Aviation Effects on Local Business: Mapping Community Impact and Policy Strategies for Noise Remediation

by

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ABSTRACT
Changing flight procedures present a natural experiment which can be leveraged to study the effects of aviation noise change on business activity. While it is widely recognized that aviation produces a variety of economic benefits and environmental disbenefits, the effects of noise on businesses sit at an understudied intersection of economic and environmental impact. Using geospatial analysis of Boston and Chicago, two metropolitan areas which experienced flight path changes, this thesis assesses the extent to which businesses near airports relocate or close in response to noise increases. Business activity was compared before and after noise changes to form the basis of a difference-in-differences approach, which controls for many of the other factors which affect business activity at a given location. This study also acts as a revealed preference approach for assessing the implicit costs of aviation noise and the role of regulators in responding to those costs. No statistically significant aggregate effect of aviation noise on business activity was found. For outlier locations with large business changes and large noise changes, exogenous non-noise factors were identified which are likely responsible. Available evidence suggests that regions of large noise increase have comparable business growth to regions which do not experience noise change, even after controlling for the effects of geographic region and initial noise levels.

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1. Introduction

This study investigated the economic impacts of noise changes surrounding two airports: Boston Logan International Airport (BOS) and Chicago O'Hare International Airport (ORD). Business activity is compared before and after changes to noise distribution, during the period 2011 to 2016. Noise exposure has been associated with concerns for public health and quality of life (Peters et al. 2018; Miedema and Oudshoorn 2001). When flight paths change, the distribution of noise across urban populations changes, and the effects of noise exposure become redistributed (Brown and Kamp 2009). Two primary types of changes to flight paths are observed (see Fig. 1): 1) the introduction of area navigation (RNAV) flight procedures, as occurred at BOS, which generally concentrated noise over communities that are located directly under flight tracks, and 2) infrastructure and runway configuration changes, as occurred at ORD, which allowed planes to take off and land from new directions.

These changes form a natural experiment which can be leveraged to study business impacts. Increases and decreases to noise exposure sort the cities into treated and non-treated regions. Business-level impacts are operationalized as business closures and relocations by aggregating cities into blocks and counting the number of businesses in each block in one year before flight path changes took effect and in another year after the changes. For measuring noise, newly modeled data, made possible through advances in radar-tracking of aircraft as part of the Federal Aviation Administration (FAA) NextGen program, allows for previously unattainable noise mappings modeled from exist aircraft locations, both before and after changes to flight procedures.

This research falls at the intersection between economic impact and community environmental impact discourses. Apart from noise and pollution concerns, the broader economic impacts of the aviation industry are considered to be predominantly positive, as aviation supplies a host of benefits to connected populations. In particular, the economic benefits of catalytic impacts, which stem from the transportation function of the aviation industry, have been thoroughly investigated (Lenaerts et al. 2021). Conversely, previous examinations of disbenefits largely focus on environmental impacts in the form of carbon emissions, reduced air quality, and noise (Grobler at al. 2019; Wolfe 2014). Each of these has been targeted for reduction by environmental impact assessments, made mandatory in the United States by the National Environmental Policy Act (Robinson 1992). However, while noise, as an environmental impact, has been shown to have a variety of individual-level disbenefits, principally on health and annoyance, and aviation connectivity has been shown to produce a variety of economic benefits, the potential business-level economic disbenefits of noise remain largely unexamined. By identifying under what conditions economic disbenefits of noise may develop, and if present, the range of their geographic distribution, policymakers can better predict the implicit costs of future flight procedure changes, improving the accuracy of the cost-benefit analyses on which these proposed changes are evaluated.

The findings presented here suggest that noise increases are not significantly associated with suppression of business. Across both Boston and Chicago, neither a naïve correlation approach nor increasingly nuanced treatment-nontreatment approaches suggest that either noise increases or decreases have a causal effect on business growth and decline. For outlier locations that do exist, like those that exhibit both high noise change and change in the number of businesses, alternative non-noise explanations for business change are identified, such as new downtown redevelopment zoning policies or the restructuring of large shopping malls.

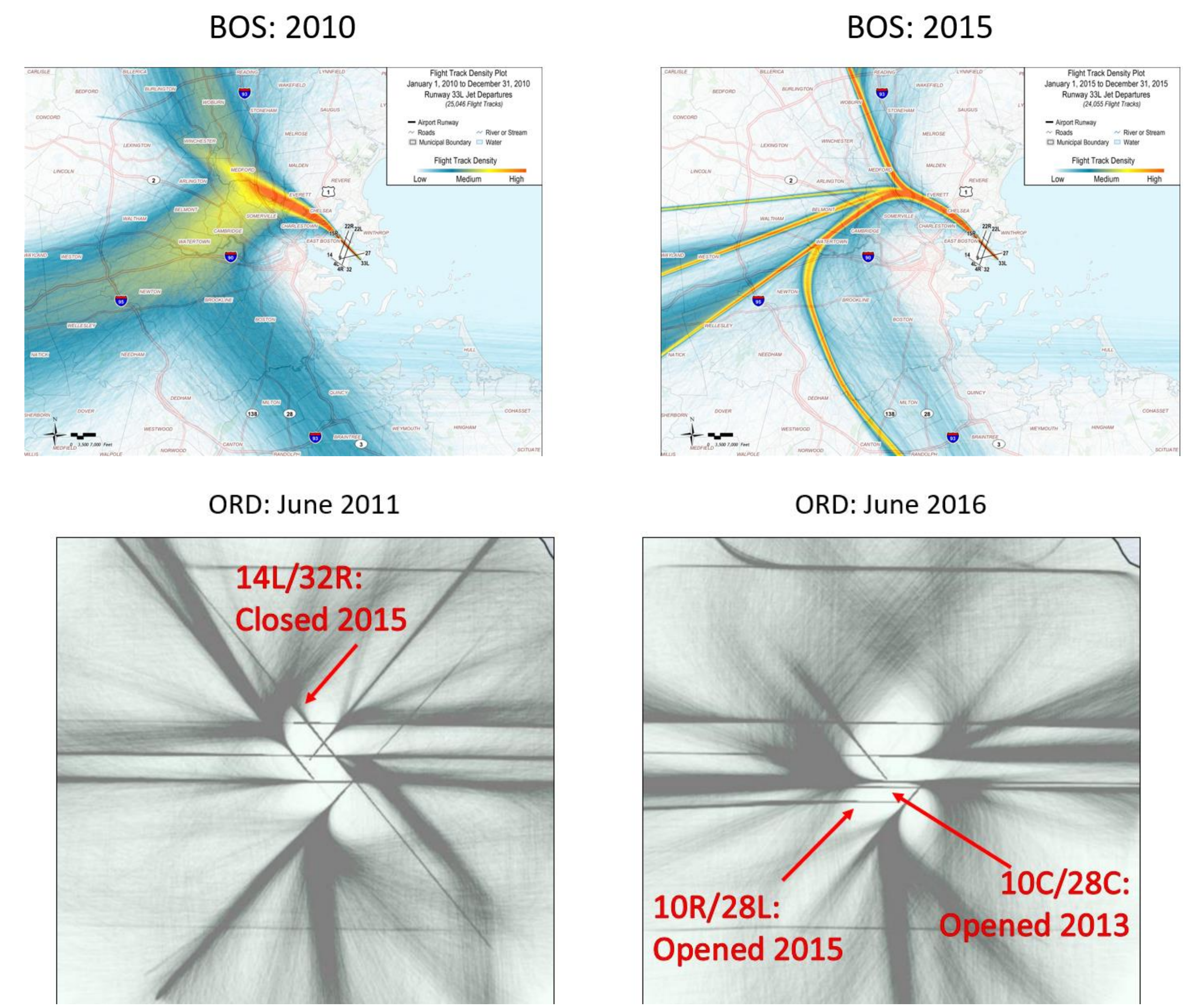


Figure 1: (top) Flight track density from one runway at BOS, showing increases from 2010 to 2015 in concentration along the center of flight paths. High track density is associated with greater aviation noise. Reproduced from HMMH. (bottom) Flight trajectories of departures and arrivals from ORD, showing changes in runway usage from 2011 to 2016, with regions of greatest increase and decrease of density highlighted in red and blue ovals. Reproduced from Madeleine Jansson.

2. Literature Review

This chapter reviews the prior research in the field, beginning with the study of the economic benefits of aviation, then synthesizing these findings with those made in the area of environmental and community impacts of noise, and ending with an examination of noise policy and dispute management.

Aviation Economic Impacts

The economic impacts of aviation are typically classified as is shown in Fig. 2. Here, the demand-side has been differentiated from catalytic impacts, while economic option value rests largely outside of the scope of this analysis. None of these categories are exclusive to aviation, and similar divisions could be drawn in industries within and without the transportation sector.

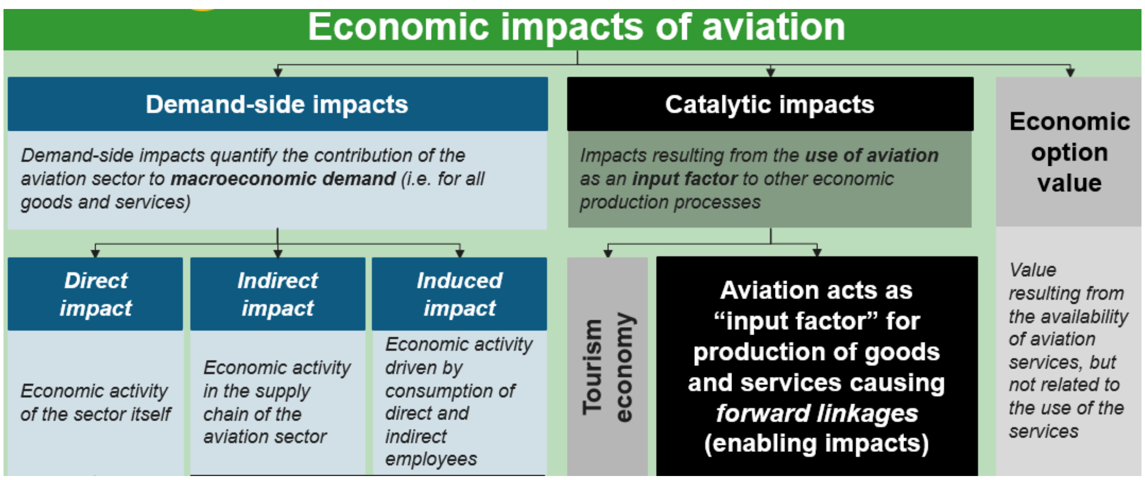


Figure 2: Breakdown of positive economic impacts into demand-side, catalytic and economic option value. Reproduced from Allroggen (2019).

The direct impacts of aviation are the first of three kinds of impacts driven by the demands of the industry. These include the demands of the industry for labor, such as all those employed by airlines and aviation operations, as well as the physical products required for aviation, such as those provided by aircraft manufacturers. In 2020, the direct impacts of aviation contributed an estimated $606 billion to GDP, globally, an amount greater than the contributions of the automotive and pharmaceutical industries (ATAG 2020). Indirect impacts widen the scope of interest to the entire supply chain, now including the raw material suppliers for products consumed as a part of the aviation industry. These are generally business-to-business interactions, where the spending of the aviation industry may support other industries, such as the food processing or information technology businesses which supply in-flight meals and customer support, but whose roles are peripheral to the aviation sectors' primary function of transporting of people and goods. These indirect jobs contribute an additional $638 billion to the global economy (ATAG 2020). Lastly, induced impacts result from the pay of employees in the industry, and their consumption in the wider economy which has been enabled by the spending of the aviation industry. Thus, unlike the business-to-business indirect impacts, induced impacts largely measure household-to-business transactions. They are largely determined by the number of total direct and indirect employees, which number 22 million globally. Induced impacts make up a smaller portion of aviation's GDP contributions than direct and indirect impacts.

While these demand-driven impacts exist for any industry, they largely ignore the economic value of the industry's particular function within the economy and society, i.e. transporting people and goods. Catalytic impacts consider aviation's unique role in connecting economic networks. Catalytic impacts are driven by use of aviation, spilling over to industries that do not exchange capital with aviation firms, and as a result it can be more dynamic than the demand-side impacts. Examples include the enabling of important face-to-face linkages between collaborating parties, increasing products' availability to new markets, and extending the reach of local employers seeking to attract labor. Sustained investments in transportation infrastructure are associated with market expansion, leading to increased specialization, productivity and accessibility (Lakshmanan 2011). Aviation links drive the intra- and international movement of factors of production which in turn positively impact local economies (Campante and Yanagizawa-Drott 2018). As a result, cities can use aviation networks strategically to plan for the future of their development (Cristea and Danila 2017). Some empirical research on quantifying catalytic effects have suffered from difficulties in assessing causality, e.g. whether connectivity drives economic performance or economic performance drives connectivity (Campante ibid), have left much remaining uncertainty despite the frequent use of instrumental variable methods. These cases require the assumption that the instrument is causally linked to the dependent variable exclusively through the intervening independent variable, called the exclusion restriction, which may be impossible to prove empirically.

Lenaerts et al. (2021) proposes using New Economic Geography (NEG) as an approach to theoretically study aviation's economic impacts. Krugman's seminal 1991 article on NEG, principally concerned with the distribution of production over space, reinvigorated the field of economic geography by sparking a transition from location theory—why do certain locations house certain industries—to a broader theory of network interactions across space, in particular, between economies in a manufacturing core and an agricultural periphery. Similar to Krugman's notion that emergent properties like agglomeration effects cause segmentation of the economy across space, NEG predicts that different segments of the economy across space may respond differently to the same stimulus. Applying the lens of NEG to the case of aviation noise as a stimulus of potential economic change, because airports may be located in near city centers, as in Boston, or far from city centers, as in Dulles, one must be wary of not only how aviation noise differs across space, but how noise effects may intersect with urban, industrial and agricultural land use types that perceive and respond to noise differently. Furthermore, although many factors other than aviation linkages affect local economic outcomes, including national trends (e.g. recession, inflation), industry-specific pivoting (e.g. manufacturing relocations to East Asia), and changing individual preferences (e.g. willingness to work for a particular wage), because many of these do not vary across space at short enough distances to be measurably different at different locations within the near-vicinity of a single airport, NEG predicts that these factors can be separated from effects due to noise. At this time, for a full discussion of incorporation of noise into geospatial analysis, the following section establishes the foundations of noise exposure.

Noise Exposure Impacts

In cases of long-term population impacts, noise exposure is measured as an average over a time period, often as long as one year. The FAA's standard noise metric, used in all of its studies of noise exposure, is the Day-Night Average Sound Level (DNL, also notated as L_{dn}) which smooths many noise events into a single equivalent sound level (L_{eq}), as if the sound pressure was constant in time instead of time-varying. The DNL metric also includes a penalty on nighttime noise under the assumption that it is more disruptive, as shown in Fig. 3. This method has the side-effect of creating noise profiles that are not representative of any individual day; for instance, all of an airport's runways are included and show high use, even though on any real day they could not be used simultaneously.

