

# *The Bose Ride™ System*

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The Bose Ride™ System.

## Summary

As the lifeblood of the U.S. economy, the trucking industry employs millions of professional drivers to deliver approximately 95% of the nation's goods. To keep freight moving, over-the-road drivers spend up to eleven hours a day in their trucks, withstanding a ride much worse than a passenger car. Even with the best conventional air-ride seats, over-the-road drivers experience constant road-induced vibration – a form of whole-body vibration. Independent scientific research has shown that whole-body vibration can reduce comfort, add to fatigue, increase stress on the spine and body, and impact visual perception.<sup>1,2,3,4</sup> These factors can lower driver performance and contribute to many of the industry's challenges, including driver retention, health care costs, and accidents – factors that impact and disrupt business.

The Bose Ride™ system is a new product that provides over-the-road truckers with an unprecedented level of protection from road-induced shocks and vibration. It replaces the air-ride seats currently in use with technology that senses, analyzes, and *counteracts* forces from the road.

The new system consists of a Bose® suspension base and an integrated, custom-designed seat top. The Bose Ride system is compatible with most makes and models of U.S.-manufactured, heavy-duty trucks and can be installed by a trained mechanic in under two hours. Based on over 25 years of research, the system's unparalleled performance is made possible through several proprietary Bose technologies:

- A high-power, linear, electromagnetic actuator capable of counteracting the forces caused by road disturbances.

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<sup>1</sup> D G Wilder, M H Pope, "Epidemiological and aetiological aspects of low-back pain in vibration environments – an update," *Clinical Biomechanics* Vol. 11, No. 2 (1996) pp. 61-73

<sup>2</sup> J Granlund, "Whole-body vibration when riding on rough roads," SNRA Publ. no. 2000:31E, p. 3 (79)

<sup>3</sup> K Teschke, A Nicol, H Davis, S Ju, "Whole-Body Vibration and Back Disorders Among Motor Vehicle Drivers and Heavy Equipment Operators: A Review of the Scientific Evidence," A Report to Randy Lane, Appeals Commissioner Workers' Compensation Board of British Columbia, Apr 14, 1999, p.15, 16

<sup>4</sup> M McCallum, T Sanquist, M Mitler, G Krueger, "Commercial Transportation Operator Fatigue Management Reference," U.S. Department of Transportation Human Factors Coordinating Committee, July 2003, pp. 2-14, 2-15

- A compact, bi-directional power amplifier that delivers peaks of 3,500 watts to the actuator while drawing less average power than a 50-watt light bulb.
- Sensors and propriety Bose<sup>®</sup> control algorithms working together to counteract road disturbances before they reach the driver.

In one evaluation of performance, Bose has shown that the new system reduces vibration to levels much lower than those experienced in high-end air-ride seats, and even slightly lower than those in a premium-quality automobile.

In our engineering field experience, 77 professional over-the-road truck drivers tested prototype and pre-production units for four to five weeks, on average, traveling through the United States on their normal runs. Over 80% responded positively to the Bose Ride<sup>™</sup> system. 84% of drivers reported improved comfort benefits, 75% reported having less soreness and stiffness, and 66% reported decreased driving fatigue.



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## Introduction

Over-the-road truck driving is known as one of the most difficult and hazardous occupations.<sup>5</sup> There are long shifts away from home in conditions that are always changing, and drivers must constantly maintain a high level of alertness and skill. According to the Bureau of Labor Statistics, U.S. drivers have the second highest rate of injuries, illnesses, and days away from work of any occupation.<sup>6</sup>

One of the factors that make over-the-road driving difficult is the shaking and jarring of the driver resulting from imperfections in the road surface. Recognizing this, the trucking industry has, over time, developed improvements in technology that have helped protect drivers from these road-induced vibrations. Truck seats, once rigidly attached to truck cab floors in the first half of the twentieth century, have today been replaced with much-better-riding air-suspension seats. In spite of these improvements, however, driver exposure to road-induced vibration remains high, and the evidence presented below shows how such motion affects driver comfort, health, performance, and well being.

## Whole-body vibration

As a truck travels down a road or highway, it encounters bumps, potholes, bridge expansion joints, and other disturbances that produce unwanted vehicle motion. The motion can be sudden and can result in severe jolts to the driver. In addition, drivers are exposed to much more frequent but less severe vibrations as the vehicle comes into contact with routine roughness in the road surface. Both kinds of undesirable motion constitute what is known as *whole-body vibration*.

Studies show that whole-body vibration can affect comfort, health, and task performance.<sup>7</sup> Concern over these effects led to the 1974 publication of *International Standard 2631: Guide for the evaluation of human exposure to whole-body vibration*, with revisions following in 1978, 1982, and 1985.<sup>8</sup> This standard, and the

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<sup>5</sup> Personal communications from S. Pratt and T. Alterman of NIOSH cited in "Commercial Truck Driver Health and Safety – Preventing Injury and Illness," RFA-OH-07-001, May 4, 2006

<sup>6</sup> Bureau of Labor Statistics, 2007

<sup>7</sup> M. J. Griffin, *Handbook of Human Vibration*, Chapter 5, "Whole-body Vibration and Health," Elsevier (1990) p. 182

<sup>8</sup> International Standard 2631: Guide for the evaluation of human exposure to whole-body vibration, Part 1 (1985)

occupational health and safety studies upon which they are based, cite the following factors as important in assessing the risks of whole-body vibration:

- Type (impulse, transient shock, or periodic motion)
- Frequency (how rapidly the motion is occurring)
- Amplitude (magnitude of displacement, velocity, or acceleration)
- Dosage (cumulative length of exposure)
- Position (body posture)

Heavy-duty trucks subject drivers to whole-body vibration in the frequency range of 0.5 to 25 cycles per second.<sup>9</sup> Whole-body vibration in heavy-duty trucks is almost three times higher than that experienced in an average passenger vehicle, and two times higher than a typical sports car (which handles well, but at the expense of driver comfort). Moreover, the length of time a professional long-haul trucker spends behind the wheel is more than five times higher per day than the operator of an average passenger vehicle.<sup>10</sup>

### *Whole-Body Vibration and the Spine*

The adverse effects of whole-body vibration on the spine can be explained by examining the biomechanics of the human body. The human spine has a natural curvature that helps it to function as a shock absorber. When standing, it takes the form of an S-shaped curve, as shown on the left of Figure-1. In this orientation, the spine exhibits a high degree of flexibility and distributes forces relatively evenly throughout the vertebral elements and inter-vertebral discs.<sup>11</sup>

