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A data-driven approach to monitoring and managing noise from ground transportation in Smart Cities

Ground transportation is a major source of acoustic disturbances (noise) despite its invaluable benefits. Smart and sustainable urban projects continue to highlight and address the impacts of transportation-generated noise on physical wellbeing, health, and public welfare (Park et al., 2018) (Ragettli et al., 2015). While the level of sensitivity to transportation noise and the degree to which such noise interferes with daily activities has been argued to be subjective, novel methods have emerged to quantify the impacts of transportation noise and the effectiveness of noise mitigation strategies (Sung et al., 2016).

In this proposed study, a data-driven approach for examining the multi-faceted nature of noise impacts is proposed. The approach, which aligns with Smart Cities initiatives, will guide urban land use and transportation planning, roadway design, and policymaking that mitigate noise impacts caused by ground transportation.

Purpose and Objectives

The purpose of the proposed research is to understand, quantify, and monitor noise generated from ground transportation systems in order to evaluate the effectiveness of strategies used to mitigate noise for users of the transportation system and urban residents. Specifically, the proposed research seeks answers to the following questions:

- What is the current state-of-the-art and state-of-the-practice concerning noise data collection techniques, noise data processing and analytics, the effects of noise pollution on travellers and urban residents, acceptable noise thresholds, and noise mitigation strategies?
- What noise levels are generated from ground transportation systems (roads, transit facilities, railroads) in Winnipeg, Manitoba? What factors principally contribute to those noise levels?
- What strategies (products, guidelines, policies) are used to mitigate noise generated from ground transportation systems? How effective are these strategies and how much do they cost?
- What advancements in noise data collection and dissemination should be considered to support decisions concerning noise mitigation measures? How can emerging data analytics and machine learning techniques be leveraged to extend the utility of available noise data?

- What is the role of noise mitigation measures in Smart Cities? In this context, what sustainable factors should be considered in the design of data collection, processing, and policy implementation strategies?

To address these questions, the proposed research pursues the following objectives:

- a comprehensive review of published literature and existing jurisdictional policies and guidelines to gain a contextual understanding of noise generation and mitigation within academic and public sector audiences;
- design, development, and implementation of a plan for collecting noise data in Winnipeg, Manitoba, considering the need to account for various factors including but not limited to land use, network characteristics, traffic conditions, weather conditions, and the presence of sound attenuation devices;
- analysis of the noise data collected to identify spatial and temporal patterns and to assess the effectiveness of existing noise attenuation devices implemented in Winnipeg; and
- conceptual design of a program for real-time monitoring and dissemination of transportation-related noise data.

Ultimately, the outcomes of the research will assist the City of Winnipeg in developing an updated version of its *Motor Vehicle Noise Policies and Guidelines*.

Background

Transportation noise is a physical phenomenon that describes the propagation of undesirable acoustic disturbances widely perceived as an environmental impact emanating from transportation systems. The impact of such noise can adversely affect quality of life, real-estate value, health, productivity, and public welfare (K. C. Sinha & Labi, 2011).

Methods of Quantifying Acoustic Disturbances or Noise Pollution

While there is near consensus that transportation noise is an environmental nuisance in modern cities (King et al., 2012), there are different approaches to quantifying such noise. Two notable methods of assessing environmental sounds are:

- Noise level method
- Noise exposure method

The City of Winnipeg currently measures sound level as a single parameter expressed in decibels (sound level method), which approximates the sensitivity of a normal human ear at varying sound frequencies (City of Winnipeg, 1984). Sound level, denoted $L_{A(period)}$, can be expressed as a time-average that characterizes one or more vehicle/train passages during a time period. Alternatively, sound exposure methods focus on characterizing the sound of one or more events (e.g., motor vehicles, rail vehicles, buses) from individual or combined sources over a duration of time, $E_{A(period)}$ (e.g., daytime, nighttime, peak periods) (American National Standard, 2005). The sound exposure method measures a weighted sound exposure as a sum of N sound exposures, E_{Ai}, from the i^{th} individual passing vehicles for a certain period.

In mathematical notation:

$$L_{A(period)}(dB) = 10\ \log_{10}\left[\frac{T_0}{T}\sum_{i=1}^{l} 10^{0.1L_{AEi}}\right]$$

$$E_{A(period)}(Pa^2s) = \sum_{i=1}^{N} E_{Ai}$$

where T_0 is the reference time of 1 second, i is the individual passing vehicle, L_{AEi} is the corresponding A-weighted sound exposure level, and T is the total time period in seconds for the duration of the time average (American National Standard, 2005).

Table 1 illustrates the relationship between sound level and sound exposure for a time-average sound level of 60 dB with the equivalent sound levels, $L_{A(period)}$, and sound exposures, $E_{A(period)}$, at different time periods, T.