Noise, often considered alongside other environmental impacts, has been of interest to acoustic and aeronautic engineers for over half a century. Much of the work in the domain of noise exposure traces back to an early meta-analysis of noise disturbance surveys, predominantly from European cities and including street and rail traffic in addition to aviation noise (Schultz 1978). Schultz defined "percent highly annoyed" as the proportion of survey respondents which indicated annoyance in the top ~28% of the given ordinal annoyance scale, with slight variations due to comparing across different survey designs (e.g. those who marked an annoyance of 6 or 7 out of a 7-point scale and those who marked 9, 10, 11 out of an 11-point scale are both highly annoyed). Schultz constructed a dose-response curve, estimating what percent of the population would be highly annoyed at a given DNL level finding 15% of surveyed populations were highly annoyed at 65 dB, leading the FAA to use 65 dB as their standard threshold of determining high noise exposure.

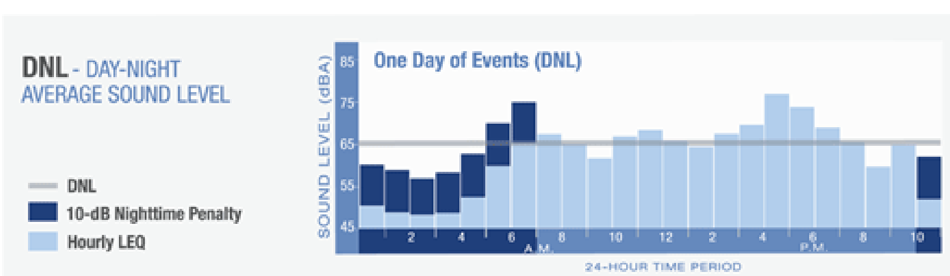


Figure 3: Sound pressure is shown discretized from many individual noise events into hourly blocks, and is then aggregated into a DNL measure across a day, including a nighttime penalty. Reproduced from the FAA.

Schultz' work has been replicated with mixed results by numerous follow-up studies. The Federal Interagency Commission on Noise (FICON) affirmed the use of the percent highly annoyed metric for future studies, but found that the 65 dB threshold was unreliable given the presence of many noise-sensitive communities at the 60-65 dB level (FICON 1992). Miedema and Oudshoorn (2001), using the same highly annoyed cutoffs as Schultz, identified closer to 25% of the population as highly annoyed at 65 dB, which is lower still than a later analysis by Brink, Schäffer, et al. (2019) which found nearly 50% of participants in a smaller Swiss survey were highly annoyed at 65 dB. Most recently an FAA Neighborhood Environmental Survey found far higher levels of annoyance, with 65% of the population highly annoyed at 65 dB, and as much as 80% of respondents indicating high annoyance at 75 dB. However, this metric is not directly comparable given that the FAA's survey has defined high annoyance as the top 2 choices on a 5-point ordinal scale, representing a greater share of respondents than Schultz's high annoyance cutoff (FAA 2020). It is unclear whether annoyance at a given noise level is truly increasing, or whether this growth in the highly annoyed population has been skewed upward due to non-comparable populations, survey designs, and curve-fitting assumptions. Regardless, they show a strong association between noise exposure and adverse community impact.

In contrast to the stated preference studies on annoyance, where participants were directly surveyed, revealed preference models aim to measure implicit valuation of noise. For example, changes to housing markets form an indirect measure of individuals' monetary valuation of noise exposure. Literature on property values and house prices show negative impacts of noise directly on economic outcomes that remain even after controlling for distance to the nearest airport. Revealed preference studies find that the depreciation in house prices due to aviation noise ranges from low estimates at less than half of a percent in total (Thanos et al. 2011; Huderek-Glapska and Trojanek 2013) to as high as 1.7% per decibel increase in noise (Winke 2016). For these studies, to control for natural spatial variation in housing prices, an exogenous change in noise from baseline is required to determine effects of noise on house prices. Choices for examination include unexpected changes to runway usage (Boes and Nüesch 2011), the introduction of mandatory noise disclosure laws for property sellers (Pope 2008), and the implementation of specific noise mitigation regulations (Trojanek and Huderek-Glapska 2018). In sum, noise-based housing depreciation has been valued through both hedonic pricing and willingness-to-pay metrics for in-home noise mitigation at approximately $23 billion in 2005 dollars, over $30 billion in 2021 (Kish 2008; He et al. 2014).

Beyond the subjective perception of noise, psychological disbenefit of annoyance, and economic effects, there are also a number of known negative health effects of high noise. In addition to the more intuitive physical effects of extremely high noise exposure, like hearing loss and tinnitus, moderate sustained noise has been associated with adverse effects to cardiovascular health (Peters et al. 2018), as well as sleep duration and quality (Basner 2010). A review on noise pollution by the World Health

Organization, additionally found that noise is associated with impaired task performance and worsening of latent mental health issues, including stress and anxiety (Goines and Hagler 2007). Taken together, these findings suggest that noise exposure, particularly long-term daily exposure to noise levels at or above 65 dB, pose enough of a threat to merit noise mitigation.

Noise Policy, Disputes, and Mitigation

Given the potential disbenefits of noise and the responsibility of local governments and federal regulators like the FAA in determining standards of where planes fly and thus which populations receive noise, noise exposure may become politicized. Moreover, changes in noise distribution from one community to another may raise equity concerns. For example, the disbenefits of noise may not reach the same segments of the population as those which receive the benefits of aviation. Communities close to the airport likely do receive direct, indirect, and induced impacts of aviation, resulting in higher employment; however, these same communities of airport employees may be less likely to use aviation or experience its other economic benefits (ATAG 2020; World Bank 2009). When communities perceive that the disbenefits of living near the airport outweigh the benefits, they may seek recourse. This thesis considers two primary modes of harm reduction: preventative and remedial.

When city governments can anticipate changing aviation noise, due to either runway use changes or the across-the-board noise increases from airport expansion or traffic growth, they can attempt to use land use control to limit residential development of areas which will receive noise increases (Zambrano 2001). This has the dual functions of not only limiting development, but also promoting transparency by announcing changes in advance, such that consumers can predict and respond to noise changes even in the event that developers ignore or circumvent zoning ordinances. However, the ability of local governments to publish these ordinances is limited by federal law. Airports are barred from developing noise mitigation programs which would significantly adversely affect interstate commerce, because the regulation of any commerce which crosses state lines, like air freight, is an exclusive enumerated power of the federal government listed in Article 1 of the United States Constitution. (Zambrano 2001). Given that the FAA was explicitly created to protect commerce, and its authorization act grants exclusive control of the airspace to the federal government, the local governments representing affected communities have limited preventative powers, and their zoning ordinances have been struck down in the courts (Ly 2014; Pavlicek 1982). Likewise, locally-imposed airport curfews banning night flights have also been repeatedly struck down and remain severely limited in application (Fidell and Mestre 2020). The state level, being subject to the same restrictions as municipalities, is equally unable to prevent noise at the source. On the noise-receiver side, municipalities can limit impact through building codes which require soundproofing in high-noise areas, generally those above 65 dB DNL. These soundproofing requirements can prove costly for airports and the FAA, typically falling the in range of $15,000 to $65,000 for a single-family home and much more for larger institutions like schools (FAA 2019). Across the fifty years since insulation programs first became available to communities, the FAA has spent over 10 billion dollars in total on soundproofing. They can also combat falling house prices due to noise chances by implementing purchase assurance programs, also known as guaranteed buyouts, to give residents the freedom to choose to move away (Fidell and Mestre 2020).

There have also been a number of cases where the FAA and other institutions have been taken to court with litigation efforts. In these cases, liability is difficult to assign, with many potential sources at fault, including the federal government, local governments, the airport, and the aircraft engine manufacturers (Bennett 1982). The quantification of noise-related damages also proves difficult, as communities often lack the ability to perform for their specific case the kinds of medical and economic analyses which have shown broad trends of cardiovascular impact and house price decline for their specific case. In these cases, litigation can instead be pinned on the FAA’s failure to follow established procedure, e.g. not publishing adequate environmental impact assessments, or estimating noise incorrectly prior to changing flight tracks (Ford 2002). This style of lawsuit owes to the concept of inverse condemnation, where a government entity fails to compensate private citizens for either taking their property or rendering unusable or economically inviable through regulation. In cases where liability is found and a procedural violation is identified, the FAA has standard procedures to soundproof homes, schools and businesses near airports (Alexander-Adams 2015). The provision of insulation materials as an in-kind benefit rather than equivalent cash transfer may eliminate the risk of fraudulent or insincere claims, but it may also be associated with deadweight loss when homeowners would gain more utility from spending the tens of thousands of dollars used for soundproofing on something else that improves their quality of life (Whitmore 2002). Nevertheless, recent controversies over non-uniformly applied soundproofing have shown that lower-income residents can be left out of programs which disproportionately benefit the middle-class, leaving many skeptical of airports’ willingness to compensate them for noise damages (Smith 2019).

Relevant to this discussion is the placement of transportation authorities within the broader political landscape as unique actors within air traffic regulation. The third sector, also occasionally termed as the civic sector, refers to organizations that are neither strictly private nor public. They may be non-profits, educational institutions, civil society organizations, or public-private partnerships, and typically include port and housing authorities. Within their functional niche, they are often natural monopolies capable of growing very large; thus these institutions have been critiqued for their degree of control over communities, while still remaining insulated from some political consequences (Adams 2014). This is often due, in part, to financial independence through revenue sources like fares, tuition, and individual donors which preclude the ability of the government to withhold tax dollars for non-compliance with policy like they might from funding-reliant institutions. While the public sector is accountable via democratic processes and the private sector is, at least theoretically, accountable to the public via market forces, third sector institutions' unique relationship to both public institutions as lobbyists and to private institutions as enablers of service provision may make them difficult to regulate. Conflict between these groups is uncommon, but certainly not unprecedented. As one scholar notes of aviation authorities in his review of noise litigation: "The struggle between simultaneously maintaining the power to control aircraft noise and avoiding the responsibility for damages caused by noise, presents a dilemma." (Bennett 1982). In this way, communities' unique relationships to noise vary at the municipality level, and thus the effect of noise on businesses may be greater or more salient in communities with an active political group which interfaces with the transportation authority, and this is a variable which will require control.

3. Methods

This thesis investigates the potential effects of aviation noise on business activity by counting the number of businesses in a grid surrounding an airport before and after changes to the local noise distribution. This chapter lays out a plan to measure whether increases to DNL are associated with the relocation of businesses to areas which receive less aviation noise. After defining the goals of this study, this chapter provides a detailed account of the research process as divided into three parts: 1) data acquisition and tests of validity; 2) geospatial analysis; and 3) quantitative methods and statistical analysis. The third of these subsections builds up multiple methodological approaches to capture a variety of potential relationships between noise and business outcomes, each other which captures different conditional variables.

Research Question

Economic effects of aviation noise were assessed by honing in on local conditions of noise and business change. Owing to the FAA's NextGen programming, new performance-based navigation (PBN) flight procedures were introduced in 2006, with the period 2011-2015 representing the time during which two such procedure types, area navigation (RNAV) and required navigation performance (RNP) were expanded to the 100 largest airports in the United States (FAA 2006). RNAV and RNP procedures allow for increased safety, predictability and efficiency by linking flight paths to aircraft performance, as enabled by advanced sensors and monitoring systems, but they also concentrate aviation noise above centerline procedures (see Fig. 1), giving rise to a natural experiment. Alternately, even more overt flight path changes are present in airports which built or decommissioned runways. This time period was also characterized by rapidly growing demand for air travel, and thus represents both a time of change in the geographic distribution of noise as well as an overall increase to total noise output. On the side of the dependent variable, outcomes for businesses under flight paths were chosen, as opposed to any other measure of economic health, stemming from language in the Federal Aviation Administration's 2018 Reauthorization, which specifically directs study administrators to perform analysis at the business level.

Two airports, and their corresponding metropolitan areas, were chosen as case studies: Boston Logan International Airport (BOS) and Chicago O'Hare International Airport (ORD). These airports have high overall traffic, which was considered necessary for noise changes to be perceptible to under-flight populations, and were known to have undergone noise exposure changes. Prior data for BOS suggests significant concentration of flight paths due to the introduction RNAV procedures, and the introduction of RNAV therefore forms a natural experiment between two periods of different noise exposure. Likewise, infrastructure changes at ORD, including the construction of a new runway and decommissioning of another as part of a modernization program spanning the period 2008 to 2021, led to modified noise profiles over the city. These two metropolitan areas were considered by the FAA Reauthorization to be high-priority targets for business impact analysis, in contrast to greenfield airports which have limited population effects due to their distance from urban centers.

Thus, with known aviation noise changes across these two cities, and based on the known negative physical, cognitive, and economic effects of noise exposure from the literature, this thesis's principle research question is defined as: Do locations which receive increases to aviation noise have suppressed business changes relative to locations which do not? This may manifest either as a net loss of businesses or slowed levels of growth. If this hypothesis is supported, then the regions with greatest noise increase would be expected to show suppressed business counts in the end year, 2016, after the noise changes have had time to take effect. If not, then evidence suggests that locations which receive aviation noise and those that do not have comparable business growth rates.

Data

Two data types were used: noise contours and business points, each of which is present for two years, creating a before-and-after picture. They are generally combined as is shown in Fig. 4. Other key source data not pictured include basemap shapefiles, produced by the state GIS departments and the U.S. Census Bureau. Data from the 2012 Economic Census was also used to validate business data and confirm inter-year reliability.

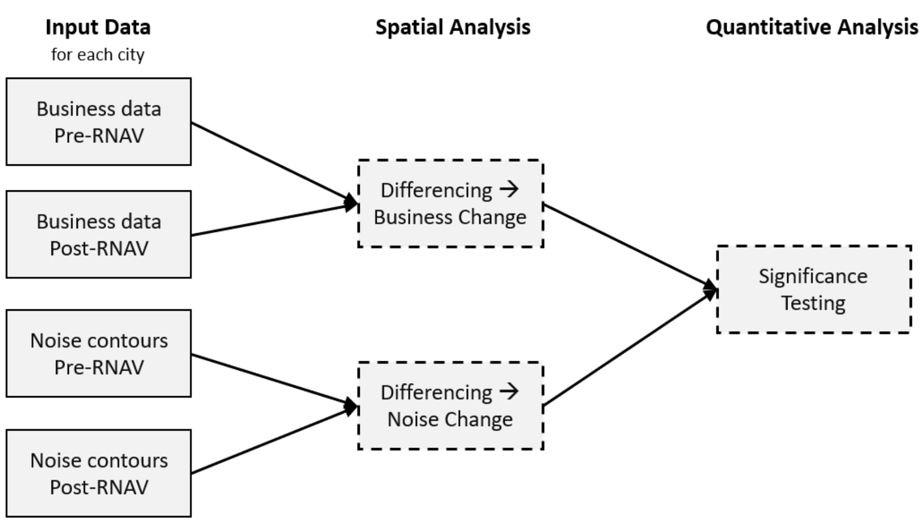


Figure 4: Input Data contribution to block diagram of analysis.