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<sup>9</sup> J. Grandlund, "Health Issues Raised by Poorly Maintained Road Networks," Roadex III, Swedish Road Administration Consulting Services, March 2008, p. 21

<sup>10</sup> Based ratio of maximum legal driving hours for a truck driver of 60 hrs/week times 50 weeks, to 540 hrs a year Americans spend in their cars. American time in car from Autobeat Daily, Oct. 13, 2000

<sup>11</sup> B. McIlwraith, "Loss of the Lumbar Curve in the Driving Seat – A Twenty Person Study," British Osteopathic Journal Vol. XIX, 1996, pp. 19-23

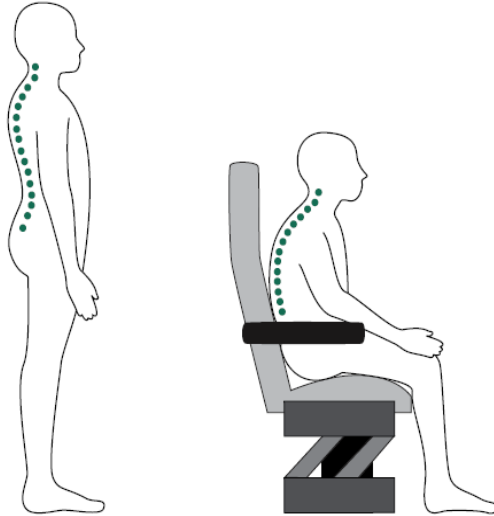


Figure-1. The curvature of the human spine shown in standing and seated postures.

When seated, however, the curvature of the lower (lumbar) back is flattened, and uneven, non-concentric, or pinching compressive forces are present in the inter-vertebral discs.<sup>12</sup> Many experts believe that the spine is less flexible in the seated position, and less effective in absorbing and dissipating vibration. A person's back is therefore more vulnerable to a harsh ride when seated, and it is believed by many experts that prolonged driving in the presence of whole-body vibration is a risk factor for acute herniated lumbar inter-vertebral disc and other back injuries.<sup>13,14</sup> Numerous studies point to vibration as a significant factor in certain low-back disorders.<sup>15</sup> Not surprisingly, industry research found that more than one-third of interstate truck drivers report backache as their most pressing health concern.<sup>16</sup> Roughly 25% of all workers' compensation claims by drivers are for back injuries.<sup>17</sup>

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<sup>12</sup> Ibid

<sup>13</sup> J. Kelsey and R. J. Hardy, "Driving of Motor Vehicles as a Risk Factor for Acute Herniated Lumbar Intervertebral Disc," *American Journal of Epidemiology* Vol. 102, No. 1, 1975, pp. 63-73.

<sup>14</sup> D Wilder, M Pope, *Industrial Safety & Hygiene News*, Vol. 27, No. 11, 1993

<sup>15</sup> JW Frymoyer, MH Pope, JH Clements, B MacPherson and T Ashikaga, "Risk factors in low-back pain. An epidemiological survey," *J Bone Joint Surg Am.* Vol 65, 1983, p.217

<sup>16</sup> "Profile of the Interstate Trucker, Part I," Newport Communications Research, 1999

<sup>17</sup> "Back Care for Truck Drivers," CFLC 13, The Hartford Loss Control Department, 2002

## *Whole-Body Vibration and Fatigue*

A number of studies that record the electrical signals associated with muscle contractions show how whole-body vibration contributes to muscle fatigue.<sup>18,19, 20</sup> Among other things, the human head weighs 10 to 12 pounds, and many muscles of the body have to work to hold the head stable. Trunk muscle effort is also required to stabilize the spine and maintain upper body posture.

Many long-haul truck drivers spend 11 hours a day and five to six days a week on the road in an environment where they are subjected to nearly constant vibration. They may not be conscious of the significant muscle effort needed to sustain a posture required for full-time alertness, but it is a fact that many experience muscle fatigue accompanied by neck and back pain after driving.<sup>21</sup> Drivers also report that at the end of a long period of driving, they need rest to recuperate, and that the time needed for recovery affects quality of life both on and off the road. For example, many report losing a day of their personal time at home between consecutive weekly runs just for physical recovery.<sup>22</sup>

## *Whole-Body Vibration and Ability to React*

In addition to fatigue, vibration can interfere with the human sensory systems and affect our ability to react.<sup>23</sup> An activity such as driving requires constant processing of rapidly changing information. To handle an eighty thousand pound vehicle, the driver must continuously process information received from the eyes and ears while relying on the hands and feet to sense what the vehicle is doing and to maintain a feel for the road.

Visually keeping track of multiple objects requires considerable mental processing in any environment. Vibration causes movement of images on the retina, making it

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<sup>18</sup> *op. cit.* Griffin, p. 182

<sup>19</sup> M. H. Pope, D. C. Wilder, and D. D. Donnermeyer, "Muscle fatigue in static and vibrational seating environments. Backache and Back Discomfort." AGARD Conference Proceedings No. 378, Paper 25. Advisory Group on Aerospace Research and Development, 1986

<sup>20</sup> C. Krogh-Lund, and P. Voss, "Physiological effects of occupational exposures to whole-body vibration," Report prepared for the European Communities Directorate General for Employment, Social Affairs and Education, Technical Report 143, Lydteknisk Institute Tastrup, Denmark, 1989

<sup>21</sup> From field testing with 81 professional drivers conducted by Bose 2005 – 2009

<sup>22</sup> *op. cit.* Bose field testing

<sup>23</sup> *op. cit.* Griffin, Chapter 4, "Activity Interference Caused by Vibration," Elsevier, 1990

more difficult to process the events that have changed.<sup>24</sup> Moreover, when the body is subjected to vibration at higher frequencies, the eye and its components oscillate, which further degrades vision.<sup>25</sup> It follows that unwanted and unpredictable motion caused by vibration degrades awareness of surroundings and could lead to increased reaction time.<sup>26</sup> And on the road, even a small delay in recognizing and reacting to an emergency situation can have serious consequences. The experience of vision-degradation on the road is well-known to truck drivers, who talk about difficulty in reading road signs and dashboard gauges.<sup>27</sup>

An extensive body of evidence can be found in the literature to support that observers cannot report or retain all of the details of their visual world from one moment to the next.<sup>28</sup> In a straightforward experiment, Bose uses an interactive exhibit to show how difficult it is to track changes in the visual field of humans. A high-resolution photograph of a typical road intersection is displayed on a high-definition monitor and subjects are told to note and count the changes in the scene, such as the brake lights of a car turning on. Then, the scenario is repeated with vibration added. Truck drivers are typically able to identify all seven out of a total of seven changes in the first situation, but are surprised to find that they average seeing only three of seven in the situation that includes vibration.