Table 1: Relationship between sound level and sound exposure for a constant sound level of 60 dB (American National Standard, 2005).

T	$L_{A(period)}(dB)$	$E_{A(period)}(Pa^2s)$
1 second	60.0	0.0004
1 minute	77.8	0.024
1 hour	95.6	1.44
1 day	109.4	34.6

There is a need to consider transportation noise impacts from these two perspectives, because exposure to single events of sound—as is contemplated in the City of Winnipeg's guidelines—may not fully capture noise impacts of prolonged exposure to noise. This approach aligns with current Canadian Standards Association procedures (CSA, 2018), (Nassrallah, 2013).

Loudness and Sensitivity to Noise

The loudness of sound is measured in terms of decibels or pressure (micro Pascals). Figure 1 illustrates common outdoor and indoor noise levels with real life examples. Noise levels on their own do not account for the magnitude of intrusiveness, which varies temporally and spatially. The City of Winnipeg employs the $L_{(dn)}$-day-night level which describes a daily level of noise with an extra 10dB penalty for nighttime (City of Winnipeg, 1984). This captures the idea that nighttime noise levels are more intrusive than those occurring during the day. Moreover, because sensitivities to noise levels vary with mental alertness, age, population, and time of day (Veneman et al., 2013), there is a need for a multi-level system of decibel penalties that account for temporal and spatial variabilities. Transportation noise is often characterized by a level of spontaneity and lack of duration that leaves no physical residue (K. C. Sinha & Labi, 2011). In other words, transportation noise is transient, unlike stationary industrial noise that can often characterize a location or vicinity. The noise comes and goes with the passage of vehicles. This feature of transportation noise underpins the need for a comprehensive data collection program to factually describe, monitor, and assess the effectiveness of noise attenuation policies.

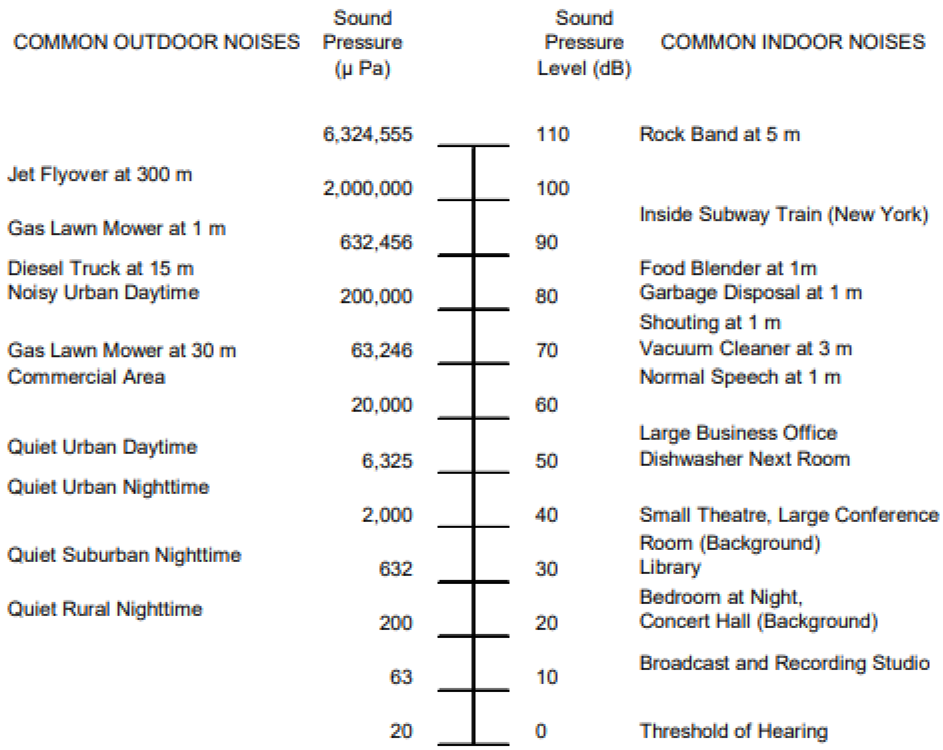

Figure 1: Common outdoor and indoor noise levels (K. Sinha & Labi, 2011).

Data Collection and Noise Mapping

Data collection is the first step to quantitatively understand noise pollution. While certain programs measure noise using static receivers in response to citizen complaints, there are opportunities to implement more systematic surveying/sampling approaches at regular temporal intervals and grid points (Asdrubali & D'Alessandro, 2018).