The business data was compiled by InfoGroup. InfoGroup collects point data on businesses, including their name, latitude, longitude, street address, industry sector (SIC and NAICS code), number of employees, and sales volume. This data was synthesized from responses to phone surveys, listings in the YellowPages, newspapers, the Security Exchange Commission, and from the postal service. Business data are published annually and are available for every year since 1997, with each year containing on the order of 10 million businesses. Prior to analysis, the data was processed by organizing it by U.S. state and removing extraneous variables, such as any available contact information of the business owner.

Fig. 5 shows summary statistics of the InfoGroup business data, which were checked for internal consistency. While data on sales volume and employment count proved too volatile across years to be deemed comparable and trustworthy (see Appendix 1), establishment counts are largely stable. Using the sector codes, the retail sector and the professional, scientific, technical, and financial services sectors were selected as two groups of businesses which were likely to be impacted by noise. Moreover, these two sector groups are each worthy of separate investigation because they may respond differently to noise from one another. Conversely, sectors like mining, construction, manufacturing, and warehousing were excluded because they operate in noisy environments and are less susceptible to noise change effects. Relatedly, sectors were cut which were unlikely to actually operate at their office address; most of the work in transportation businesses may take place away from the listed address, and thus the noise they receive is unpredictable.

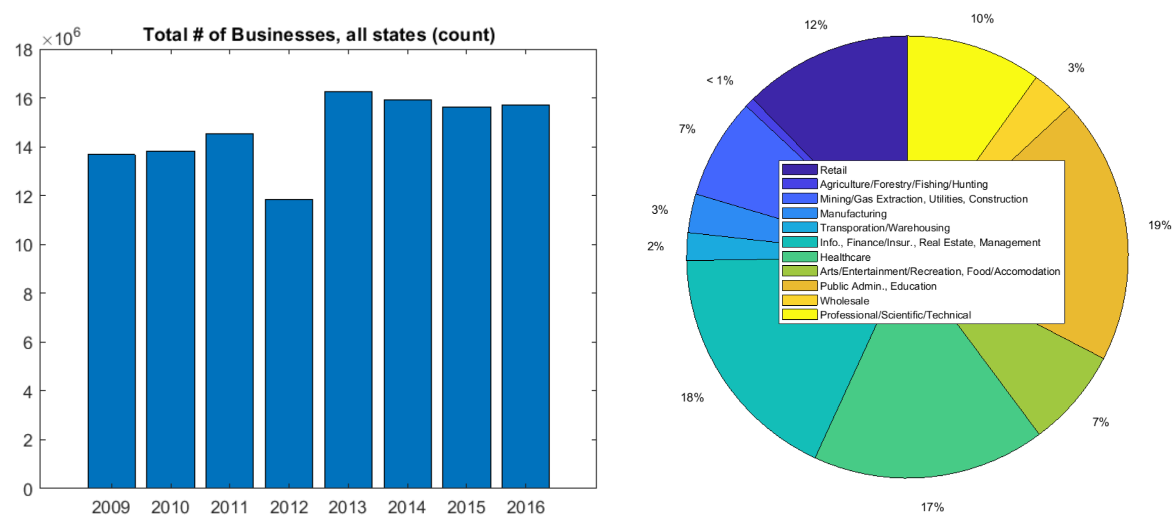


Figure 5: (left) InfoGroup recorded an average of 15 million business listings each year during the period 2009 to 2016. While the year-to-year change approximately matches totals recorded by the Economic Census, the marked decrease in 2012 is unrealistic and is likely due to internal methodological changes in InfoGroup's data gathering.
(right) Sectoral breakdown, across all U.S. states in 2015, by establishment count. Retail and Professional, Scientific and Technical Services, make up similar shares of the economy.

Our noise data was modeled in the Aviation Environmental Design Tool (AEDT). Boston data was shared by HMMH. For Chicago, in-house noise modeling at the International Center for Air Transportation was necessary because existing data from previous national noise studies, which used total number of flights to scale published procedures rather than real dispersed flight tracks, proved insufficient to show the fine-level concentration effects of RNAV/RNP. Contours were created from several hundred thousand radar-measured flight tracks collected between the months of May and August as part of the Airport Surface Detection Equipment Model X (ASDE-X) roll-out, beginning in 2011. A small number of flights, less than two percent, were excluded because their departing runway or aircraft type were unknown. The DNL was also normalized by the number of hours included per day, which due to ASDE-X system outages, generally occurring during the middle of the night, was sometimes fewer than twenty-four. To reduce computation time, a half-width method, developed in Jensen (2018), generated sets of contours as a look-up function which can be applied to many flight path geometries and save time by precluding the need for high-fidelity modeling of every trajectory. This method, once calibrated for a given set of initial conditions, calculates the width of each noise contour based on just two factors: aircraft's distance along the flight track and its altitude. Then bilinear interpolation can be used to generate a continuous noise grid.

Geospatial Analysis

The geospatial component of the research is shown in Fig. 6, showing changes to data type during processing. A number of even more fine-grained steps catch edge cases, such as ensuring that the business and noise grids are aligned with one another and excluding cells which are entirely underwater. For a more detailed set of all GIS operations used, see Appendix 2, which shows a visual representation using ArcMap's Model Builder. Both noise and business data were mapped using ArcGIS. Each city is projected using the relevant U.S. State Plane projection, from the set of conformal projections which are adapted and centered to best display each state in the United States. Geographic tools were used to modify the data format of the noise data from contours (line shapefile) to a continuous interpolation (high resolution raster) to a grid of noise values sampled from the center of each cell in city-wide grid (points). Likewise, the business locations (points) were aggregated on the same city-wide grid creating total business counts per cell. Conformal projections were used to ensure that these gridded maps appear as squares, and are not distorted into rectangles; the division into grid squares turns the continuous variable of aviation noise into a choropleth. Conversely, equal area projections may distort the shape of the grid and may make cells appear with different dimensions, even if each cell contains the same true area. For our purposes, since areas and polygon sizes are not dependent variables of analysis, an equal area projection is not necessary.

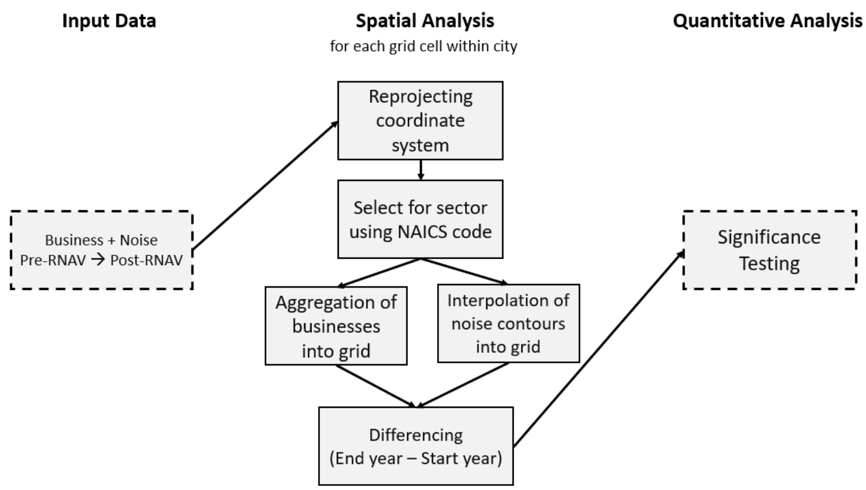


Figure 6: Geospatial analysis steps, pictured within block diagram of broader analysis.

Further, in recognizing the modifiable areal unit problem of choropleth mapping, a sensitivity analysis was performed on the grid size to ensure that results are not contingent on the specific borders of the cells. A grid size that is too fine captures businesses that relocate across the street, a change that could not be caused by noise since aviation noise changes imperceptibly on the scale of only 100m ground-range distance. Conversely, a grid size that is too large will fail to capture relocations within a single cell that may have been caused by real differences in noise across a cell. Thus, grid size should approximately match the scale of perceptible noise changes. For Boston, the shortest distance over which noise increases by 3 dB DNL is approximately 300m. Therefore, Boston was gridded at 200m resolution. Chicago, with its overall larger extent, was gridded at a slightly lower resolution of 475m to reduce computation time in modeling.

Maps of all of the base data are shown in Fig. 7-8, including noise levels and business activity before and after noise redistributions, for both Boston Logan International Airport and Chicago O'Hare International Airport. For both airports, the areas of highest noise concentration shown radiating outward following arrival and departure paths. In Boston, moving from 2011 to 2016, there was an increase in noise across most of the region west of the airport, in part due to overall traffic increases. Moreover, concentration effects show that noise increase is most strong over the flight tracks; thus not all areas experience the increase in traffic equally. While noise generally decreases with distance from the airport, due to the rising altitude of the departing aircraft, this relationship is by no means linear. For instance, note that the Fenway neighborhood (due east of BOS, where the Charles River narrows) is nearer to BOS than Milton (south south-east of BOS), but Fenway only received less than 50 dB DNL in 2011 and some parts of Milton receive more than 55 dB DNL.

Corresponding business patterns of the greater Boston Metropolitan Area are shown in Fig. 7. For both the retail sector and combined professional, scientific, technical and finance sectors, the maps show that most cells contain zero businesses, although some cells do contain businesses in unpictured sectors, e.g. wholesale. Many prominent non-occupied areas represent parks or major transportation infrastructure. In the quantitative analysis, these cells were excluded, since their lack of year-to-year growth is entirely a result of land use policy, not noise change. Other areas, like Boston's downtown, show high levels of activity; the high business density of downtown shows agglomeration effects, forming a long tail on the business distribution where just a few cells have hundreds of businesses—more than some outlying towns have combined. The retail map shows the major thoroughfares, forming veins leading out from the city center, while the professional and technical sectors, being generally less present along roads and more common in city centers, dot across the landscape in high-density clumps.

For Chicago, shown in Fig. 8, differences are characterized by the decreased noise to the north of ORD, and along the northwest, northeast, southwest, and southeast diagonals. Here, the spatial of extent of the noise modeling was reduced to avoid interference with Chicago Midway International Airport (MDW), for which no ASDE-X radar data was available. While this reduced extent leaves much of the South Side outside of the scope of this analysis, it fortunately still contains all of Chicago's central business district, which was determined to be wholly outside of MDW's 45 dB contour. ORD itself is contained within the city of Chicago, whose border extends to the northwest through a thin isthmus to a circle immediately around the airport.

In Chicago's business maps, the lower frequency of zero-business cells is a consequence of increased cell size from 200 to 475 meters; with cells containing five times as much area, the likelihood of there being no businesses in a cell decreases, and the ranges of the bins in the legends have been accordingly expanded to promote comparability to Boston. The zero cells that do exist, again, correspond mostly to undeveloped spaces, such as the Des Plains river which stretches from downtown to the southwest toward the map legend. While the coarser resolution is no longer sufficient to show the influence of most individual roads, a few, such as the East-West Cermak Rd are visible, as is the city's square block structure in many of its North Central neighborhoods. Relative to retail businesses, the data reflect that the concentration of professional, technical, financial, etc. businesses is greater along the lakefront and in Lincoln Park.

Moving forward, these maps form the basis of our quantitative analysis, where noise and business data can be compared on their matching grids via differencing.

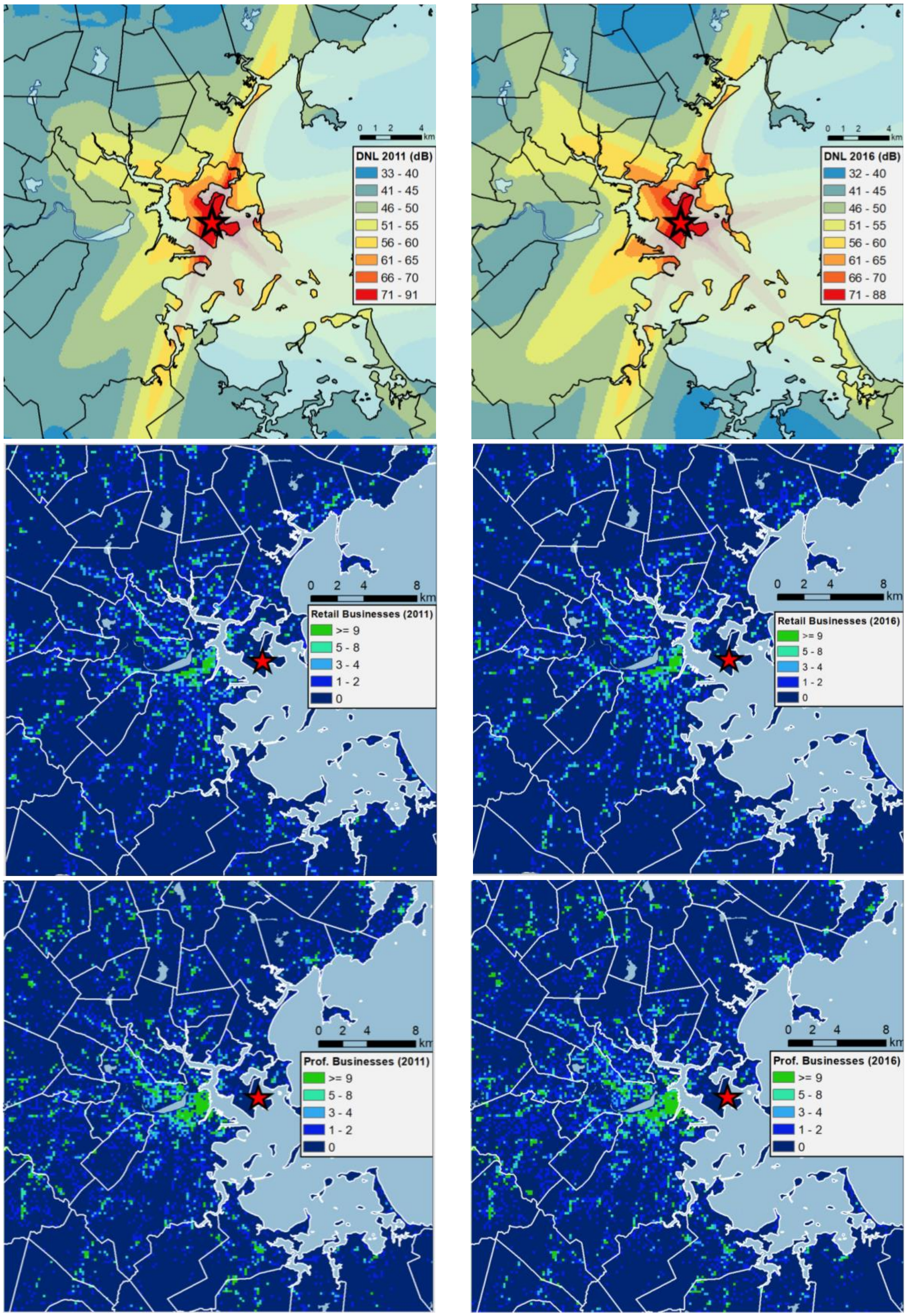


Figure 7: Boston geospatial data showing (top) Noise levels before and after RNAV, in DNL, binned at 5 dB intervals; (middle) retail business locations before and after RNAV, gridded at 200m resolution; (bottom) professional business locations before and after RNAV. Lines in basemap are municipal boundaries, the BOS airport is starred.