### *Whole-Body Vibration and Comfort*

Various vibration studies show that motion is related to displeasure, dissatisfaction, and discomfort. At very low frequencies (less than 1 Hz or one cycle per second), vibration can lead to motion sickness and feelings of malaise.<sup>29,30</sup> Above that range, the effects are more in the realm of unpleasantness, annoyance, and disturbance. ISO 2631 offers guidance for evaluation of this kind of discomfort over the frequency range from 1-100 Hz.<sup>31</sup>

For drivers, discomfort due to vibration is influenced by body posture, position, body orientation, size, weight, age, gender, and fitness. Despite individual variations

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<sup>24</sup> *op. cit.* Griffin

<sup>25</sup> Man-System Integration Standards, Volume I, Section 5, Natural and Induced Environments, 2000, p. 58

<sup>26</sup> *Ibid*

<sup>27</sup> *op. cit.* Bose field testing

<sup>28</sup> See for example D. J. Simons and R. A. Rensink, "Induced failures of visual awareness," *Journal of Vision*, Vol. 3, No. 1, (2003), Introduction

<sup>29</sup> N. J. Mansfield, *Human Response to Vibration*, see Fig. 1.6, CRC Press (2005)

<sup>30</sup> *op. cit.* Griffin, pp. 428

<sup>31</sup> *op. cit.* ISO 2631

in sensitivity, the general cause-and-effect relationship is clear: vibration of the kind found in long-haul trucks is likely to be a significant source of discomfort for the average driver, a prediction repeatedly substantiated by direct driver testimony.<sup>32</sup>

### *Why Poor Ride Quality is Tolerated*

With the adverse effects of whole-body vibration noted above, one might wonder why poor ride quality is tolerated by drivers and the industry. Drivers are certainly aware of the problem: in a Washington State study, for example, on a one to five ranking of seven physical risk factors, 37% of truck drivers ranked whole-body vibration as four or five (high risk).<sup>33</sup>

One answer is that people tend to accept things they think cannot be changed. For example, few people ever complained about noise in passenger aircraft prior to the availability of active sound cancellation headphones because high noise had come to be expected by air travelers. It was only when these travelers experienced what it was like to have most of that noise *removed* that they readily articulated the discomfort and fatigue they were previously feeling. Similarly, most are familiar with the sudden feeling of relief when a noise source, such as the buzz from fluorescent lights or the whoosh from a ventilation fan, is shut off. We don't complain until the source of discomfort, annoyance, or fatigue is removed, and we realize something better is possible.

We believe the situation for long-haul truck drivers is similar. Because there is no better solution to contrast existing ride shortfalls, drivers and their employers tend to tolerate the poor ride quality as part of the job. As in the air traveler example above, most drivers we interviewed as part of our research had few complaints about the quality of their ride.

### *Impact on Fleet Service Quality and Costs*

The preceding sections have described poor ride quality as an overlooked factor that has the potential to affect driver health, comfort, performance, and well being, which in turn can affect the profitability of the businesses that employ these drivers. In Figure-2, the shaded region suggests how elements of driver performance could map to safety, productivity, and quality of life – factors that can ultimately affect fleet costs and bottom-line profitability.

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<sup>32</sup> *op. cit.* Bose field testing

<sup>33</sup> P. Spielholz, J. Cullen, et.al., "Assessment of perceived injury risks and priorities among truck drivers and trucking companies in Washington State," *Journal of Safety Research* No. 39 (2008), pp. 569-576

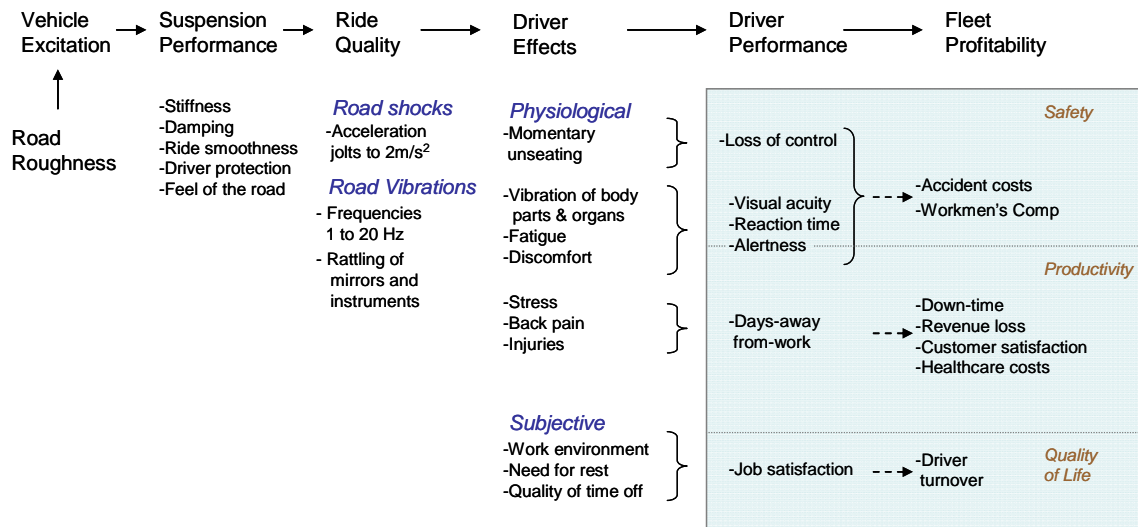


Figure-2. Potential impact of whole-body vibration on fleet costs and profitability.

For instance, whole-body vibration can affect driver fatigue and visual acuity. It's common knowledge in the industry that these factors are central to safe operation. Studies strongly suggest a connection between whole-body vibration and health risks such as back pain. These likely health implications can have a financial impact on fleet operations, since they could result in greater health insurance and workers' compensation insurance costs, unplanned driver absences, and delayed deliveries, and the resulting decreases in customer satisfaction.