The data collected from a well-designed sampling program can be used to develop propagation models upon which noise maps are heavily-reliant. An effective data sampling approach should consider various modes (e.g., highway, railway) and various spatial and temporal variabilities (e.g., land use, network, weather, traffic composition, traffic flow parameters) (Pallas et al., 2015). Although the City of Winnipeg recognizes that the Federal Government is responsible for noise emission levels emanating from railway vehicles (City of Winnipeg, 1984), an effective data sampling design should include grade crossings and corridors with heavy railway activity for comprehensive noise mapping (Maeda et al., 2011).

Noise maps communicate the levels of noise and exposure due to transportation, construction, and other activities using geographical information systems (GIS) (Bocher et al., 2019). Noise maps and data may be communicated in dashboards and in real-time for public consumption and more informed policymaking.

The first step however is a quality noise data collection program followed by accurate models for noise propagation.

Data Analytics and Machine Learning

Recent research in the analysis of ground-based transportation noise has applied emerging data analytics and machine learning techniques (Zhang et al., 2020). These include:

- data summarization to quantify the impacts of transportation noise pollution;
- propagation modeling for noise mapping; and
- policy-oriented data analytics (e.g., as supported by spatial cluster analyses).

Creating data summaries have been a significant part of legacy sound data processing, especially for transportation policymaking. This has enabled numerical quantification of the impacts of noise pollution (transportation noise) on health, work productivity, and physical interactions. Studies have explicitly shown that long-term transportation noise pollution is highly associated with a reduction in physical activities (Foraster et al., 2016).

Noise mapping has benefited from propagation models that consider such factors as: geometric spreading, weather, time of day, atmospheric sound absorption, ground impedance, topography and geometry, vegetation, and environmental conditions. These models calculate the contribution level of different noise sources at the receiver locations (in $L_{A(period)}(dB)$) to estimate the levels of noise across a given geographical location. Such models have been adopted in certain Canadian cities (Alberta Transportation, 2019). While most of these models are physics-based, they are not without limitations. With the emergence of data science and artificial intelligence, the limitations of physics-based propagation models can be addressed. Studies have already shown that machine learning-based propagation models are capable of predicting community noise levels with an accuracy of $\pm 2\,dB$ compared to measured noise levels or ground truth data (Zhang et al., 2020).

Lastly, spatial data analytics can be used to cluster locations with similar features and challenges related to transportation noise. Such cluster analyses may be extended temporally (i.e., by hour of day or seasonally) for the purpose of attenuation programs and policymaking (Office, 1989; Park et al., 2018). (Park et al., 2018).

Work Plan, Financing Plan, and Schedule

Work Plan

The work plan for the proposed research comprises five (5) major tasks which are outlined in the following sections.

Task 1 – Environmental scan

This task involves a comprehensive review of published literature and existing jurisdictional policies and guidelines to gain a contextual understanding of noise generation and mitigation within academic and public sector audiences. With specific focus on ground transportation, the scan will examine a large spectrum of transportation noise sub-fields as well as existing mitigation techniques, including:

- noise generation from ground transportation systems (roadway and railway);
- the impacts of noise on health and well-being

- costs and effectiveness of noise mitigation techniques and strategies;
- noise policies, guidelines, and practices in Canadian urban areas and selected Smart Cities;
- noise data collection methods and technologies; and
- noise data processing advancements.

The literature will be compiled and synthesized in a database format, which will provide a resource for reports and publications generated from the subsequent research tasks. We anticipate a focused effort on this task in the first three months of the project; however, the task will be revisited as needed throughout the project.

Task 2 – Design and development of data collection plan

This task builds on the findings of the environmental scan through the design and development of a noise data collection plan for the City of Winnipeg. The following inter-related questions will be considered in the design and development of this plan:

- *What noise data should be collected?* The proposed research focuses on noise generated from ground based transportation systems (i.e., roadways and railways). Specifically, we anticipate collecting noise data from personal vehicles, trucks, buses, and trains.
- *Where should noise data be collected?* Transportation-related noise varies spatially as a function of numerous land use, network, and traffic flow parameters (e.g., speed, volume, flow conditions), as well as the presence of noise mitigation devices. The data collection plan needs to appropriately sample various aspects of these parameters.
- *When should noise data be collected?* Transportation-related noise varies temporally as a function of time of day, day of week, and season. The data collection plan needs to sample in ways that capture these periodicities. Moreover, the duration of noise monitoring at a single location impacts the types of measurements that can be reported (e.g., sound pressure, octave bands, sound level or exposure level).
- *How should noise data be collected?* At minimum, the data collection effort will rely on existing data collection devices currently used by the City of Winnipeg to manage noise-related complaints. As part of the data collection plan, however, the feasibility of other noise data collection devices will be considered.
- *How should noise data be processed and managed?* The data collection plan will consider effective approaches to process and manage the collected data, accounting for the inherent “messiness” of data, data governance best practices, and principles related to data veracity, velocity, value, variety, and volume (Ishwarappa & Anuradha, 2015).