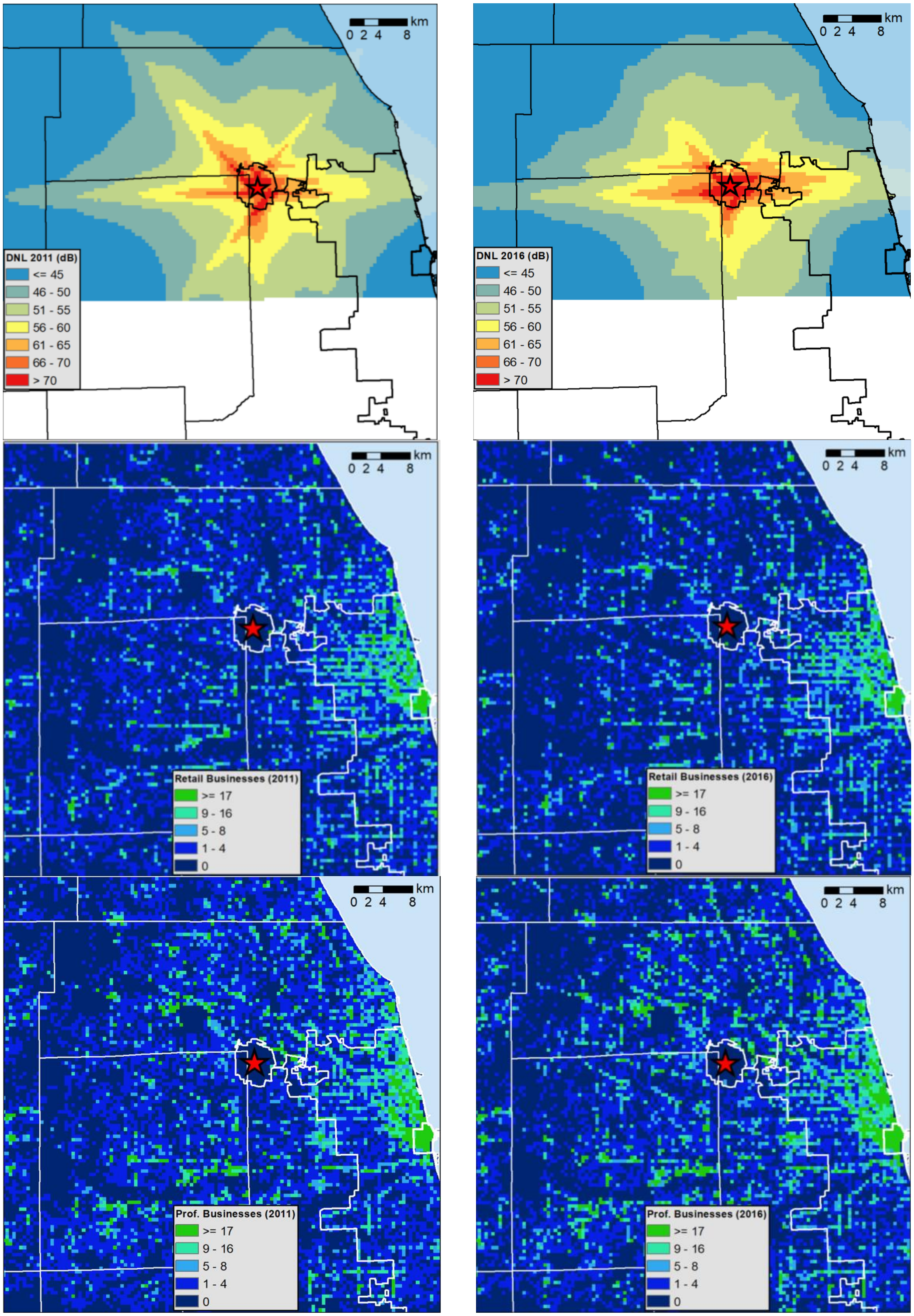


Figure 8: Chicago geospatial data showing (top) Noise levels before and after runway construction, in DNL, white areas showing reduced extent due to unknown MDW interference; (middle) pre and post retail business locations, gridded at 475m; (bottom) professional business locations. Basemap lines, from thinnest to thickest, show county boundaries, the municipal border of Chicago proper, and its downtown. The ORD airport is starred.

Quantitative Analysis

The block diagram in Fig. 9, shows the top-level process of building the noise-economic association and how it was evaluated. In particular, two key stratification variables—contiguous geographic region and initial year noise level—were examined to control for spatial biases, because different regions may be subject to different relationships between noise change and business change. For example, aviation noise may suppress business everywhere *except* in the central business district (CBD), where core-agglomeration effects outweigh aviation losses, and if the CBD is wholly contained in the noise increase treatment group (as is the case for Boston), results would be skewed.

Due to the wide variety of factors which affect economic outcomes, this study uses a difference-in-differences (DID) methodology to control for natural variation in starting levels, like the number of retail businesses in a very populated area being greater than the number of businesses in a sparsely populated area, across otherwise comparable regions and so long as those regions are affected by parallel trends. This approach takes inspiration from Card and Kruger's 1994 study on minimum wage, which used the natural experiment of changing minimum wage laws in New Jersey to compare employment across the Pennsylvania-New Jersey border. In the context of aviation noise, our natural experiment comes in the form of 1) area navigation (RNAV) procedures, which have led to decreased dispersion of aircraft trajectories and concentrations of noise, and 2) infrastructure changes, which in some cities have dramatically changed the locations which receive high levels of noise. By identifying areas of increasing noise and decreasing noise, and likewise identifying locations with changes to business count, this methodology bypassed needing to explain extant levels at any given point in time or in space, which are multiply-determined. Instead, it assumes that most factors which determine business activity do vary geographically over a city, such as neighborhood populations, land use types, and accessibility via public transit, but remain constant in time, particular over a short time window of fewer than ten years. If one location experiences economic growth at a faster rate than another, and noise was the only determinant of business activity that was not constant during the time of growth, then it is likely that noise was the cause of that growth.

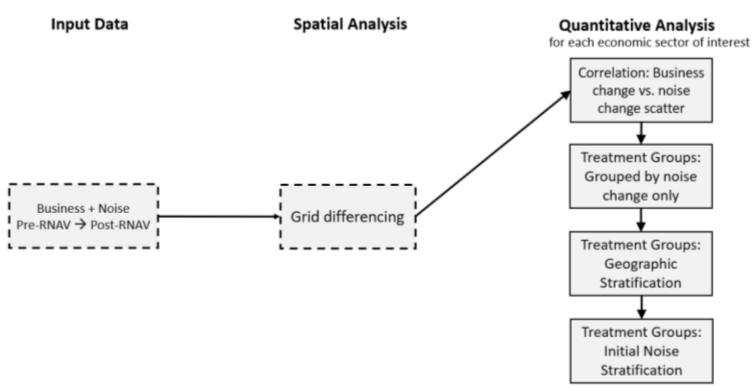


Figure 9: Highlighted quantitative analysis steps within block diagram of broader analysis.

Showing this difference-in-differences approach mathematically makes clearer the remaining need for stratification. We consider a plot of land j with starting number of businesses Y, as a proxy for economic output. This Y may be a function of noise level *L* in addition to a set of non-noise variables, denoted as the vector **x**. These might include the presence of natural resources on that land or whether it is contained within a particular political boundary. In addition, assume business counts to be driven by other random factors which are uncorrelated with *L* and **x**. These impacts are captured in ε. Assuming that the relationships are linear and independent with added y-intercept *C*, we have:

$$Y_j(L, x_1, x_2, \ldots, x_N) = \beta_0 L + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_N x_N + C + \varepsilon \tag{1}$$

The difference in business outcomes between Y_j and another plot of land Y_k, are measurable, using data described in the preceding subsections. Likewise, data has been modeled within the International Center for Air Transportation to accurately measure L, the noise levels at both Y_j and Y_k. In the absence of **x**, this would be sufficient to determine β_0 as the slope between two points. Also assuming that, on average, the two error terms ε_j and ε_j cancel one another, we would have

$$Y_j - Y_k = \beta_0 L_j - \beta_0 L_k \Rightarrow \beta_0 = \frac{Y_j - Y_k}{L_j - L_k} \text{ (for single-variable case only)} \tag{2}$$

but with **x**, we instead have

$$Y_j - Y_k = \beta_0(L_j - L_k) + \beta_1(x_{1,j} - x_{1,k}) + \beta_2(x_{2,j} - x_{2,k}) + \ldots + \beta_N(x_{N,j} - x_{N,k}) \tag{3}$$

requiring perfect knowledge of which factors constitute **x** and the coefficients of their relationship with Y. For any economic factors which do not vary across space, e.g. the federal minimum wage in the United States context, $x_{N,j} - x_{N,k}$ will reduce to zero, but many variables will not. In the general case, it will be not only difficult to accurately measure the values of the variables in **x**, it may be impossible to even qualitatively generate an exhaustive list of the factors which comprise **x** without making many simplifying assumptions. To eliminate this omitted variable bias, we consider the first difference between Y at time 0 and Y at a later time 1. In locations with known noise change, we define $L_{j,t=1} - L_{j,t=0} = \Delta L$. If **x** is constant between the two times, then $x_{N,t=1,j} - x_{N,t=0,j} = 0$, and likewise if the intercept *C* is constant in time then $C_{j,t=1} - C_{j,t=0} = 0$. Furthermore, we assume that all coefficients $\beta_0, \beta_1, \ldots, \beta_N$ are constant in time. Thus,

$$\Delta Y_j = Y_{j,1} - Y_{j,0} = \beta_0(\Delta L_j) \tag{4}$$

and then re-comparing between the two locations

$$\Delta Y_j - \Delta Y_k = \beta_0(\Delta L_j) - \beta_0(\Delta L_k) \Rightarrow \beta_0 = \frac{\Delta Y_j - \Delta Y_k}{\Delta L_j - \Delta L_k} \tag{5}$$

as desired. The DID methodology uses the first difference to handle changes which do not vary across time, for which the time difference will be zero, and also changes which do not vary across space, for which the second difference will go to zero. As examples, for the former, consider the location of the airport itself, which might have an effect on where businesses develop, but the effect of which should remain constant in time; for the latter, consider the federal target interest rate, which varies over time but cannot affect different locations differently. The assumption that **x** is constant through time is most reasonable over short time intervals. For instance, populations do change, and the geographic distribution of that change is non-uniform; the Boston-Cambridge-Newton Metropolitan Statistical area grew by 4.1% during the time period of examination, 2011 to 2016, while the population of Boston, its central city, grew slightly disproportionately by 4.4%, potentially leading to an increase in businesses activity within the city relative to its neighbors, unrelated to noise exposure (United States Census Bureau, Metropolitan and Micropolitan Statistical Areas Population Totals and Components of Change: 2010-2019).

Moving beyond this basic regression model, we may also consider nonlinear effects. Human perception of noise is nonlinear—a doubling of acoustic sound level yields far less than a doubling of perceived loudness, hence the logarithmic decibel scale—and as such, it is reasonable to hypothesize that there may exist a threshold of DNL beneath which no effect on businesses is observed. Moreover, several authors have identified a phenomenon of excess response; annoyance following an abrupt noise change moves beyond what would be expected based on standard dose-response curves, and thus this change effect compounds noise damages beyond mere exposure (Brown and Kamp 2009). This effect is largely absent below at least 1 dB increases, consistent with other findings that reductions to noise exposures by -1 to -2 dB did not observably improve health outcomes (Brown and Kamp 2017) and that even noise changes (not DNL) are generally not perceptible above at least 3 dB. This nonlinearity might cause the difference-in-differences perspective above to conceal a real relationship by not adequately removing the baseline effects of L on business activity. The effects of noise were therefore also tested using a treatment-nontreatment method. Assigning each plot of land to a treatment (noise change) or nontreatment (little to no noise change) group may reveal these effects. Balancing the goals of maximizing effect size, maximizing significance of effect, and testing sensitivity across a range of arbitrary thresholds, the treated population were defined in separate groups as those cells which received noise increases of $\geq |\pm 1|$ dB, $\geq |\pm 2|$ dB, and $\geq |\pm 4|$ dB.

However, one might also consider cases where the quantitative model above breaks down. If the coefficient vector β is itself a function of location, then our method will not produce a universal β_0 that characterizes the slope of the noise-economic relationship for all locations, but rather a $\beta_{0,j}$ which is applicable only for a small region. In this case, treatment groups may be skewed when certain regions respond to changes in noise differently than others, and these regions are not distributed randomly between treatment groups. For instance, central business districts exhibit uniquely high business densities and receive special attention from city planners, and thus may be immune to suppression effects from noise in a manner inconsistent with surrounding points, which might receive real business impacts from noise increase. Geographic stratification of treatment and nontreatment groups into smaller sub-regions that are more internally comparable may remove the biasing effect of the CBD.

Furthermore, one might consider when the coefficient vector β is a function of the noise level L in a given year. One hypothesis might suggest that those who previously received low noise may be more sensitive to increase than those who had already acclimated to high-noise environments. This hypothesis is termed relative deprivation, borrowing a term from prior work in collective action problems which show that political involvement may be stimulated not by an absolute change in resources but a change relative to the standard to which citizens are accustomed (Gurr 1970). Relative deprivation suggests that the noise-business relationship may be path dependent, two locations with equal noise levels might respond differently depending on how the locations had arrived at those noise levels, and whether the increase in noise was sudden or gradual. This breaks the difference-in-differences approach derived above because start year noise may be present in the business outcome determination of Y_1 but not in Y_0, resulting in a non-cancellation during the first differencing. This dependency can again be removed with stratification by subsetting only locations that received low noise before procedure changes and then proceeding with significance testing, such that initial noise level does not vary across the sample and cannot be the cause of different business outcomes.

4. Results

Boston

Correlation Analysis

Fig. 10 shows the changes from 2011 to 2016 after differencing the noise and business data shown in Fig. 7. The areas of greatest noise increase, sometimes in excess of +5 dB DNL, are toward the northwest of BOS, as the flight track bifurcates over North Cambridge and Medford. As of 2021, work is underway to remediate this noise increase by reintroducing dispersion into the flight tracks. Conversely, the regions in-between runways, to the north, east, and south, saw noise decreases of generally no more than -4 dB. These change contours were used to form the basis for our first set of treatment groups, those based purely on the change in DNL.