Quality of life is frequently cited as a reason for high turnover in the trucking industry,<sup>34,35,36</sup> and the average cost to replace a driver with a trained replacement is estimated to be around \$6,000. With long-haul driver turnover rates that commonly reach 100% per year, even a modest reduction in turnover represents a significant cost reduction for trucking businesses. We assume that the effects of poor ride quality are a contributing factor to driver turnover. It is possible a technology that enables a better quality of life will lead to a reduction in turnover.

<sup>34</sup> D. Bertalotto, "Strategies for Overcoming the Driver Shortage," J.B. Hunt Transport, Inc. Executive Briefing, Dedicated Contract Services, Oct. 12, 2005

<sup>35</sup> D. Britton, "Are your driver recruiting and retention skills ready for the upturn?," Trucking Info, Oct. 2, 2009

<sup>36</sup> "U.S. Trucking Industry Challenges and Emerging Multimode Network Architectures," Frost & Sullivan, 2006

## Shortcomings of Current Solutions

To reduce the harmful vibrations that reach the driver, truck designers incorporate multiple suspensions in modern-day vehicles, as shown Figure-3. In addition to the chassis suspension, some manufacturers suspend the cab to further reduce its motion. Trucks typically also include seat suspensions to further isolate the driver from motion of the cab floor.

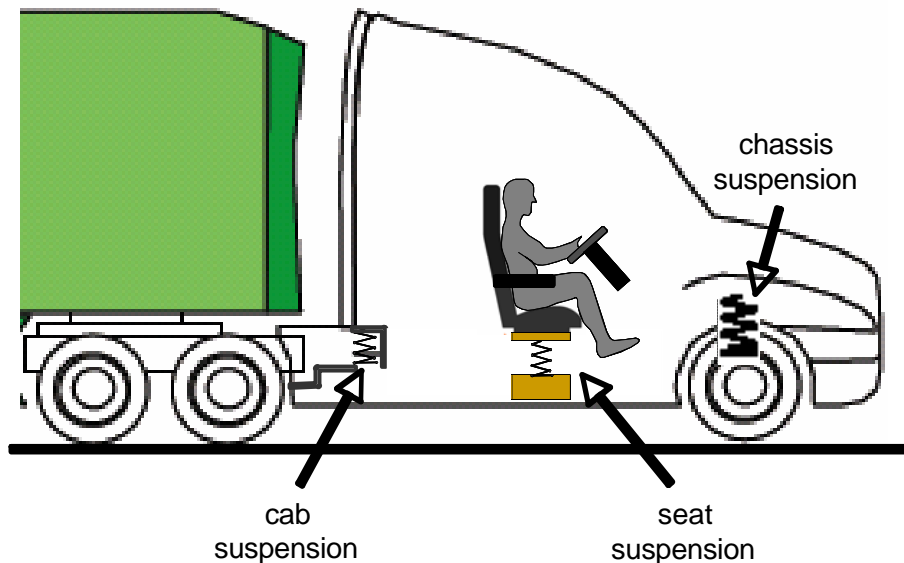


Figure-3. Drivers are cushioned from road-induced vibration by up to three different suspension systems.

Contemporary seat suspension systems are the result of decades of improvements. What started as rigid seats bolted to the cab floor has progressed to provide what is today a relatively smoother, more comfortable ride. Regardless, in these large vehicles that are designed primarily to haul freight, drivers are still exposed to high levels of whole-body vibration. Why don't current solutions do more to protect drivers?

Conventional air-suspension systems used in most truck seats have an air bag acting like a mechanical spring when inflated, and sometimes another mechanical device called a damper. Air-ride seats, as they are called, offer a significant improvement over the earlier box seats and rudimentary mechanical spring seats, but the design suffers from limitations to its effectiveness.

The air-spring in an air-ride seat provides freedom of motion for the suspended mass (seat, driver), along with a restoring force that is proportional to the displacement from rest position. If a damper is included, it provides a means to dissipate energy and prevent excessive overshoot.

The use of a spring as the principal suspension element involves a fundamental tradeoff between isolation and control. A "soft" suspension provides a high degree of



isolation from the road, but even a small force results in significant displacement; such a system is always in motion as it reacts to the minor disturbances in the road. The suspension feels sloppy and reduces payload control. Worse yet, every time a significant road imperfection is encountered, the seat can slam into the travel stops, delivering a severe shock to the driver. A stiff suspension, on the other hand, limits relative motion and overshoot, but provides little protection from whole-body vibration. It transmits more of the rapidly changing, smaller, but ever-present road imperfections. All spring (or spring and damper) systems exhibit this fundamental tradeoff: they must sacrifice either isolation or control.

Aside from the intrinsic tradeoff inherent in air-ride seat suspensions, there is a more fundamental reason these systems fail to adequately protect drivers from road shock and vibration. Consider the case where a truck wheel goes into and then out of a pothole. When an air-spring suspension enters the pothole, the wheels drop into the hole and the cab floor moves down, as shown in Figure-4. The air-spring, which is mechanically attached on one end to the cab floor and on the other end to the moving seat, is then stretched and exerts a downward force on the seat. The extended spring pulls the driver down into the hole, and with some possible overshoot, returns to its nominal length.