Task 3 – Implementation of data collection plan

This task involves field work and activities related to installation and testing of sound meters and other readily-available acoustic measurement devices, as investigated in Task 2. Equipment procurement is not envisaged as part of the proposed research. This task involves close partnership with City of Winnipeg staff and, as needed, engaged third parties with expertise in equipment installation, testing, and operation. To initiate the data collection, we propose to execute a pilot study to generate a preliminary data set that will help illuminate issues and necessary adjustments at an early stage. We also expect that this task will involve ongoing evaluation—using the familiar strengths-weaknesses-opportunities-threats

(SWOT) framework—and periodic revisions of the plan throughout the implementation phase. We anticipate collecting data for a 12-month period.

Task 4 – Noise data analysis

Once the data collection plan has been implemented, we will verify, validate, and analyze the data collected with the view to develop insights for future policymaking. Data integration is a key barrier to improved utilization of data generated by sensors. This task will develop conceptual methods to assess and establish data linkages between locations, activities or events, and road/rail traffic conditions. These linkages will depend on the geo-spatial distribution of these data sets. The sound levels at sites where sensors are located are often easy to retrieve, however estimating sound levels at points between sensor locations may be challenging. The use of propagation models has often been helpful to address this problem. This task will consider improving the accuracy of physics-based propagation models with machine learning techniques.

Outputs of the noise data analysis will include:

- noise data summaries and analysis of unique events and scenarios;
- noise mapping with propagation modelling and machine learning improvements;
- spatial noise level forecasting and future conditions sensitivity analysis; and
- proposed attenuation/mitigation effects and scenarios.

This task requires a reorganization of various streams of geo-referenced data (from sound meters) and sensor locations in a GIS environment. GIS-based propagation modelling and spatial analytics are crucial to the success of this task.

Task 5 – Synthesis of research findings

This task synthesizes findings from Tasks 1 through 4. The synthesis will address the questions raised in the objectives and provide a roadmap for new ground transportation policy and guidelines in the City of Winnipeg. Specifically, the synthesis will consider:

- opportunities for integrating sound exposure measurements into the policy;
- scenarios for sliding levels of noise penalties;
- costs and effectiveness of noise mitigation strategies and techniques;
- adaptability of the policy to future land use and transportation conditions;
- opportunities for an ongoing, proactive, and real-time noise monitoring program.

Further to the final point, as part of the synthesis, we will offer an initial assessment of the feasibility and potential costs and benefits of an ongoing noise monitoring program for the City of Winnipeg, taking advantage of emerging and non-traditional noise measurement devices and adhering to data governance best practices concerning data dissemination, visualization, and public disclosure.

Financing Plan and Schedule

We are considering applying for funding for this research through the Natural Sciences and Engineering Research Council (NSERC) of Canada Alliance Program. This program provides financial support for various types of partnerships, including those between university researchers and municipal governments. In this arrangement, the City of Winnipeg would make some cash contribution and provide in-kind support for the project. NSERC would provide the majority of funds. We envision the following in-kind contributions from the City of Winnipeg:

- Sharing of information on current policies and practices.
- Equipment training and oversight of data collection program.
- Access to historical and new noise data.

The budget for the proposed research will be developed once the work plan has been discussed in further detail with City of Winnipeg staff. The majority of the budget will be used to support one graduate student (MSc) and one post-doctoral fellow (PDF) conducting the research, working under the supervision of Dr. Jonathan Regehr, P.Eng. A portion of the budget will be reserved to support travel (to relevant conferences), data collection costs, other direct research costs (e.g., office supplies), and indirect costs of research (institutional overhead).

We anticipate commencing work on January 1, 2021 and completing the project by June 30, 2023 (30-month duration). Table 1 provides a tentative research schedule and identifies key personnel. NSERC Alliance Grants do not specify a deliverable schedule; rather, the expectation is that research is disseminated as agreed to by the involved partners. This could include internal presentations and/or technical memoranda, graduate student theses, and academic publications.

Table 1: Schedule for the proposed research

Task	Anticipated start/end dates	Key personnel
Task 1: Environmental scan	01-Jan-21 to 31-Mar-21, ongoing	MSc, PDF
Task 2: Data collection plan	01-Apr-21 to 31-Aug-21	MSc, PDF, CoW staff
Task 3: Data collection	01-Sep-21 to 31-Aug-22	MSc, PDF, technologist, CoW staff
Task 4: Data analysis	01-Apr-22 to 31-Mar-23	MSc, PDF, CoW staff
Task 5: Synthesis of findings	31-Mar-23 to 30-Jun-23	PDF, CoW staff

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