The business changes show scattered effects with few areas of concentrated growth and decline. The areas of greatest activity, near downtown Boston, show regions of growth right next to regions of decline, suggesting either fluctuations in business population as new businesses fail to survive, as well as relocations of less than one kilometer. In outlying areas, change patterns are largely dominated by new developments. In the southwest corner of the retail map, for instance, there was visible decline in North Dedham and growth in South Dedham which directly corresponds to the opening of the Legacy Place shopping mall in 2009, to which businesses migrated to benefit from agglomeration. In this way, while some changes appear random, others have clear explanations after examining local commercial conditions. The professional sectors, on the whole, appear to show more volatility than retail. A few patches show intense decline, as in downtown Quincy, or growth, as in Cambridge's Kendall Square; neither of these locations show especially strong signals on the retail change map.

Turning to the correlation between noise change and business activity, Fig. 11 shows the lack of correlation between business and noise change. Overall, there does not appear to be a strong trend; there exist cells that exhibit minor growth and decline at every level of noise increase and decrease, for both sectors. The range on the professional sector changes includes several cells with an absolute change of greater than 100 businesses, a much wider range than retail. The p-value for a linear fit is high, and its associated R^2 statistic is very near zero, showing that linear fitting is inappropriate for both the retail and professional data. Moreover, there do not appear to be any strong thresholding effects, where a trend appears past a certain minimum level of absolute noise change. In these scatter plots, points that had zero businesses in both sector groups both before and after RNAV are excluded; these points often represent parks, highways and other areas that have non-noise reasons for being undeveloped. Still, many points appear on the x-axis, because no change is a common outcome even for cells that do contain businesses.

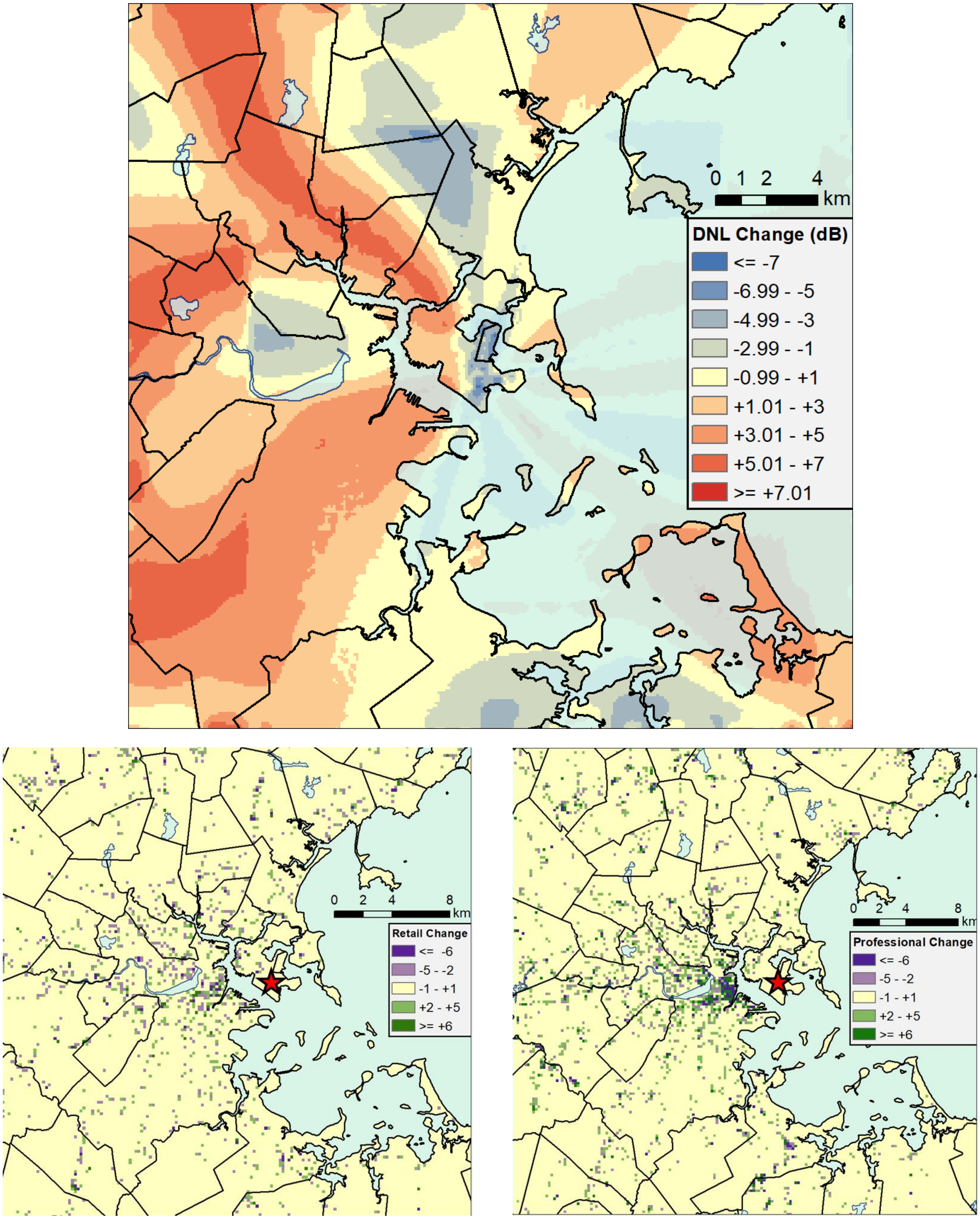


Figure 10: Boston-area difference maps for (top) DNL, binned at 2 dB intervals; (left) retail businesses; and (right) professional businesses. In the business change plots, yellow regions show little to no business change, purple regions show retail decline, and green regions show growth.

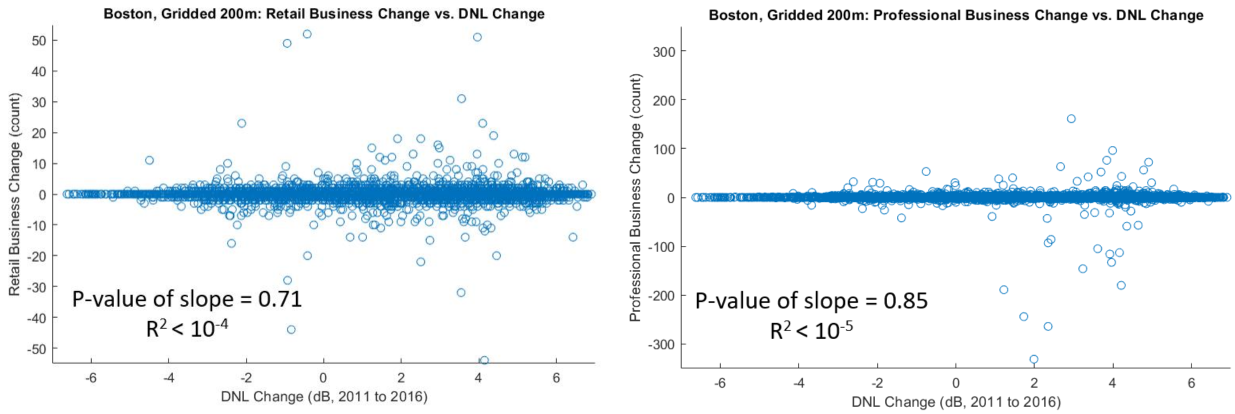


Figure 11: Correlation analysis showing the business changes vs DNL changes in each cell in the greater Boston area for the retail sector (top) and professional, scientific, technical, finance, and insurance sectors.

Outlier Analysis

It is possible that noise has no aggregate trend, but may adversely affect just some locations in the city, which are particularly noise sensitive. Outlier points, by definition, do not obey the general trends in the data, and further examination of outliers, as shown in Fig. 12, will ensure that noise is not driving this deviation. In, particular, above 1.5 dB of noise increase, there exists a cluster of cells which experienced large losses of businesses in the professional sector. Without exception, all points that correspond to professional sector losses in excess of 100 businesses are located in a single geographic cluster in downtown Boston, where it is likely that broader economic trends and policies, like the 2010 formation of the Downtown Boston Business Improvement District which focused on retail growth, drive these outcomes. Indeed, many of these same cells did experience retail growth. Furthermore, later data from Chicago will confirm that this pattern of downtown is not unique to Boston. Additionally, there is a region of larger than normal professional decline in Quincy, which has been characterized by decades of decline following the closing of an influential shipyard (Tiernan 2019). The points of highest retail growth and decline are driven by changes within two shopping malls: Square One, in Saugus, and Copley Place in Back Bay, Boston. In each of these cases, business changes are directly attributable to intra-mall renovations or anchor stores going bankrupt; no high magnitude changes are attributable to noise. None of these outliers points to the existence of an isolated noise trend, or a community response to noise changes.

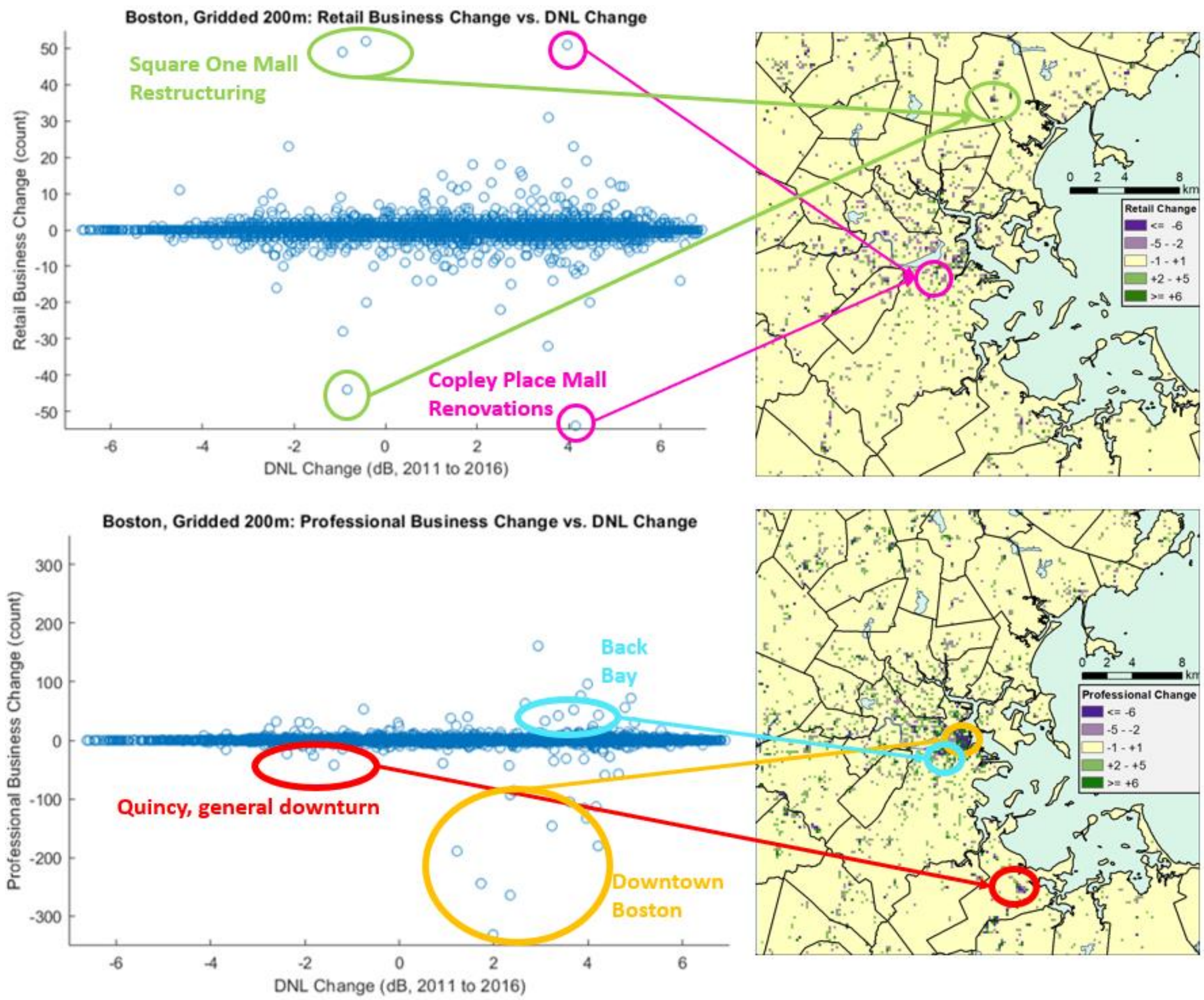


Figure 12: Outlier analysis for Boston scatterplots. Locations of highest retail growth and decline come in pairs; they are not independent. Locations of substantial professional sector growth and decline are also geographically correlated, but do not show significant dispersion in noise.

Noise Change Thresholds

Having ruled out aggregate linear effects and noise-sensitive outliers, the following sections turn to treatment group analyses, able to detect nonlinear or threshold-based effects, to test robustness of the apparent null result implied by the correlation analysis. The statistics for the nontreatment group, those cells which experience between -1 and +1 dB DNL of noise change, are shown in Table 1. These nontreatment means set a baseline against which all subsequent treatment groups will be compared. The first set of these treatment groups is defined strictly by the noise change shown in Fig. 10, using cutoffs of 1, 2, and 4 dB DNL to ensure that the results are not sensitive to the arbitrary treshold. The results of this analysis are shown in Table 2. For each treatment group, and for each sector, the table includes the net number of businesses gained or lost, the mean number of businesses gained or lost per cell, and the difference between the mean business change in each treatment group and the mean business change in the nontreatment group; significance is determined by a two-sample t-test. Put differently, the latter answers the question: how much more did the cells in the nontreatment group grow or decline relative to the cells in the treatment group? Positive values indicate that the nontreatment group grew more than the treatment group; negative values indicate the treatment group exhibited higher growth. All regions of noise increase, no matter how strong, are comparable to the nontreatment zone. In none of the zones was the mean absolute business change greater than 1, reaffirming that in all zones, most cells do not grow or decline in number of businesses, irrespective of noise. Both positive and negative business growth appear across zones that received increases and decreases to noise, giving indication that noise change does not produce outcomes that are significantly different from nontreatment.

Table 1: Nontreatment cells' and total population's summary statistics.

