FAA (1994)	New York (JFK)	1.2 (NA)
BAH-FAA (1994)	New York (La Guardia)	0.67 (NA)
Blaylock (1977)	Dallas	0.99 (.330)
DeVany (1976); NAS (1977)	Dallas	0.80 (.267)
Dygert (1973)	San Francisco (San Mateo)	0.50 (0.250)
Dygert (1973)	San Jose	0.70 (.422)
Emerson (1969; 1972)	Minneapolis	0.58 (.366)
Fromme (1978)	Washington DC (National)	1.49 (.753)
Kaufman (1996); Espey & Lopez (2000)	Reno	0.28 (.183)
Levesque (1994)	Winnipeg	1.30 (.342)
Mark (1980)	St. Louis	0.56 (.240)
Maser et al. (1977); Quinlan (1970)	Rochester (urban)	0.86 (.319)
Maser et al. (1977); Quinlan (1970)	Rochester (suburban)	0.68 (.279)
McMillian et al. (1980); McMillan (1979)	Edmonton	0.51 (.224)
Mieszkowski & Saper (1978)	Toronto (Mississauga)	0.87 (.212)
Mieszkowski & Saper (1978)	Toronto (Etobicoke)	0.95 (.187)

Myles (1997)	Reno	0.37 (.111)
Nelson (1978)	Washington DC (National)	1.06 (.714)
Nelson (1979; 1980)	Buffalo	0.52 (.200)
Nelson (1979; 1980)	Cleveland	0.29 (.128)
Nelson (1979; 1980)	New Orleans	0.40 (.195)
Nelson (1979; 1980)	St. Louis	0.51 (.267)
Nelson (1979; 1980)	San Diego	0.74 (.233)
Nelson (1979; 1980)	San Francisco	0.58 (.184)
Nelson (1979; 1980)	Six airports	0.55 (.200)
O'Byrne et al. (1985)	Atlanta (blocks)	0.64 (.200)
O'Byrne et al. (1985)	Atlanta (houses)	0.67 (.300)
Price (1974)	Boston (rentals)	0.81 (.238)
Tarassoff (1993)	Montreal	0.65 (.325)
Uyeno et al. (1993); Biggs (1990)	Vancouver (houses)	0.65 (.164)
Uyeno et al. (1993)	Vancouver (condos)	0.90 (.323)

8.2 Airports Analyzed and Population Database Sources

Region	Number of Airports	Population Databases
Africa	3	GRUMP, South Africa
Asia	13	GRUMP, Philippines
Australia & Oceania	7	Australia
Europe	40	EEA, GRUMP, UK
Middle East	13	GRUMP
North America & Caribbean (excluding US)	10	Canada, GRUMP
US	95	US
Total	181	

Population Databases

US	US 2000 Census, block groups
EEA	EEA 2001 Population density based on 2000 Corine Land Cover (http://dataservice.eea.europa.eu/dataservice/metadetails.asp?id=1018)
GRUMP	Gridded Rural-Urban Map Project (http://sedac.ciesin.columbia.edu/gpw/global.jsp)
Australia	2006 Census Mesh Map (http://www.abs.gov.au/ausstats/abs@.nsf/mf/1209.0.55.002/), estimating 2000 population using Statistical Local Area population changes between 2000 and 2006
South Africa	2001 Census at Sub-place level (http://www.statssa.gov.za/census01/html/C2001CommProfile.asp),
Canada	2001 Census at Dissemination Area level