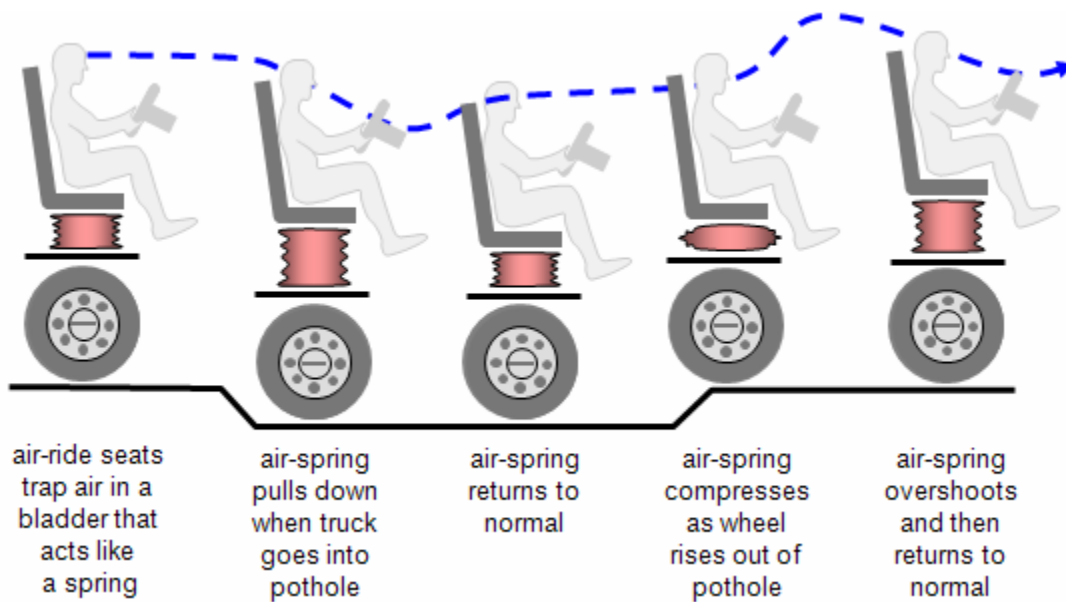


Figure-4. The motion of a typical air-ride seat suspension system over a single pothole is shown. Note that pothole size and driver motion are not to scale and are magnified for illustration purposes.

As the wheel of the truck rises out of the pothole, the cab floor rises, compressing the air-spring. Except when the vehicle is moving very slowly, the force of the compressed spring rapidly rises and transmits a jolt to the driver above. The seat top

and driver respond with a force being exerted from below with an accelerated trajectory out of the pothole. With the momentum of the driver and seat top, the air-spring stretches beyond its normal extension, and pulls the seat and driver back to its nominal weight-adjusted position.

Whether dropping into the pothole or coming out again, the air-spring suspension system reacts with forces that are, in fact, opposite to what is ideally needed: instead of holding the seat up to minimize driver motion when the truck enters the pothole, the suspension pulls it down, and instead of lowering the seat when the truck leaves the pothole, the suspension pushes up on the seat. This behavior is fundamental to the design, and is important in understanding why drivers still experience whole-body vibration.

## The Bose Ride™ System

The Bose Ride system represents a technological breakthrough. Unlike conventional systems whose air-springs and dampers only react to motion, the Bose Ride system uses position and acceleration information to compute and generate the *counteracting forces* required to protect the driver from unwanted motion and vibration. This fundamental difference – counteracting rather than reacting – can be shown by revisiting the same pothole used to illustrate the behavior of air-suspension seats.

As a truck with the Bose Ride system enters the pothole, the wheels drop into the hole, as shown in Figure-5. At that instant, rather than pulling down, the Bose Ride system actually *extends*, precisely *lifting* the driver relative to the floor so as to minimize driver motion. The system then begins to gently lower the driver back to the center position. When the truck reaches the far end of the pothole, and the wheels are forced upwards, the Bose Ride system, at that instant, precisely *lowers* the seat relative to the floor to again minimize driver motion. The system then gently raises the driver to the center position to follow the road profile and be ready for the next event. The Bose Ride system is capable of this behavior over all typical road surfaces and all typical truck speeds.

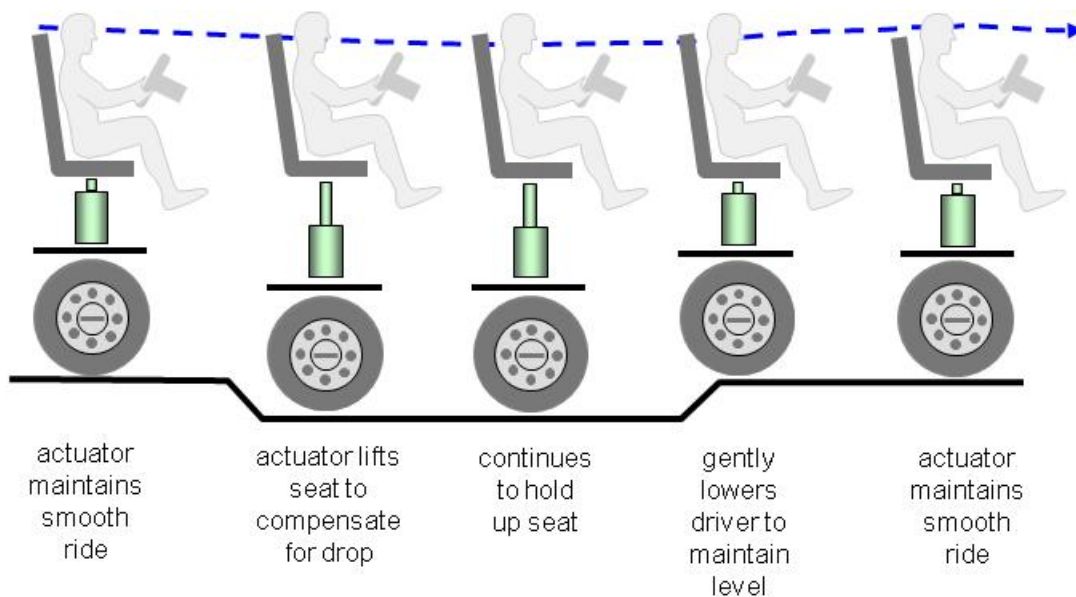


Figure-5. The Bose Ride system is shown minimizing driver movement when it encounters a road disturbance. Note that pothole size and wheel motion are magnified for illustration purposes.

A side-by-side comparison of the conventional air-ride seat and the Bose Ride™ system is shown in Figure-6 From top to bottom, the figure shows performance on

scales ranging from an encounter with a single pothole to that of motion and vibration found over the course of a full day's drive.