	Nontreatment: Noise Change ≥ -1 and ≤ +1 (1166 cells)	**Total (All 5271 cells)**
Retail Business Change	Net: +21; Mean: +0.02	Net: -19; Mean: -0.00
Professional Business Change	Net: +399; Mean: +0.34	Net: +507; Mean: +0.04

Table 2: Net retail business changes (count), mean number of business changes per cell, and difference of means (abbreviated DoM) between the nontreatment group business change mean and the treatment group business change mean, for each of the noise change treatment groups, rounded to two decimal places. Significance is denoted as
*** p < 0.05, * p < 0.1*

Grouped by Noise Change Only	Noise increase ≥ 1 dB (3286 cells)	Noise increase ≥ 2 dB (2513 cells)	Noise increase ≥ 4 dB (1213 cells)	Noise decrease ≤ -1 dB (819 cells)	Noise decrease ≤ -2 dB (459 cells)	Noise decrease ≤ -4 dB (43 cells)
Retail Business Change	Net: +5 Mean: +0.00 DoM: +0.02	Net: +24 Mean: +0.01 DoM: 0.01	Net: -2 Mean: -0.00 DoM: +0.02	Net: -45 Mean: -0.05 DoM: +0.07	Net: -19 Mean: -0.04 DoM: +0.06	Net: +7 Mean: 0.16 DoM: -0.14
Professional Business Change	Net: -136 Mean: -0.04 DoM: +0.38	Net: +301 Mean: +0.12 DoM: +0.22	Net: +340 Mean: +0.28 DoM: +0.06	Net: +244 Mean: +0.30 DoM: +0.04	Net: +168 Mean: +0.37 DoM: -0.02	Net: +17 Mean: +0.40 DoM: -0.05

Contiguous Geographic Regions

Consider another more nuanced case: if citizens of Hull, in the southeast, feel strongly connected to their town they may have civic reasons to remain in business even if the noise increase might otherwise incentivized them to close or relocate, so no pattern of relocation appears while their cells are present in the analysis. By subsetting regions of noise increase and decrease, it may allow patterns to emerge between regions that show no effect in aggregate. Contiguous geographic treatment groups also eliminate the risk of Simpson's paradox: a statistical phenomenon in which the aggregation of multiple groups can distort or reverse real trends, e.g., if noise increases suppressed businesses among the cells in two towns, but one town happened by chance to have both greater noise increases and stronger business growth than the other. Fig. 13 defines the continguos geographic zones. All regions that received an absolute noise change of greater than or equal to 2 dB DNL are subdivided into five geographically contiguous zones, two of which received noise decrease and three which received noise increase. The border between Brookline and Newton was used to divide Zones 1 and 2, as this line roughly corresponds to which runway at BOS affects these two zones. Resuts are shown adjacent to each zone. None of the retail zones significantly different from the nontreatment mean, that average business change the set of cells which received between -1 and +1 change to dB (see Table 2). The professional sectors show one significantly different region, to the southwest. This phenomenon is almost certainly driven by downtown, as this region contains the strong negative outliers that could have been produced by the Downtown Boston Business Improvement District. Furthermore, in light of the fact that there have been over ten two-sample t-tests performed thusfar for Boston, a Bonferroni correction for multiple hypothesis testing is appropriate, reducing the necessary significance level for confidenace to below $\alpha < 0.01$, a level of stringency that none of the weakly significant zones are able to meet, suggesting that these results could have been produced by chance.

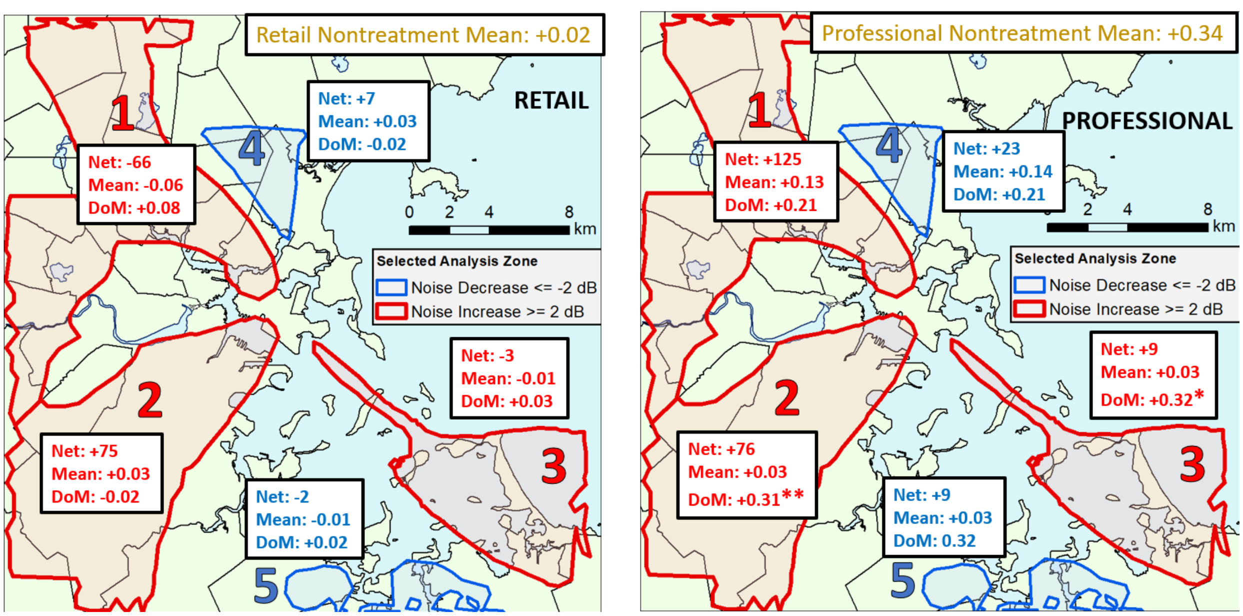


*Figure 13: Treatment groups based on contiguous geographic zones. Zones 1, 2, and 3 show increase, while Zones 4 and 5 show noise decrease. Each of these zones is independent; none contain shared cells. Each zone is labelled with its corresponding net business change, mean business change per cell, and the difference of means (abbreviated DoM) between the treatment group mean and the nontreatment means. Significance denoted as: ** $p < 0.05$, * $p < 0.1$*

Relative Deprivation Regions

In the last set of treatment groups, shown in Fig. 14, zones are not geographically contiguous, but are instead grouped by the requirement that they received low noise before the introduction of RNAV procedures. Under a relative deprivation hypothesis, these locations may show greater response to noise change than populations which had already acclimated to

high noise; that is the deprivation of quiet is more affective in some populations than others. Because DNL levels below 45 dB DNL is rarely instrusive—most dose-response curves find less than five percent of the population is highly annoyed below 45 dB—an increase in DNL may push populations over a threshold of noise perceptibility. If the set of cells which receive noise increases, when aggregated, include some populations which are acclimated, and some populations which are not acclimated because they are used to low noise, this might hide a trend. Furthermore, analysis of noise complaints received by the FAA shows that there are many complaints submitted from regions below 45 dB DNL (2011), particularly from towns like Belmont and Arlington, parts of which received noise increases that pushed them over the 45 dB threshold by 2016. These complaints suggest that businesses there may also feel the effects of noise increase.

The zonal summary statistics and difference of means values are shown in Fig. 15. None of the three zones show business change patterns statistically different from the nontreatment group at the $p < 0.05$ level. The worst-performing region, economically, was the first geographically-contiguous stratification zone, to the Northeast, which had a mean cell business decline of -0.06 relative to the growth of +0.02 businesses per cell in the nontreatment group, but this difference is quite small relative to the standard deviation of retail changes among the cells in that zone.

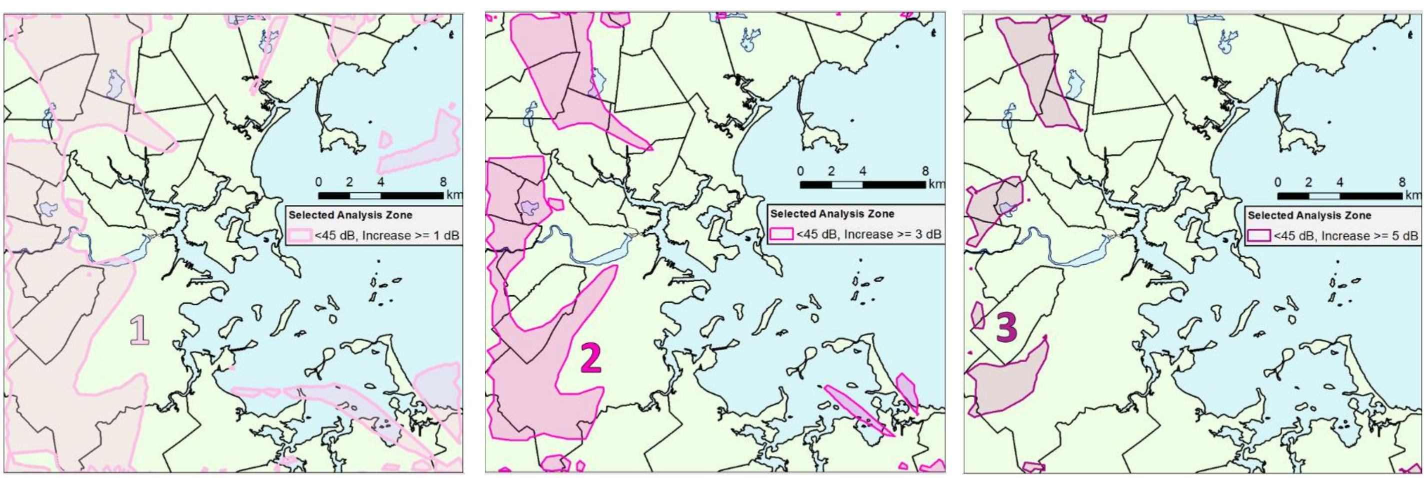


Figure 14: Last set of treatment group zones, for testing a relative deprivation hypothesis. All three are subsets of the cells which received below 45 dB DNL, with Zone 1 (left) receiving an increase of at least 1 dB, Zone 2 (middle) receiving an increase of at least 3 dB, and Zone 5 (right) receiving an increase of at least 5 dB. These criteria mean that the zones overlap, such that Zone 2 and 3 are strict subsets of Zone 1, and Zone 3 is a strict subset of Zone 2.

The professional, scientific, technical, finance, and insurance sectors show a more varied picture, with two of the three geographically-contiguous increase zones and one of the relative deprivation zones showing at least weakly significant differences from the nontreatment mean (+0.34 professional businesses per cell). The latter of these, in relative deprivation Zone 2, has a negative difference-in-differences estimator, suggesting that it actually outperformed the nontreatment zone, in contrast to the contiguous geographic increase Zone 2 which shows underperformance relative to the nontreament zone. This difference is largely accounted for by noting the inclusion of the high-decline cells in downtown Boston (see the outliers analysis in Fig. 12) which are included zone of highest significance, but not the outperforming relative deprivation zone.

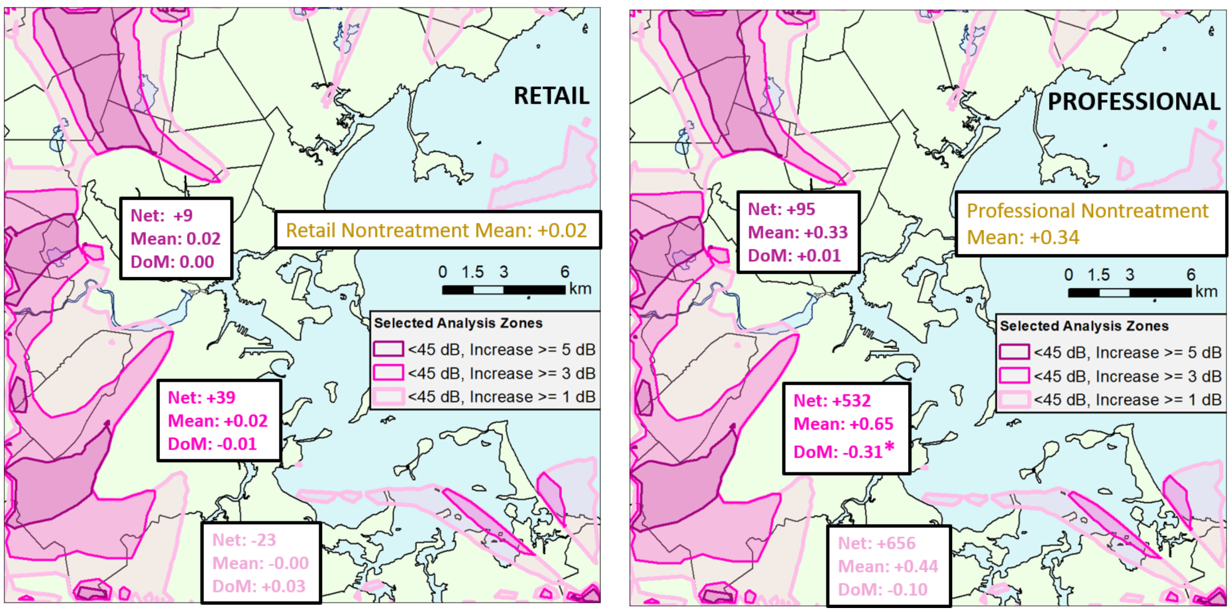


*Figure 15: Zonal statistics for treatments groups subject to relative deprivation stratification, for both the (left) retail and (right) professional sectors. Significance given by: ** p < 0.05, * p < 0.1*

Chicago

Correlation Analysis

Repeating the procedure for the Chicago O'Hare International Airport (ORD), difference maps are shown in Fig. 16, showing noise and business levels in each cell in 2011, before runway changes, subtracted from the corresponding cells in 2016, after the runway changes took place. Noise increase is not as pronounced as in Boston, rarely in excess of + 3 dB. ORD's East-West runways show increased traffic to compensate for the decommissioning of several diagonal runways that leave the intercardinal directions with reduced noise. This leaves most of downtown Chicago, the region with the greatest density of businesses, with reduced noise. This is an important counterfactual given that most of Boston's downtown had noise increases. This difference map has reduced spatial extent owing to the Midway International Airport (MDW), for which radar data was unavailable and which produces more noise than ORD over the South Side of Chicago.

The business change plots show many regions of concentrated growth and decline, with some stronger patterns than appeared in Boston. Broad categorizations are possible from visual inspection: Chicago's North Side experienced large professional sector growth; Chicago's Far North experienced moderate retail decline; and shopping centers such as Finley Square in Downers Grove, IL show concentrated regions of both growth and decline that dot the map in clusters. As in Chicago, some regions like large parks contain no business change because they contain no businesses, and these are excluded in all quantitative analysis. The large Chicago metropolitan area shows signs of urban sprawl, with regions of growth and decline abutting one another instead of concentrating into small pockets as they did in the towns surrounding Boston.

Correlating the noise change and business change in Fig. 17 shows a similar picture to that of Boston. For both retail and the professional sectors, three-quarters of all cells have an absolute change of two or fewer businesses. Among the cells with greater business growth and decline, they are present at the full range of noise change. The locations of moderate business change generally appear between -4 and +4 dB DNL change, not at extreme noise changes. This is likely as a result of the far higher number of cells between -4 to +4 dB, suggesting that unusually high or low business change is more a result of natural statistical variation than it is a result of noise change. Again, linear fits show weak correlation and low statistical power, nor do there appear to be any strong thresholding effects.

