

# Chapter 1

## Background

This chapter provides background on the research that was conducted throughout the course of this study. An introduction is given on noise, vibration, and harshness (NVH) in vehicles. This is followed by the results of a literature search and the presentation of the objectives of the research. Finally, the organization of the manuscript is included in this chapter.

### 1.1 Introduction

Noise, vibration, and harshness (NVH) in vehicles has received increased attention in recent years. In lighter vehicles, such as cars, pickup trucks, and the common utility vehicles, the emphasis has been on improving customer satisfaction and brand image. As vehicle quality has improved across the industry, automobile manufactures are searching for other ways of differentiating themselves from their competitors. The advertisements for luxury vehicles have raised customers' awareness and sensitivity to noise and vibrations inside the vehicle. Therefore, the industry has identified NVH as one of the areas that can be used to improve or maintain market share. The improvements in noise and vibration reduction have further raised customer expectations, forcing the automobile industry to look for yet more improvements in reduction.

The heavy vehicle industry is lagging behind the light vehicle industry in this respect by several years; it is only recently that the noise and vibration issues have come to the forefront of research in heavy vehicles. This emphasis is partially driven by increased customer expectations, partially by a push for further labor productivity, and partially by litigation and labor negotiations. As their personal automobiles have become quieter, the operators of heavy vehicles have started noticing the noise and vibrations in their heavy vehicles. The difference in noise and vibration between a heavy vehicle and an automobile has increased

from a few dBA to several (sometimes many) dBA. This factor is reflected in the buying decisions, of owner-operator customers, and in labor negotiations, of union employees. Indeed, targeted customer studies have shown that comfort issues such as less noise and vibration play an important role in customers buying decisions of heavy vehicles, along with more traditional factors such as price, brand loyalty, and quality. Similarly, in negotiations, labor unions have been demanding a quieter and more comfortable working environment in the vehicles they operate many hours in a day. In recent years, several cases have been brought before the courts by employees complaining of health damage due to long-term exposure to noise and vibration in heavy vehicles. In some cases, the employees have won substantial sums of money against their employers.

All of these factors have contributed to the increased sensitivity of the transportation industry to comfort issues, such as reducing interior noise and vibration in vehicles. One of the most effective methods of reducing noise and vibration in ground vehicles is resiliently mounting the operator compartment away from the sources of vibration, such as the power plant, ground input, and accessories. The resilient mounts effectively serve as a limiting factor for the vibration energy that can travel to the operator compartment. Reducing the vibration energy in the structure causes lower levels of vibration and structure-borne noise.

## 1.2 Literature Review

An extensive literature search was conducted to determine the past studies in the area of noise, vibration, and harshness for vehicle applications. Figure 1.1 shows a flow chart of the literature search according to keywords we used and the number of “hits” for each key word. The database INSPEC, which is one of the major data bases in engineering, was used for this search. Although this database may not be all-inclusive, it includes the vast majority of the open literature studies.

This literature search resulted in a large number of articles in general areas such as “vibration isolation” and “vehicle noise and vibration.” The number of articles, however,

quickly reduced for narrower search topics, as shown in Figure 1.1. A summary of the narrower search areas is provided next.

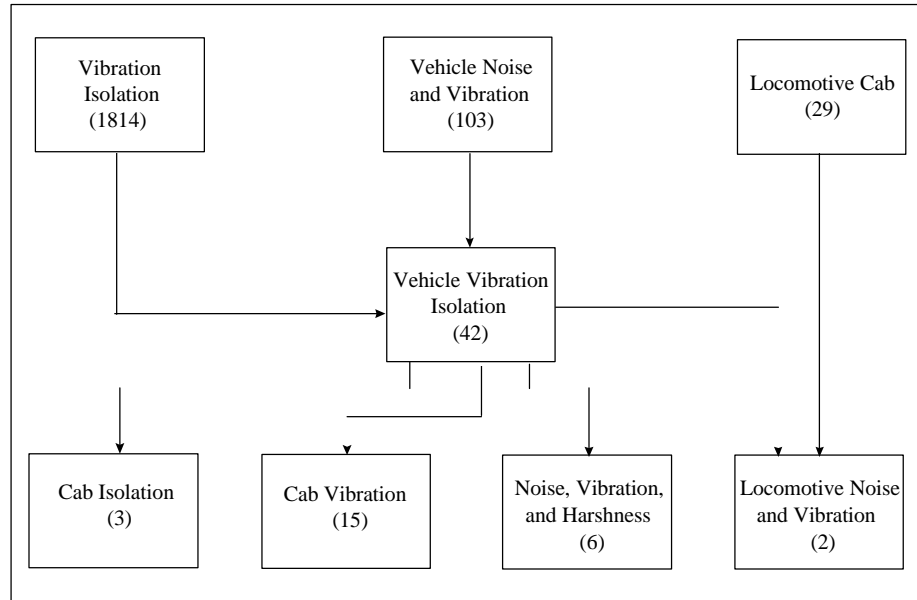


Figure 1.1 Literature Search Flow Chart According to Keywords and Number of “Hits”

### 1.2.1 Vehicle Vibration Isolation

The majority of the studies in this area address the application of various types of suspension systems for reducing vehicle vibrations [1-11]. The majority of these references reflect the vast number of studies that have been conducted in the past two decades in the areas of passive, semi-active, and active primary and secondary suspensions. Primary suspension refers to the suspension system at the vehicle axle, which serves to connect the axle to the vehicle body and control road-induced vibrations to the body. Secondary suspensions are the systems used for connecting other major components, such as the engine, cab, and seat, to the vehicle body. Secondary suspensions are commonly used to isolate the vibration sources from the operator compartment.

The studies by Gao et al. [1], El Beheiry and Karnopp [3], Shimamune et al. [4], Dukkipati et al. [5], and ElMadany and El-Tamini [8] provide mostly analytical and simulation analyses of primary suspensions for reducing road vibration transmission to the vehicle body. Other studies by Choi et al. [2], Nagai et al. [7], and Alexandridis and Wever address secondary suspensions [11]; Choi and his colleagues have analytically evaluated the benefits of an active mount, and compared the results with passive mounts. The active mount consists of electro-rheological (ER) fluid and piezoelectric actuators, and uses an H-infinity control technique. This study shows that the active mount provides a lower dynamic stiffness across a wide frequency bandwidth.

In another study, Nagai et al. [7] studied an optimal active secondary suspension for a magnetically levitated vehicle system. Using a laboratory-scale suspension equipped with a microcomputer, they have shown that the system can increase passenger comfort for a semi-truck cab suspension. Alexandridis and Wever [11] have analyzed an active mount with an optimal controller. The linear quadratic gaussian (LQG) controller is designed based on minimizing a performance consisting of vertical and horizontal accelerations at the cab and driver seat, as well as the cab suspension stroke.

A relatively complete review of various mount systems is provided by Nagai [6] and von Flotow [9]. Nagai [6] provides a comprehensive summary of recent research on active suspensions for ground vehicles, and von Flotow [9] gives an overview of active control of machinery mounts.

## 1.2.2 Cab Vibration

Among the fifteen articles in this area, the majority addressed analytical studies relating to designing and optimizing cab suspensions on heavy trucks and farm equipment [12-16]. In references [12] and [16], Hansson and Sankar, respectively, studied cab suspensions for farm equipment. Hansson studied the effectiveness of time invariant state feedback and different observers in terms of vibration isolation and power consumption. The results show that it is possible to design an effective active suspension. In [16], Sankar et al. use a finite element

model to analyze a farm tractor cab suspended on three mounts. They show that the flexibility of the cab structure is important to evaluating vibration reductions in the cab due to the soft suspensions.

In [13-15], different actively controlled mounts are studied for semi-truck cab suspensions. All of these studies involve the application of active control methods that are based on linear and nonlinear optimal control concepts. Although the results of these analytical studies are promising, their applicability and actual performance benefits are questionable, since none of the studies include any experimental or field data.

Our experience has shown that the applicability of active control schemes is limited for most vehicle suspension applications, due to their complexity and cost burden. Semi-active control schemes, however, have often been applied successfully.

### 1.2.3 Noise, Vibration, and Harshness (NVH)

The number of studies found was surprisingly low; only six references were listed in the database with these keywords [17-22]. The majority of these studies involve analytical methods in model validation [17], or measurement and signal processing techniques related to NVH [19,20]. One study addressed the use of damping treatment to reduce structure-borne noise due to power train vibrations [21]. This study determined the performance of damping material at critical power train frequencies using a laser imaging system.

### 1.2.4 Locomotive Cab

Except for one reference, Stationary Locomotive In-Cab Noise Measurements [23], the studies under this topic mostly addressed locomotive cab issues other than noise and vibration. Reference [23] is a study by the Association of American Railroads (AAR) that addressed in-cab noise measurement standards, but does not pose any relevance to our work.

## 1.2.5 Locomotive Noise and Vibration

The studies found in locomotive noise and vibration were quite limited [24-25]; both date back to the mid-seventies and address issues other than locomotive cab vibration. Johnsson et al. [24] discuss the use of special laser equipment (i.e., a system 1000 by Selcom) for vibration measurements at frequencies greater than 20 kHz. The equipment is used to measure the relative displacement between the locomotive wheel and rail for the examination of surface quality and surface vibration.

The second study, Routine Tests of CKD Diesel Locomotive, that we found in this area includes a test procedure that evaluates the safety of the locomotive for freight and passenger operations [25]. This study only deals with the noise and heat generated at the wheel-rail interface as a measure of the operational health of the locomotive.

## 1.2.6 Cab Isolation

The three studies found under these keywords are quite similar to those found in the area of vehicle vibration isolation [11, 26, 27]. These studies mostly deal with active and semi-active isolation of the cab, using optimal control methods. All three studies are analytical, without any experimental validation.

## 1.3 Research Objective

The primary purposes of this study are to:

1. establish the vibration characteristics of a typical locomotive cab used in freight applications,
2. evaluate the effect of various structural modifications on interior noise, and

3. measure the noise and vibration reductions due to soft-mounting the cab on elastomeric mounts.

## 1.4 Outline

Chapter 2 presents the locomotive setup for vibration testing. It includes the cab installation, the actuation mechanism, and the data acquisition system. Chapter 3 provides the test results for the cab in its baseline configuration. The effects of various modifications of the cab are studied and vibration reductions due to structural modifications are compared with the baseline cab. Chapter 4 presents various techniques for soft-mounting the cab; it further gives the soft-mounted cab configuration and test results. It is shown that soft-mounting the cab can significantly reduce interior noise and vibrations. Chapter 5 includes a simulation approach for predicting the effect of soft mounts with different stiffness values on noise and vibration reduction. A discussion is included on the difficulties of the simulation approach and methods for overcoming them. Finally, Chapter 6 summarizes the results of the study and provides recommendation for future studies.