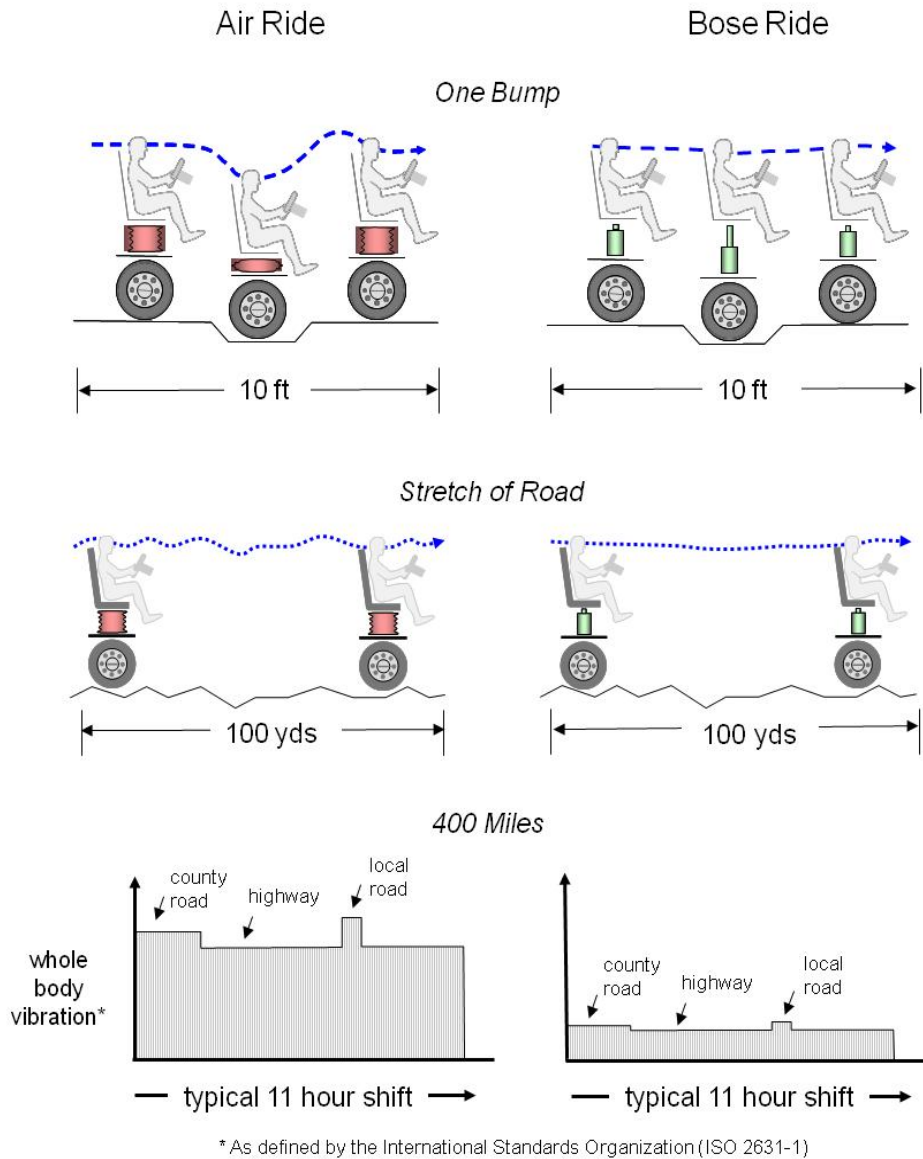


Figure-6. The comparison of performance between a conventional air-ride seat and the Bose Ride system over a single pothole, a stretch of road, and a typical 11-hour shift are shown schematically. (Curves of motion and road disturbances are magnified for illustration purposes.)

## *System Overview*

Effective road vibration reduction requires a system that is fast enough to sense high-speed vehicle motion, and then intelligently counteract those forces. To do this, significant technological advances were required in the areas of actuation, power amplification, and control theory. To be commercially viable, the new approach had to be integrated into a compact package that was easy to install, and was proven reliable in a demanding transportation environment. See Figure-7.



Figure-7. The Bose Ride™ system.

A view of the integrated system elements used in the Bose Ride™ system is shown below in Figure-8. The Bose Ride system uses an automotive-grade microprocessor, running proprietary algorithms, smart sensors, a regenerative switching amplifier, and an electromagnetic actuator to continuously and nearly instantaneously control motion.



Figure-8. Shows the location of the various system elements of the Bose Ride system.

The microprocessor uses position and acceleration information to continuously compute the forces required to counteract the road-induced disturbances. A pneumatic system automatically adjusts to support the weight of the driver, and then continually makes adjustments to minimize electrical power consumption.

## *System Elements*

### *Electromagnetic Actuator*

The Bose Ride system uses a proprietary linear electromagnetic actuator powerful enough to manage drivers from 100 to 350 lbs., and fast enough to counteract unwanted motions in fractions of a second. Inside the actuator are magnets and coils

of wire so that when current is applied to the coils, the actuator retracts or extends, creating relative motion between the cab floor and the truck seat. Under command of the system controller, the electromagnetic actuator generates a force to continuously counter the effects of bumps, potholes, and other road disturbances.

Unlike hydraulic active systems, which operate only at very low frequencies, the high-speed electromagnetic technology in the Bose Ride™ system is responsive over a broad frequency spectrum, enabling cancellation of road-induced vibrations over the entire range of frequencies included in the ISO definition of whole-body vibration.<sup>37</sup>

#### *Bi-Directional Switching Amplifier*

The bi-directional switching amplifier in the Bose Ride system conditions and delivers electrical power to the electromagnetic actuator in response to signals from the control algorithms. In this approach, energy is actually drawn from road vibrations and then re-used. As a result, the Bose Ride system is highly efficient: The compact amplifier can deliver peaks of 3,500 watts while only consuming an average power equivalent of a 50-watt light bulb. As a result, the system is powered by an ordinary electrical connection to the existing truck battery.

#### *Control Algorithms*

The Bose Ride system is controlled by a set of mathematical algorithms developed over a period of 24 years of research at Bose. These control algorithms operate by monitoring sensor signals and sending command signals to the regenerative switching amplifier thousands of times each second from the micro-controller. The architecture also allows for software enhancements to be made without the need for hardware changes, as future improvements and updates become available.

#### *Fail-Safe Operation*

Self-checking control algorithms in the Bose Ride system monitor the dynamic performance of many system elements. Using redundant sensors, safety checks are performed concurrently to ensure that the system is accurately executing the command instructions. By comparing the command signals to actual quantities being controlled, the system is able to ensure optimized operation. If the algorithms are unable to correct deviations, the controller automatically stops operation of the electromagnetic control loop, and the system defaults to passive air-ride operation using integrated pneumatic components. In the unlikely event this becomes necessary, the Bose Ride system remains in air-ride mode, and the truck can continue to operate safely until the Bose Ride system can be serviced.

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<sup>37</sup> *op. cit.* ISO 2631

### *Mechanical Design*

In order to achieve the precision required, the mechanical design of the Bose Ride™ system must have a high degree of stiffness and low friction to respond smoothly to rapidly changing dynamic forces. The extra heavy-duty frame, oversized bearings, and other precision mechanical components are used for this purpose.

### *System Performance*

The Bose Ride system has been extensively tested to ensure it will operate reliably in the hostile environment of a heavy-duty tractor-trailer, where temperatures, humidity, vibration, and hours of service required can often be extreme. Trucks equipped with the new system have been tested on a variety of roads and different conditions for many years and found to be highly effective in improving drive comfort and reducing whole-body vibration. The following sections detail some of the performance testing conducted to satisfy the standards required for a product of this kind.

### *Reliability, Quality, and Safety Testing*

While new to the trucking industry, Bose provides products in industries with high standards for usability in hostile environments, including for soldiers working in battle conditions, commercial automobiles, and aviation. The testing and expertise required ensuring the quality, reliability, and safety of these products is performed at Bose, and it has been applied in the development and manufacture of the Bose Ride system. The core elements and the system have been designed and tested to deliver years of service.

Prior to field testing, a rigorous laboratory testing regimen was designed. Qualification and evaluation of performance was conducted at the component, subsystem, and system levels, with tests conducted in the following categories: mechanical, electrical, electromagnetic compatibility, software, safety, packaging, environmental, and reliability.

In each of the above categories, sequences of tests were performed to explore product performance and life under the worst anticipated circumstances. Mechanical load tests were conducted in accordance with the Federal Motor Vehicle Safety Standards FMVSS 207 and 210. Broader safety testing included controller and motor tests, fault insertion, hardware and software safety assessments, and hazard assessments. Reliability was evaluated by a combination of accelerated aging, thermal and vibration tests, cycling of mechanical linkages, and electronics life tests.

The product was subjected to extensive environmental tests to ensure reliable operation in the worst of possible settings. These included: vibration exposure, high and low temperature, humidity, condensation, shock, repetitive shock testing, salt, fog, dust, driving rain, wear tests, and ultraviolet tests.



### Vibration Reduction Testing

Vibration measurements on the Bose Ride™ system were made to compare performance with a conventional air-ride truck seat, and as a point of reference, a premium-grade automobile.

These vibration data were analyzed in accordance with the International Standards Organization (ISO) specification ISO 2631-1, which defines a “health caution zone,” above which caution with respect to potential health risks is indicated.<sup>38</sup> An accelerometer was used to record acceleration-weighted measurements on three typical roads used by long-haul trucks in New England: highway, local roads, and an industrial park. The magnitude of the vertical vibrations was recorded and, per the guidelines provided in the standard, frequency weightings applied to calculate the estimated vibration-dose-value (eVDV) for an 11-hour driving period. The results are shown below in Figure-9.

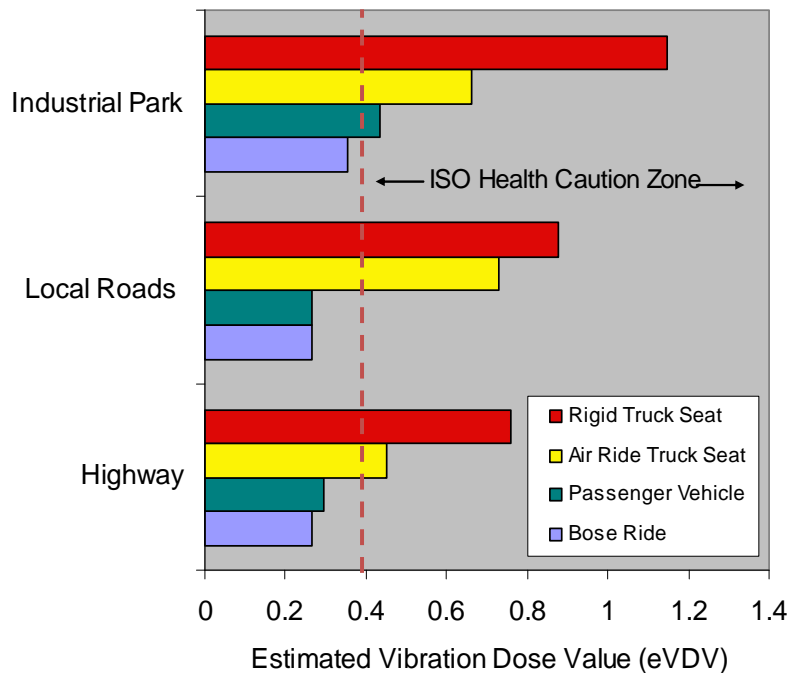


Figure-9. Estimated (normalized) vibration dose values as defined by ISO 2631-1 for an 11-hour day, and for three different road types, are shown.

Results show that a driver using the Bose Ride™ system receives the lowest dosage of whole-body vibration. A truck with the Bose Ride system limits the vibration dosage received by the driver over an 11-hour period to well below the

<sup>38</sup> *op. cit.* ISO 2631, p. 3

health caution zone in any of the road types tested. In contrast, an air-ride seat exceeds the limit in both the industrial park and local road types, and was at the health caution limit in the highway setting. Remarkably, the vibration dosage received from the Bose Ride system was equal to or lower than a high-end passenger vehicle.

From these road data, Bose engineers estimate that on a profile typical of what one might find on local roads, a heavy-duty truck driver with an air-ride seat could drive only 5.6 hours (or significantly less than allowed by hours of service regulation) prior to reaching the health caution zone threshold for whole-body vibration. With the Bose Ride system, the driver could drive five times longer before reaching the equivalent dosage (Note: the relationship between time, amplitude, and exposure limits is not linear).

## *Field Evaluation with Professional Drivers*

Extensive testing of the Bose Ride™ system in the field was performed with a variety of drivers, routes, and equipment, to ensure that the product performs as designed, and to gauge the reaction of drivers. A total of 77 over-the-road drivers used a Bose Ride system in their own truck for multiple weeks. These over-the-road drivers consisted of owner operators, small fleet drivers, and several major truckload carrier fleets. The fleet drivers were selected by their employers and included a mix of experience level and characteristics such as age, height, weight, body type, and history and absence of back problems.

In each of the 77 tests, the Bose Ride system was installed in the driver's vehicles for an average of four to five weeks, with the unit removed following completion of the test period. Most experienced drivers took one or two days to adapt to the different feel of the Bose Ride system. For a very small number of drivers, the adaptation period was as long as three weeks. Driver experiences, observations, and personal preferences were then recorded in post-trial surveys and interviews.

Most drivers responded positively to the new system, as shown in Figure-10 (next page). Eighty-four percent (84%) of trial drivers evaluated in field testing responded positively to the Bose Ride system, and 88% of those reported a quality-of-life improvement.

Eight percent (8%) of drivers felt that the Bose Ride system was too tall for them. This group includes those that describe themselves as "low-riders," or drivers that drive with their air-ride seats completely deflated.

Eight percent (8%) of drivers participating in the test did not like the motion of the Bose Ride system. The Bose Ride system provides a different riding experience: The driver's motion is reduced while the truck and cab are still shaking around them, and some of these drivers disliked the relative motion while others want no relative motion at all.

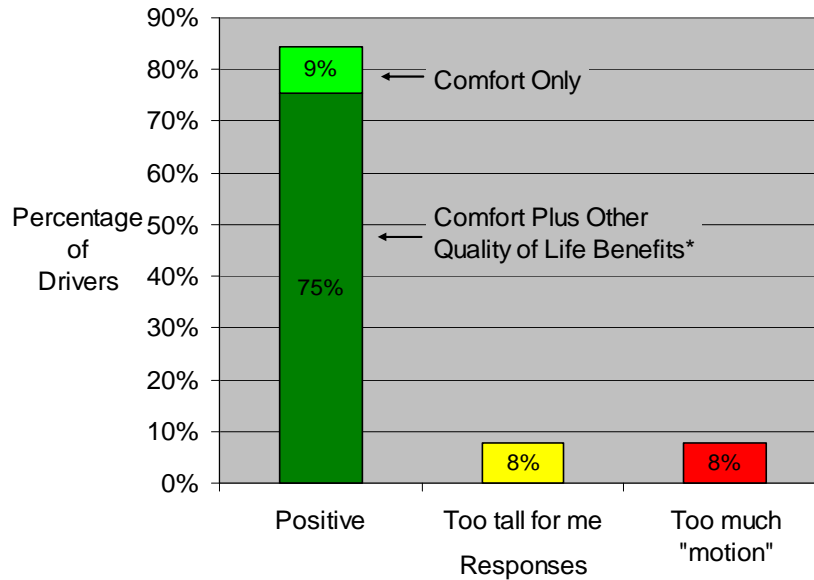


Figure-10. Responses of 77 over the road trial drivers testing late prototypes and the production design of the Bose Ride system.

\*Quality-of-life benefits comprise comfort, plus a minimum of one or two other benefits, including fatigue reduction, and less soreness and stiffness.

Post-trial interviews also provided insight into driver perception of specific product benefits, and a number of verbatim quotes from drivers participating in the research in the same proportion of positive to negative reactions as found in the testing are given in the Appendix.

Test results from 77 over-the-road drivers were as follows:

- 84% of drivers reported improved comfort benefits.
- 75% of drivers reported having less soreness and stiffness
- 66% reported decreased driving fatigue.

Repeated themes heard from drivers included:

- Elimination or reduction of back pain.
- Reduction in fatigue.
- Reduction or elimination of body pain.
- Less time for physical recovery between runs.
- Sleeping better, with more restful sleep.
- Feeling less tired and having more quality time with family.

## **Conclusion**

Our research found that although the problem of poor ride quality is often overlooked because it is accepted as part of the job, it nevertheless directly affects drivers, key contributors to the profitability of trucking businesses. With any radical innovation, we recognize that some period of commercial use is required to definitively prove economic benefits. In the meantime, however, we have found that 84% of the over-the-road drivers that used the Bose Ride™ system reported improved comfort benefits, 75% reported having less soreness and stiffness, and 66% reported decreased driving fatigue. From the quality-of-life improvements, we are confident that better ride quality can lead to higher job satisfaction, lower driver turnover, and lower operating costs for fleets.

## **Acknowledgments**

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## Appendix: Verbatim Driver Quotes from Field Evaluation

These quotes were taken from interviews with the 77 professional fleet drivers who participated in field evaluation to test the Bose Ride™ system. See the preceding section called “Field Evaluation with Professional Drivers” above for details. The quotes below were chosen to reflect the overall results obtained in our research, and they are presented in the same proportion of positive, ambivalent, and negative reactions found in the field experience.

### *Positive*

“I drove nine and a half hours and I didn’t realize it...I didn’t realize it because my body wasn’t hurting. I felt good driving.”

– S.W., Team Driver

“It’s the little ones that hit you all day long, I think, that affect you at the end of the day – and that’s what the [Bose] seat takes away.”

– E.G., Over-the-Road Driver

“This thing is far superior to anything I have ever sat in as far as comfort and reducing fatigue, hands-down.”

– D.P., Team Driver

“My back hasn’t bothered me since I got the seat. That’s the greatest thing. I just turned 52 years-old last week and my bladder isn’t what it used to be. I used to have to stop every two hours at least, and now I can drive across the state and not have to stop.”

– K.D., Over the Road Driver

“At the end of your shift you feel a lot better. You know – you do have more energy because your body is not as beat up. I don’t think it is. I would recommend that to anybody. You feel a lot better, yeah.”

– J.R., Line Haul Driver

“You pay more attention because you feel better, you know? I think you are more alert because you’re not as tired.”

– J.R., Line Haul Driver

“I feel a lot rested towards the end of the day. Like you just drove 540-plus miles and really didn’t even think you did...”

– J.A., Over-the-Road Driver

“That shoulder problem – a lot of that is from when you are jarring, you are squeezing harder. So you are tense. After a while, like I said, my shoulder didn’t hurt as bad. It got better and better. I wasn’t squeezing as hard. You are not holding on. Your whole body is not fatigued...”

– J.S., Over-the-Road Driver

“It took about two weeks. And then I woke up one morning and the light went on...ding...I wasn’t hurting any more. My back doesn’t hurt. The one thing that is hard about this job on my body is all the sitting.”

– D.T., Over-the-Road Driver

### *Too Much Motion*

“My impression was pretty good. It was overall good. It took me three or four days to get used to it. It was like floating on air. It has a yo-yo-like motion. It floats. You have to get used to it.”

– J.C., Over-the-Road Driver

### *Too Tall for Me*

“You have to get used from the factory seat to the seat that you put in it. The seat was too high for me – my head. To me, I’m a low-rider. I sit low in the seat.”

– J.J., Over-the-Road Driver