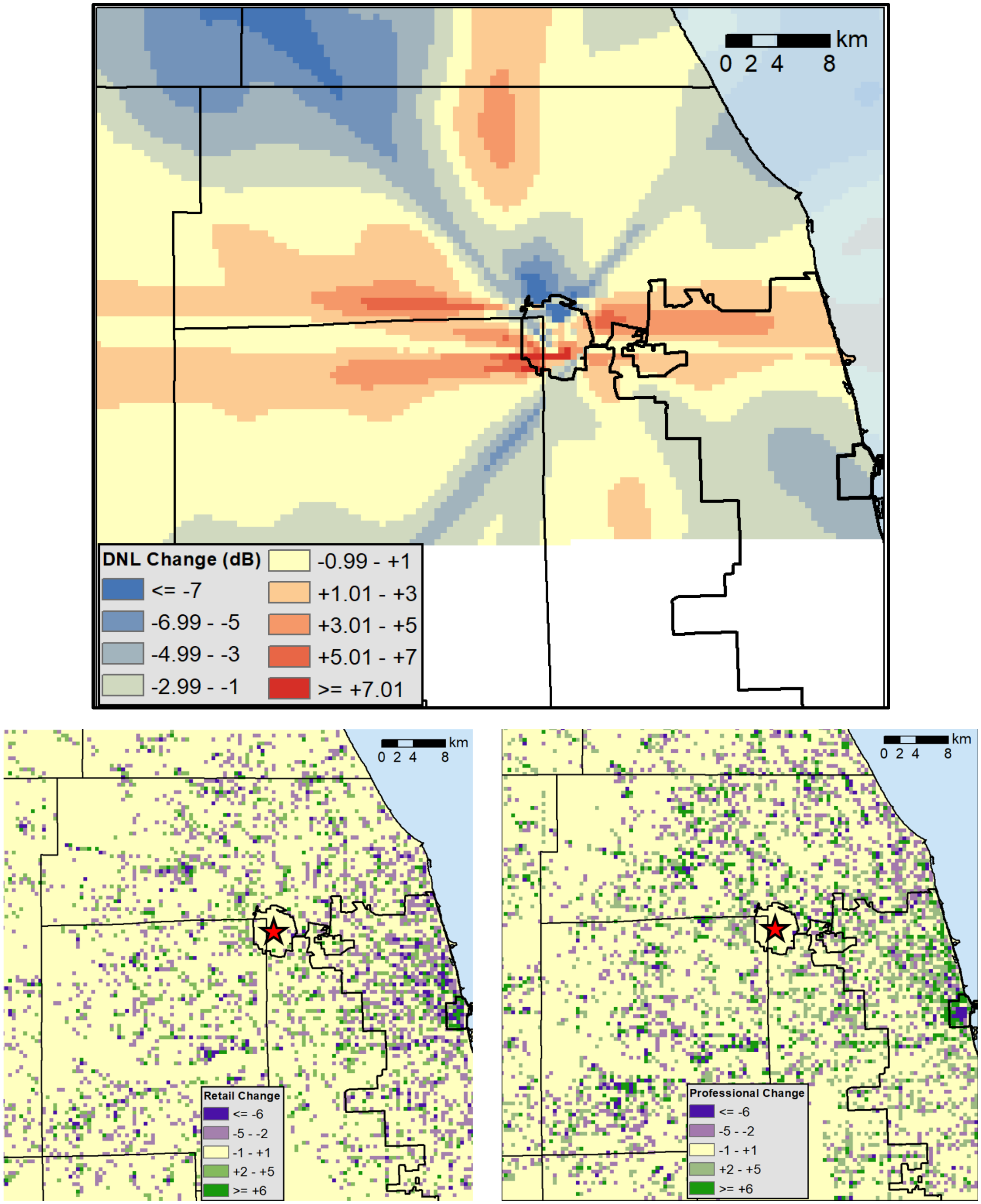
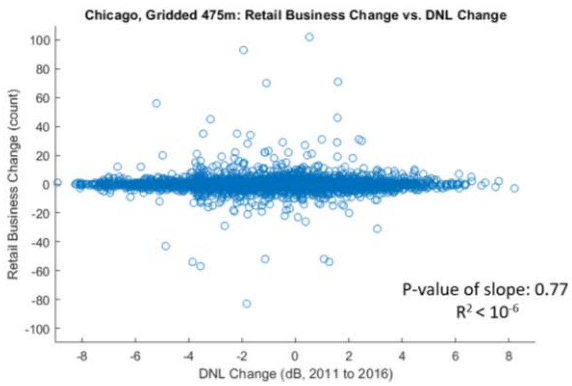


Figure 16: Chicago-area difference maps for (top) DNL, binned at 2 dB intervals, with white region excluded due to interference from MDW; (left) retail businesses; and (right) professional businesses. In the business change plots, yellow regions show little to no business change, purple regions show retail decline, and green regions show growth. Basemap lines, from thinnest to thickest, show county boundaries, the municipal border of Chicago proper, and its downtown



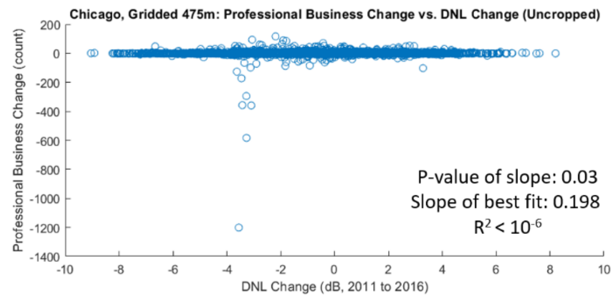
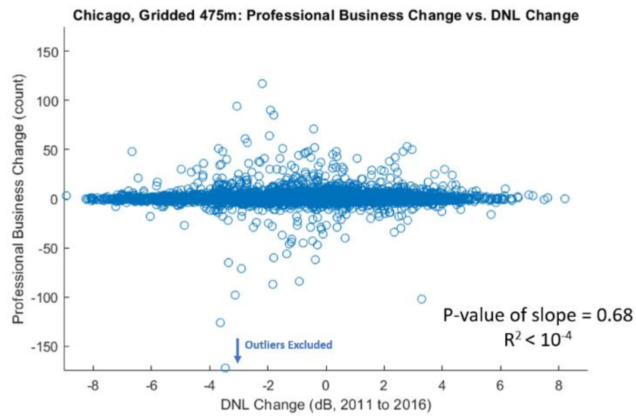


Figure 17: Correlation analysis showing the business changes vs DNL changes in each cell in the greater Chicago area for (left) the retail sector and (right) professional, scientific, technical, finance, and insurance sectors. The professional sectors are shown twice at different scales, to account for the presence of extreme outlier cells which lost hundreds of businesses.



Outlier Analysis

In the professional scatterplot in Fig. 17, a few negative outliers dominate the scale. These and other high absolute business change points are explored in Fig. 18. Most strikingly, these cells with hundreds of professional businesses lost are exclusively located in the central business district, known as the Loop, of Chicago. The cell of maximum loss, at over 1200 businesses, contains some of the tallest skyscrapers in the US, including the Willis Tower and 311 South Wacker Drive, each with many commercial tenants. While the Loop still contains the highest density of professional businesses in the city, these change patterns may be reflective of rising corporate downtown rents that push the numerous small firms out to the suburbs, or the increased availability of remote working diminishing the attractiveness of renting any office space at all. Barring a single certain explanation, nevertheless, all of the Loop saw substantial aviation noise decreases, so it is unlikely that noise played a role in relocation. Furthermore, the comparable professional sector decline in both Chicago and Boston suggest that the noise differences between them had little impact. As in Boston, regions of especially high magnitude retail change are typically associated with shopping malls, and may exist as pairs or small clusters of cells, as some parts of the mall are renovated or reopened. With these viable alternative explanations, there remains insufficient evidence that noise change is responsible for any individual cell's business change.

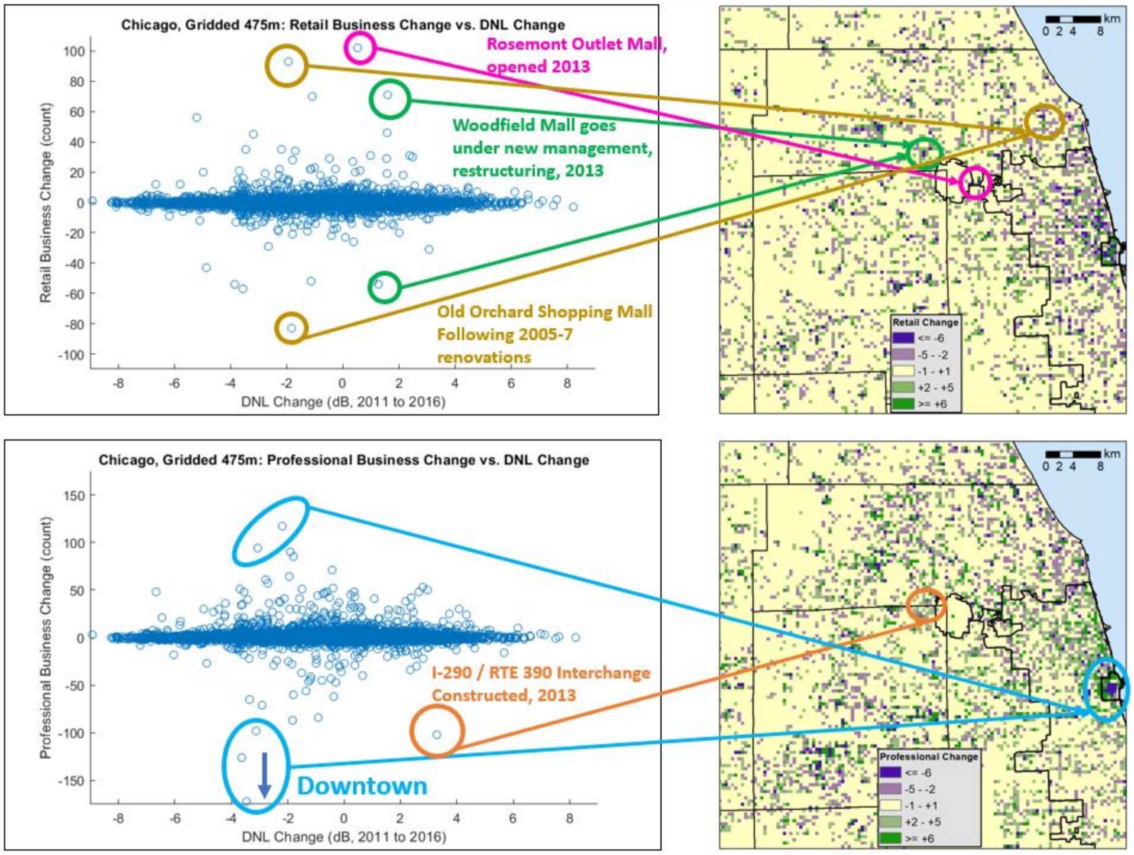


Figure 18: Outlier analysis for Chicago scatterplots. Locations of highest retail growth and decline come in pairs; they are not independent. Locations of substantial professional sector growth and decline do not appear significantly correlated with noise.

Noise Change Thresholds

Although it does not appear in Fig. 17 that there are any trends that exist only at high-magnitude noise change, this can be tested explicitly through treatment-nontreatment methods. Table 3 shows the mean change in number of businesses in each cell for the retail and professional sectors, among cells that did not receive noise change. To identify whether regions with noise change outperformed or underperformed regions with no noise change, two-sample t-tests compared the means of treatment groups, defined by the level of noise change received, against the nontreatment mean. Results are shown in Table 4. Only one treatment group, the noise decrease ≤ -2 dB for professional sector businesses, is significantly different from the nontreatment mean; the difference of means is positive, meaning the zone underperformed relative to the nontreatment group, with a mean business change per cell 1.55 businesses fewer than the nontreatment mean. By contrast, some treatment groups business change mean shows zero difference from the nontreatment mean. The explanation for this phenomenon is simple; referring back to Fig. 16, the ≤ -2 dB noise change zone includes the central business district, and its high loss outlier points. This effect vanishes after moving to the ≤ -4 dB treatment group precisely because downtown

Chicago's outliers are no longer included. Otherwise, Table 4 shows that both positive and negative mean business changes exist at both positive and negative noise increases, suggesting no aggregate noise effects.

Table 3: Nontreatment cells' and total population's summary statistics.

	Nontreatment: Noise Change ≥ -1 and ≤ +1 (2786 cells)	**Total (All 7098 cells)**
Retail Business Change	Net: -418; Mean: -0.15	Net: -1409; Mean: -0.199
Professional Business Change	Net: +1587; Mean: +0.57	Net: +1508; Mean: +0.22

Table 4: Net retail business changes (count), mean number of business changes per cell, and difference of means (abbreviated DoM) between the nontreatment group business change mean and the treatment group business change mean, for each of the noise change treatment groups, rounded to two decimal places. Significance is denoted as
*** p < 0.05, * p < 0.1*

Grouped by Noise Change Only	Noise increase ≥ 1 dB (1724 cells)	Noise increase ≥ 2 dB (1035 cells)	Noise increase ≥ 4 dB (155 cells)	Noise decrease ≤ -1 dB (2588 cells)	Noise decrease ≤ -2 dB (1759 cells)	Noise decrease ≤ -4 dB (650 cells)
Retail Business Change	Net: -426 Mean: -0.25 DoM: +0.10	Net: -253 Mean: -0.24 DoM: +0.09	Net: +14 Mean: +0.09 DoM: -0.24	Net: -565 Mean: -0.22 DoM: +0.07	Net: -439 Mean: -0.25 DoM: +0.10	Net: -81 Mean: -0.12 DoM: -0.03
Professional Business Change	Net: +1113 Mean: +0.65 DoM: -0.08	Net: +588 Mean: +0.57 DoM: +0.00	Net: +125 Mean: +0.81 DoM: -0.24	Net: -1192 Mean: -0.46 DoM: +1.03	Net: -1730 Mean: -0.98 DoM: +1.55**	Net: +292 Mean: +0.45 DoM: +0.12

Contiguous Geographic Regions

Given that individual regions may skew the aggregate effects of noise, isolating geographic regions may reveal any latent noise change effects. Fig. 19 shows five noise change regions, three with noise increase and two with noise decrease, that each have |≥ 2| dB noise change. As before, only one group has a mean business change statistically different than the nontreatment group: Zone 5, containing the central business district in downtown Chicago, which has a far lower rate of professional business change per cell. Aside from this outlier effect, no other regions present statistically significant difference of means. All three increase zones underperformed relative to the nontreatment baseline in the retail sector, but high enough variance of business activity within each region to be plausibly produced by random chance.

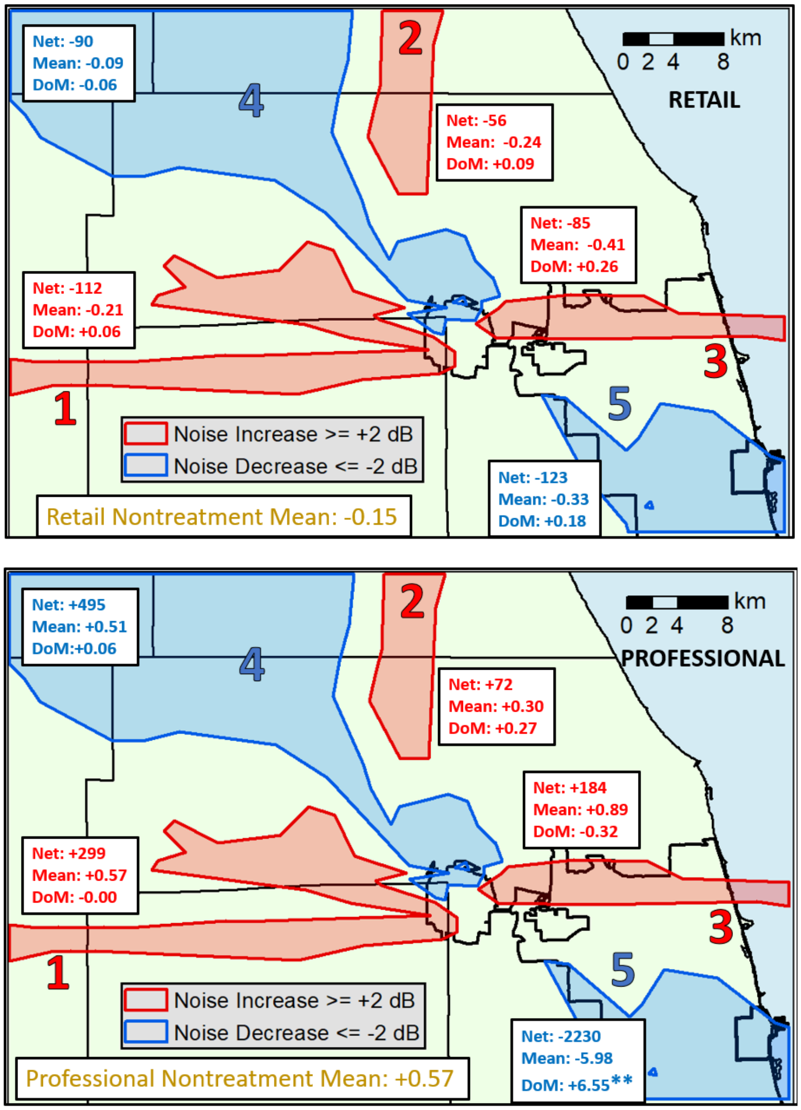


*Figure 19: Treatment groups based on contiguous geographic zones. Zones 1, 2, and 3 show increase, while Zones 4 and 5 show noise decrease. Each of these zones is independent; none contain shared cells. Each zone is labelled with its corresponding net business change, mean business change per cell, and the difference of means (abbreviated DoM) between the treatment group mean and the nontreatment means. Significance denoted as: ** $p < 0.05$, * $p < 0.1$*

Relative Deprivation Regions

Finally, accounting for the perceptual effects of relative deprivation on populations with differing levels of starting noise, Fig. 20 defines one treatment group for noise increase among cells that had less than 45 dB DNL in 2011. Unlike Boston, most areas below the 45 dB contour decreased in noise, so zones which might be affected by a relative deprivation effect are small. The other two groups used in Boston, those with greater than +3 and +5 dB, respectively, do not exist in Chicago. They contain fewer than one hundred cells and are statistically meaningless at the levels of variance observed in the business change data. The single relative deprivation treatment group is not significantly different from either the retail change mean or the professional change mean.

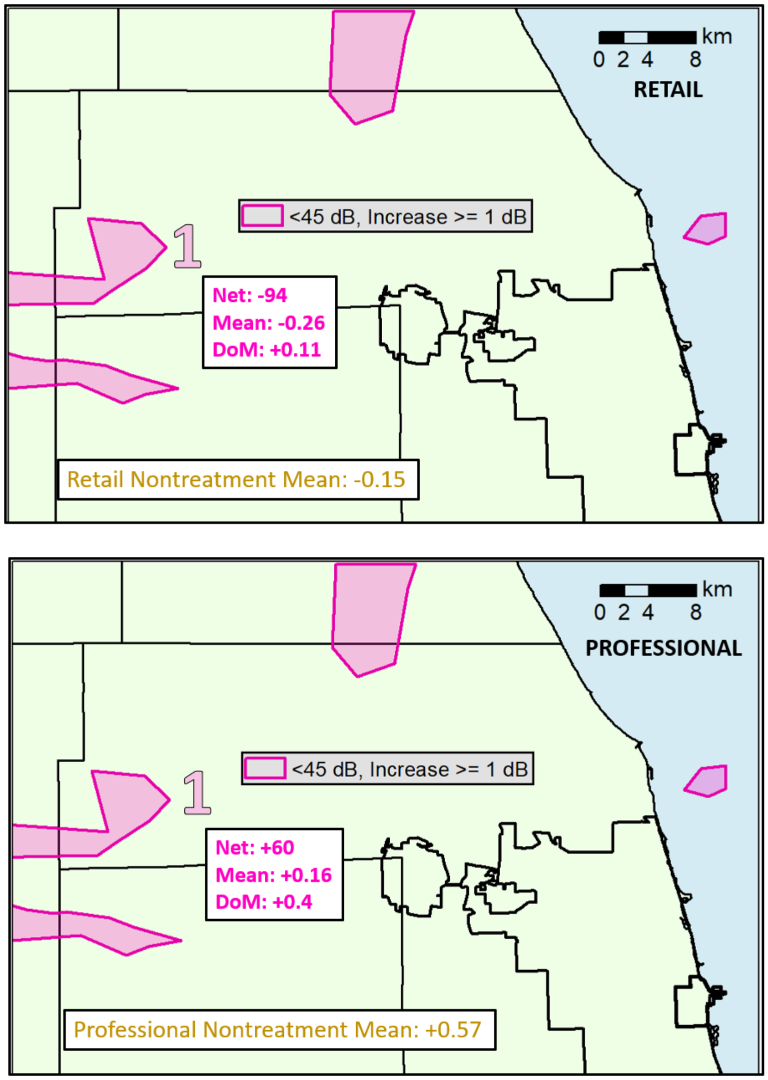


*Figure 20: Last set of treatment group zones, for testing a relative deprivation hypothesis. Highlighted zone received below 45 dB DNL in 2011, with an increase of at least 1 dB. Includes zonal statistics, for both the (top) retail and (bottom) professional sectors. Significance denoted as: ** $p < 0.05$, * $p < 0.1$*

5. Conclusion

In the regions surrounding the Boston Logan International Airport and the Chicago O'Hare International Airport, noise changes presented an opportunity for a natural experiment to test the effects of noise on closures and relocations among local business. After collecting and analyzing the relevant geospatial data, this thesis did not find evidence in either city that changes to noise exposure, measured as annual DNL, had statistically significant causal effects on business activity. Business growth and decline in regions with high magnitude noise changes were not significantly different from business changes in regions with no noise change. Noise change does not appear to be linearly correlated with business change and there do not appear to be nonlinear or threshold effects defining a noise-economic relationship. While it cannot be ruled out that there may still exist individual businesses that relocated as a result of aviation noise, noise relocations do not appear in statistical aggregate. Any outlier locations with business changes measuring in the dozens or hundreds of businesses, such as the downtowns in Boston and Chicago, were explainable by exogenous non-noise factors. In particular, because both downtowns deviated from the mean in the exact same way, with dramatic reductions to professional, scientific, technical, financial and insurance businesses, but Boston's downtown experienced noise increase while Chicago's downtown experienced noise decrease, this evidence further suggests business changes are driven by non-noise factors. Having two cities also helps control for possible larger regional effects, for example, if Midwesterners happened to be more noise sensitive than New Englanders. As such, any quantification of the cost imposed by noise on businesses is moot.

Community impact is an important consideration in planning any procedure changes and anticipating potential adverse effects. Given these results, non-business concerns, like those for public health and house prices, for which significant relationships with noise have been established by prior literature, should outweigh concerns for under-flight businesses when planning new flight procedures. Moreover, the known positive demand-side and catalytic economic impacts of airports almost certainly lead to net positive effects for businesses near airports, in spite of noise. Since the costs of business relocation are so high, further research into the economic costs of noise may benefit from assessing the effects of noise through lower-cost dependent variables, such as productivity losses, which may show responses to noise where no relocations exist.

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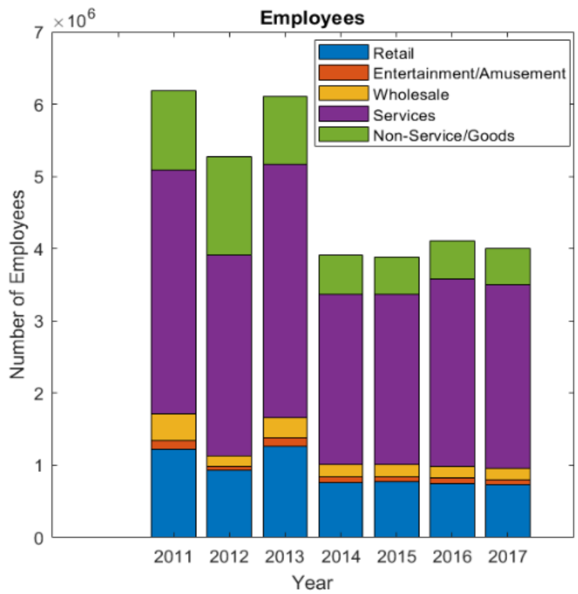
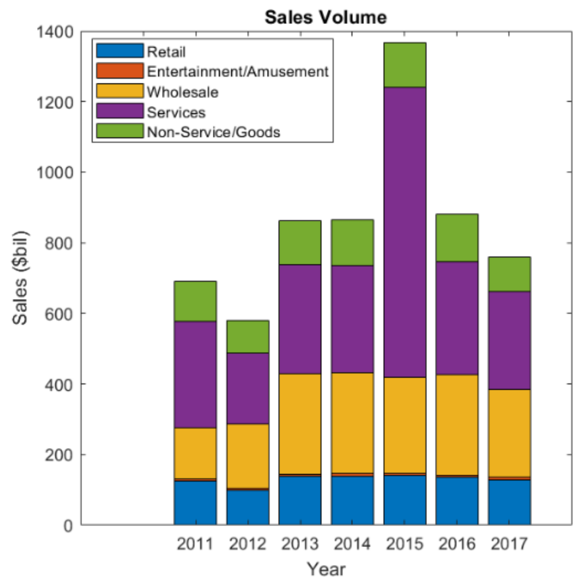
Appendix 1: Employee and Sales Volume Data

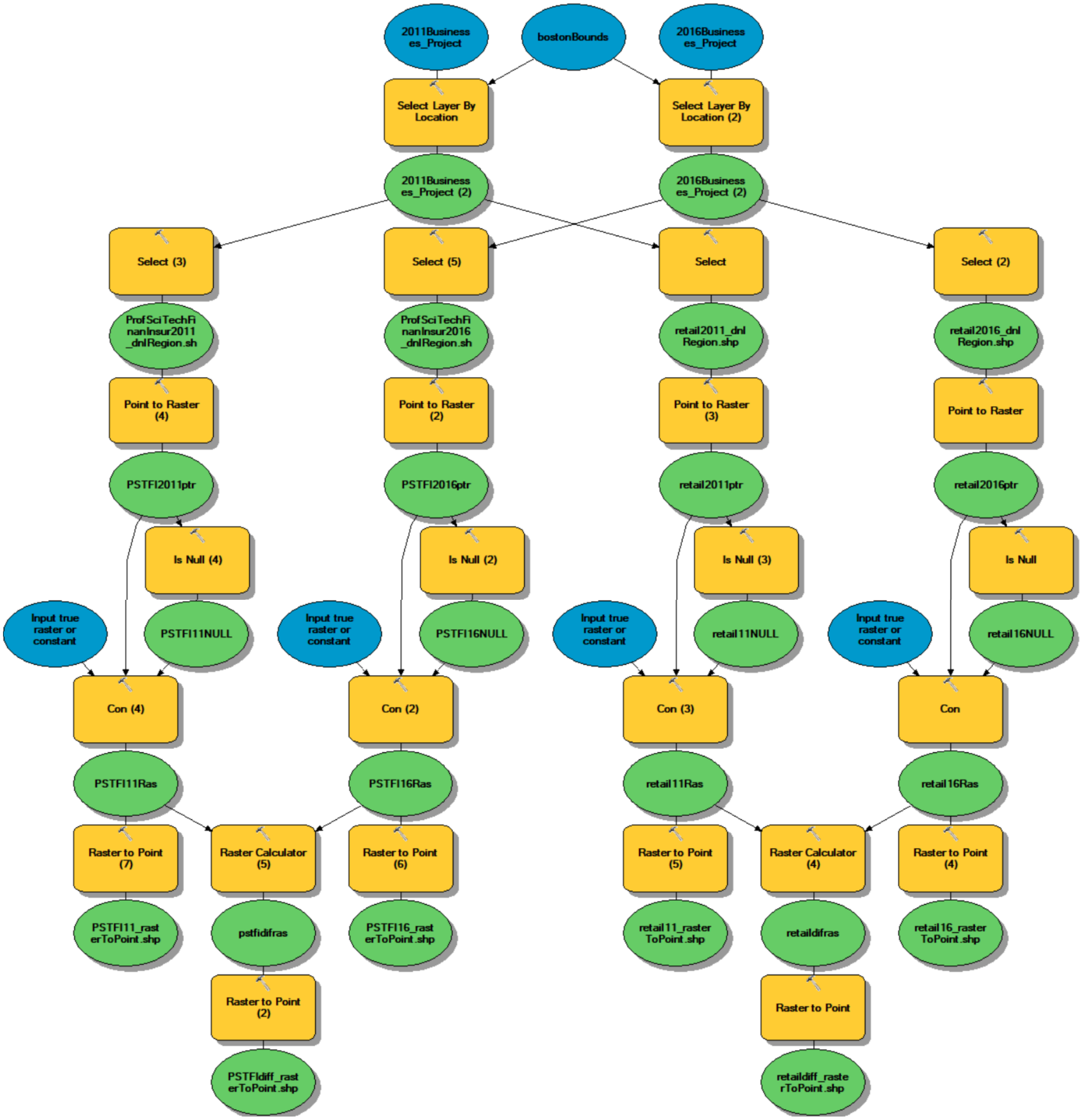
InfoGroup data on the total number of employees and total sales volume, stratified by sector, in the Commonwealth of Massachusetts, to which this analysis was restricted at the time when the determination to cut employees and sales volume from the study was made. A large unexplained drop in the number of employees in 2013, a crucial central year between the pre-RNAV and post-RNAV periods, precludes the use of sales volume per employee as a crude measure of productivity.





Appendix 2: ArcMap Model Builder

Business analysis, from point businesses to aggregate counts of the number of businesses in each cell within a bounding box.



Noise analysis, from contours interpolated to average DNL within each grid cell: