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Identifying Equipment Factors Associated with Snowplow Operator Fatigue

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Received: 18 July 2019; Accepted: 24 August 2019; Published: 1 September 2019

Abstract: A recent body of research in fatigue management indicates that other factors, including in-cab and external equipment, contribute to operator fatigue. The goal of this project was to identify winter road maintenance equipment (in-cab and external) that may increase or mitigate snowplow operator fatigue. To accomplish this goal, questionnaires from 2011 snowplow operators were collected from 23 states in the U.S. Results confirmed previous research that fatigue is prevalent in winter road maintenance operations. Winter road maintenance equipment that produced excessive vibrations, noise, reduced visibility, and complex task demands were found to increase snowplow operators' self-reported fatigue. Similarly, equipment that reduced vibrations and external noise, improved visibility, and limited secondary tasks were found to reduce snowplow operator's self-reported fatigue. Based on the questionnaire responses and the feasibility of implementation, the following equipment may help to mitigate or prevent snowplow operator fatigue: dimmable interior lighting, LED bulbs for exterior lighting, dimmable warning lights, a CD player or satellite radio in each vehicle, heated windshield, snow deflectors, narrow-beam auxiliary lighting, and more ergonomically designed seats with vibration dampening/air-ride technology.

Keywords: winter road maintenance operations; drowsiness; snowplow; fatigue; visibility; vibration; noise

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1. Introduction

Although there are numerous definitions of fatigue, it can generally be described as a combination of symptoms that include degraded performance and reduced alertness. These negative symptoms associated with fatigue may have a statistically significant effect on one's ability to safely operate a motor vehicle, especially a heavy vehicle. For example, research estimates that fatigue is a contributing factor in 13% to 31% of heavy vehicle crashes [1,2]. Regardless of this discrepancy, it appears that fatigue-related crashes among truck drivers are endemic given drivers' extended driving periods and work hours combined with shifts that can start at various times of the day and night.

During the winter months, winter road maintenance operators drive trucks equipped with snowplows or snow blowers to clear the roads of snow and ice. Previous research found that fatigue was prevalent among snowplow operators, as these workers often work long, stressful hours as they are not bound by prescriptive hours-of-service rules [3,4]. Theoretically, these factors may result in higher crash rates [1,2], lower productivity [5], and increased health issues among snowplow operators [6]. Thus, snowplow operator fatigue is a serious issue that can affect the safety of all drivers and passengers on the roads. A recent report investigating fatigue in winter road maintenance operations found that in-cab and external equipment may contribute to driver fatigue [3]. The contributing factors to the development of winter maintenance operator fatigue included vibration, noise, and visibility.

1.1. Literture Review

1.1.1. Vibration and Fatigue

Chronic and sustained whole-body vibration has been shown to contribute to adverse health risks, including driver fatigue [7]. For example, sustained vibrations ranging from 0.5 to 80 Hz can cause the muscles in the area that are experiencing vibrations to contract, either voluntarily or involuntarily, leading to muscle fatigue [8]. Additionally, monotonous and low-frequency vibration around 3 Hz has been shown to increase fatigue [9,10]. Similarly, the International Organization for Standardization (ISO) maintains that vibrations near 5 Hz should be avoided in the design of vehicle suspensions (ISO 2631-1:1997).

Vibrations are often transferred to a driver through the seat while sitting down or through the feet on the pedals. Researchers, equipment manufacturers, and vehicle manufacturers have recognized the importance of integrating vibration countermeasures into vehicle cabs. Some of the most common countermeasures to combat vibration are new or updated equipment, vibration dampeners, and increased maintenance [7]. Further, air-suspension and air-filled seat cushions have been shown to reduce vibrations in heavy vehicles [11–13]. Finally, rubber-encased snowplow blades have been shown to reduce vibrations during winter road maintenance operations [14].

1.1.2. Noise and Fatigue

In-cab and external sounds have been shown to affect an operator's level of fatigue [15,16], and they were reported by snowplow operators and managers to be important sources of fatigue in winter road maintenance operations [3]. However, sound can affect fatigue differently depending on the type and frequency of the sound [17]. Low-frequency, continuous sound has been found to increase fatigue [18–21]. Examples of low-frequency, continuous sounds in vehicles include those originating from diesel engines or vehicle-produced vibrations [22]. Similar to vibration, low-frequency, continuous sound may increase an operator's fatigue by increasing cognitive workload. High-frequency, intermittent sound, on the other hand, has been found to increase alertness and vigilance [23,24]. Horns are one example of high-frequency, intermittent sounds in vehicles.

Drivers frequently suggest listening to the radio as an effective countermeasure to fatigue. Operators in Camden et al. reported frequently listening to the radio/music as a means to counter fatigue; however, the same operators reported the radio/music to be only sometimes effective in reducing fatigue [3]. Similarly, other research found limited support for the effectiveness of listening to the radio/music to reduce fatigue [25,26].

1.1.3. Visibility and Fatigue

Snowplow operators often experience limited visibility as a result of frozen precipitation. Reduced visibility may lead to fatigue due to increased workload, sustained attention, eye strain, and glare. Eyestrain and eye discomfort have been found to increase subjective ratings of fatigue and rates of unintentional lane deviations [27]. It has also been speculated that glare from lighting contributes to driver fatigue. However, glare does not uniformly contribute to driver fatigue [28,29]. For example, Shiftlett et al. found that glare produced fatigue in some individuals, but not consistently [29]. This likely indicated other factors (e.g., sleep loss, vibrations, and high-demand conditions) contributed to glare's effect on susceptibility to fatigue.

There is a growing body of research that investigates the potential of equipment lighting to decrease fatigue. Specific types of lighting equipment that may decrease fatigue are interior blue lights and light-emitting diode (LED) headlamps. Short-wavelength light in the 424 to 477 nm range (i.e., blue light) has been linked to the suppression of melatonin, which plays a large role in the regulation of circadian rhythms [30–33]. Two studies found that short-wavelength light reduced driver fatigue [34,35].

In addition to interior lighting, exterior vehicle lighting plays an important role in a winter maintenance operator's visibility, especially during nighttime operations with falling snow and ice. During darkness, falling snow and ice often reflect light back to the driver that can contribute to eye discomfort and possibly fatigue [36]. Auxiliary lights mounted away from the operator's direct line of sight (i.e., on the passenger side) reduced back-reflected light and eye discomfort [37–39]. Additionally, narrow beam light (i.e., spot lights) produced less back-reflected light compared to wide beams of light [40,41].

1.2. Objective

Although Camden et al. [3] found that vehicle and snowplow equipment contributed to the development of fatigue, they did not investigate specific equipment that may increase or decrease fatigue in snowplow operators. Thus, the goal of this project was to (1) identify specific snowplow equipment (in-cab and external) associated with increased snowplow operator fatigue and (2) identify snowplow equipment that may be used to mitigate snowplow operator fatigue.

2. Materials and Methods

Based on the results from the literature review, a questionnaire was developed to collect winter snowplow operators' opinions and perceptions regarding equipment factors associated with fatigue. The below sections discuss the participants, questionnaire, questionnaire distribution, and analyses. This study was approved by the Virginia Tech Institutional Review Board (IRB number 16-989).

2.1. Participants

Participants included snowplow operators in states that participate in the Clear Roads national research consortium. Clear Roads' mission is to investigate winter road maintenance best practices, including materials, policies, equipment, technologies, and procedures. At the time of this project, there were 33 member states in Clear Roads. The only inclusion criterion to participate in this project was an individual's job responsibility. Only those individuals that performed winter road maintenance operations were eligible.

2.2. Questionnaire

The questionnaire was designed to assess equipment that may increase or decrease fatigue. The complete questionnaire can be found in Camden et al. [42]. The topics included in the questionnaire are shown below.

- Municipality or state agency where employed to perform snowplow operations. Responses were open ended.
- Years of experience in winter road maintenance operations. Responses were open ended.
- Make, model, and year of winter road maintenance equipment most frequently used (e.g., tractor, pick-up truck, grader, front-end loader, and dump truck with plows and/or spreaders). Responses were open ended.
- How often fatigue is experienced while driving. Likert-scale responses (options included never, sometimes, about half the time, most of the time, and always).
- Shifts (e.g., time of day, length, and the part of shift when fatigue is most often experienced). Responses were open ended.
- Impact of vibration-related equipment on their fatigue (e.g., air-suspension seat, air-cushioned seat, automatic tire chains, non-automatic tire chains, rubber-encased blades, blade float device, segmented blades, belly plow, wing plow, tow plow, and front plow). Likert-scale responses (options included always increases tiredness, sometimes increases tiredness, neither increases nor decreases tiredness, sometimes decreases tiredness, always decreases tiredness, and do not have on truck).

- Impact of equipment-related noise on their fatigue (e.g., noise from plow or engine, music, citizens band (CB) or Department of Transportation (DOT) radio, and audible alerts from equipment). Likert-scale responses (options included always increases tiredness, sometimes increases tiredness, neither increases nor decreases tiredness, sometimes decreases tiredness, always decreases tiredness, and do not have on truck).
- Impact of visibility-related equipment on their fatigue (e.g., antiglare glass, exterior strobe and flashing lights, interior vehicle lighting, auxiliary lighting, windshield wipers, heated mirrors and windshield/windows, and snow deflectors). Likert-scale responses (options included always increases tiredness, sometimes increases tiredness, neither increases nor decreases tiredness, sometimes decreases tiredness, always decreases tiredness, and do not have on truck).
- Impact of in-cab equipment on their fatigue (e.g., number of and placement of equipment controls, mobile phone, a collision avoidance system, a system to assist with lane positioning, back-up cameras, heads up displays (HUD), and LCD displays). Likert-scale responses (options included always increases tiredness, sometimes increases tiredness, neither increases nor decreases tiredness, sometimes decreases tiredness, always decreases tiredness, and do not have on truck).
- Additional suggestions to decrease fatigue. Responses were open ended.

2.3. Data Collection Procedures

The research team worked with a Clear Roads representative in each of the states to recruit snowplow operators to complete the questionnaire. We provided online and paper versions of the questionnaire to these Clear Roads representatives. The Clear Roads representatives sent the questionnaire to snowplow operators in their state. Participation in the questionnaire was voluntary, and all responses were anonymous (no personally identifying information was collected). Responses to the online version of the questionnaire were entered automatically into a secure online database. Responses to the paper version of the questionnaire were mailed to the research team, which entered the responses into the secure online database.

Participates were given the opportunity to enter a random drawing for one of ten $50 gift cards. To enter the drawing, snowplow operators provided the research team with their contact information on a separate form that was not linked to their responses on the questionnaire. Four months after distributing the questionnaire, the research team randomly selected 10 participants in the raffle, each winning a $50 gift card. The gift card was mailed to each raffle winner.

2.4. Analysis

Questionnaire responses were analyzed to assess the relationship between winter road maintenance equipment and the development of fatigue. Chi-square tests and Fisher's exact tests were performed to identify statistically significant differences in the distributions in responses. Paired sample *t*-tests were also performed to assess how each equipment type impacted the development of fatigue, an approach modeled after De Winter and Dodou [43]. First, snowplow operators' ratings of how often each type of equipment impacted the development of fatigue (termed fatigue impact) were given a numerical score. This numerical score translated the categorical responses into a Likert scale (always increases = 5, sometimes increases = 4, never impacts = 3, sometimes decreases = 2, and always decreases = 1). Average ratings for each type of equipment were calculated using the numerical values from all snowplow operators who responded for that particular equipment type. The average rating was tested against a null hypothesis of the equipment having no fatigue impact ("never impact" or an average score of 3 using the corresponding numerical score value) using a *t*-test.

3. Results

A total of 2011 snowplow operators from 23 different states provided responses (out of 33 Clear Roads states). Table 1 displays the number of participants per state. A small portion of the winter maintenance operators (14 or 0.17%) chose not to provide their state.

Table 1. Distribution of participants by state.

State	Number of Snowplow Operators	Percentage of Snowplow Operators
Alaska	65	3.23%
Arizona	24	1.19%
Colorado	265	13.18%
Connecticut	5	0.25%
Delaware	138	6.86%
Illinois	131	6.51%
Kansas	63	3.13%
Maine	80	3.98%
Michigan	10	0.50%
Montana	150	7.46%
Nebraska	77	3.83%
New Hampshire	10	0.50%
New York	119	5.92%
North Dakota	38	1.89%
Ohio	1	0.05%
Oregon	42	2.09%
Pennsylvania	57	2.83%
South Dakota	91	4.53%
Utah	48	2.39%
Vermont	32	1.59%
Virginia	466	23.17%
West Virginia	48	2.39%
Wyoming	37	1.84%
Blank	14	0.70%
Total	**2011**	**100.00%**

Figure 1 displays the winter maintenance operators' years of experience in winter operations. More than one-third (37.2% or 747) of the winter maintenance operators had at least 15 years' experience working in winter maintenance operations. Approximately one-quarter (25.5%) of winter maintenance operators had 1 to 5 years' experience in winter maintenance operations, 17.30% had 6 to 10 years' experience, 13.3% had 11 to 15 years' experience, and 5.9% had less than a year of experience.

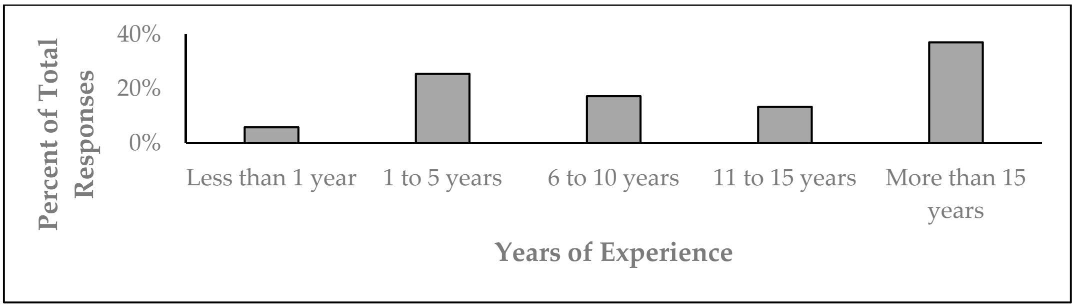

Figure 1. Distribution of winter maintenance operators' experience in winter operations.

3.1. Shift Characteristics

Figure 2 shows snowplow operators' responses regarding their normal shift time of day (day, night, or both). The majority of snowplow operators reported shifts during day and night (58.9% or

1184 snowplow operators). Another 22.2% (447 snowplow operators) of snowplow operators reported having the majority of shifts during the day, and 17.9% (360 snowplow operators) reported a majority of shifts during the night. Only a small percentage (1% of or 20 snowplow operators) did not respond to this question.

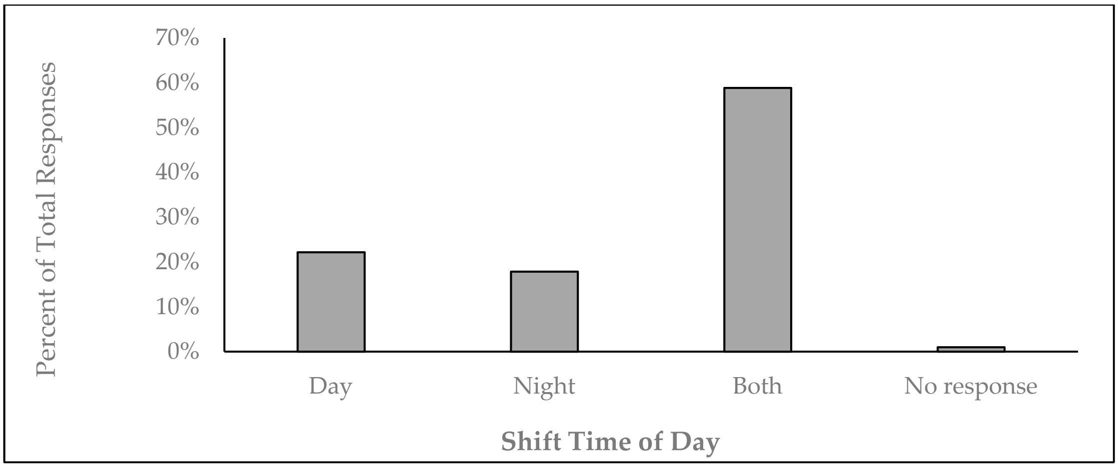

Figure 2. Distribution of shift time of day.

Typical shift lengths during winter emergencies ranged from less than 8 h to more than 16 h (see Figure 3). The most commonly reported shift length was 12 h (37.8% or 761 snowplow operators), followed by shifts between 8 and 12 h (29.8% or 600 snowplow operators) and shifts between 12 and 16 h (20.6% or 414 snowplow operators). Very few snowplow operators reported shifts less than 8 h (1.1% or 20 snowplow operators), 8 h (2.5% or 51 snowplow operators), 16 h (1.7% or 34 snowplow operators), or more than 16 h (5.9% or 118 snowplow operators).

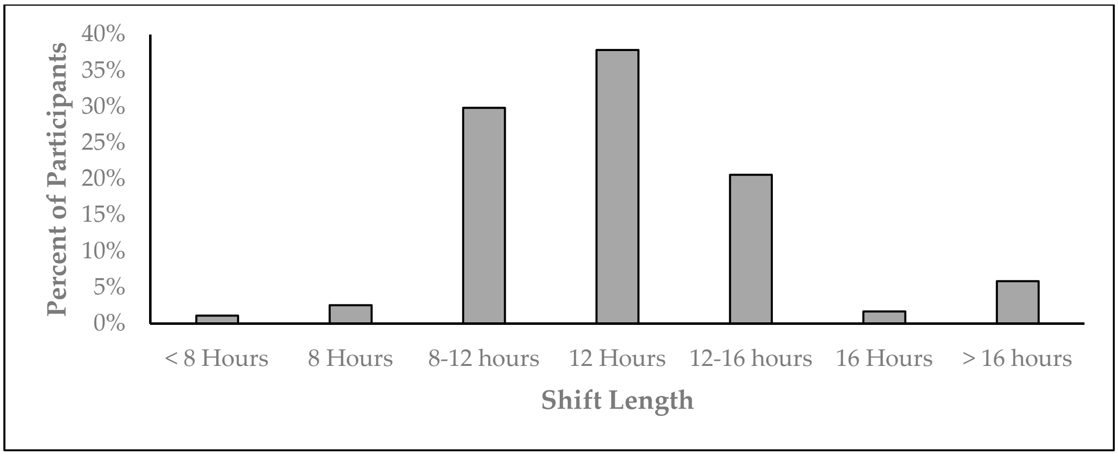

Figure 3. Typical shift length during winter emergencies.

3.2. Prevalence of Fatigue

Figure 4 shows snowplow operators' self-reported fatigue while operating a snowplow during winter emergencies. Overall, approximately 94% of snowplow operators reported feeling fatigued at some point while operating a snowplow during winter emergencies. The most frequently reported answer was "sometimes" (61.97% or 1237 snowplow operators). Just over 18% of snowplow operators reported feeling fatigued "half the time" (364 snowplow operators). Approximately 10% of snowplow operators felt fatigued "most of the time" (199 snowplow operators), and approximately 4% of snowplow operators felt fatigued "always" (79 snowplow operators). Less than 6% of snowplow operators never felt fatigued during their shift (117 snowplow operators).

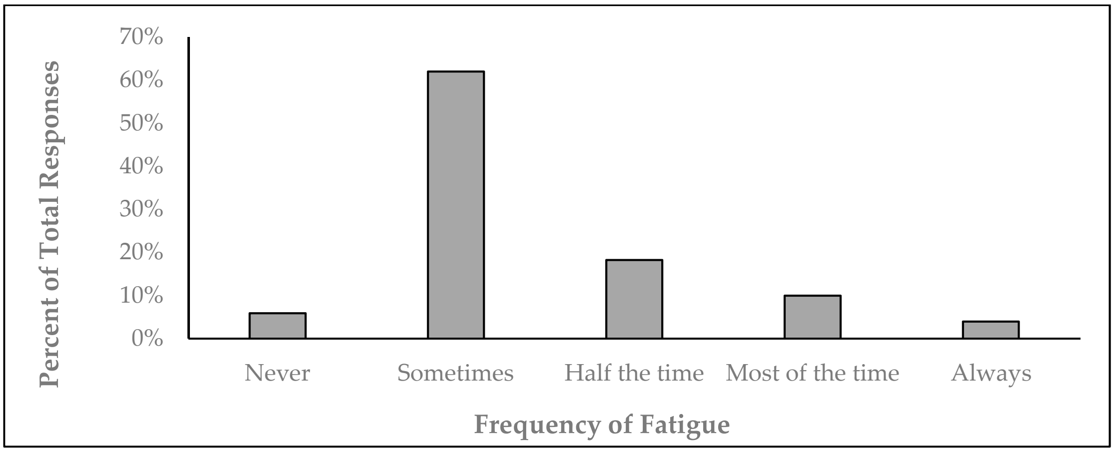

Figure 4. Frequency of self-reported fatigue during a winter emergency shift.

Table 2 reports the shift time of day by fatigue frequency. Although all three shift time categories showed similar distributions in fatigue frequency, shifts with night driving had higher proportions of fatigue than day shifts. For example, approximately 1.6% of day shift snowplow operators, 5.6% of night shift snowplow operators, and 4.4% of snowplow operators who worked both shifts always felt fatigued. Similarly, snowplow operators with day shifts reported a lower proportion of fatigue. For example, approximately 7.6% of day shift snowplow operators, 6.4% of night shift snowplow operators, and 5.0% of snowplow operators who worked both shifts reported never feeling fatigued.

Table 2. Frequency of self-report fatigue by shift time of day.

Frequency of Self-Reported Fatigue	Majority Day Shift	Majority Night Shift	Both Day and Night Shift
Never	7.61%	6.41%	5.02%
Sometimes	71.81%	55.99%	59.91%
Half of the time	12.30%	19.78%	20.00%
Most of the time	6.71%	12.26%	10.64%
Always	1.57%	5.57%	4.43%

The distribution of fatigue frequency was compared to the shift times using a chi-square test. The results are shown in Table 3 below. The test results confirm the pattern observed above. Snowplow operators working mostly day shifts showed a statistically significant different distribution in fatigue ratings than snowplow operators working night shifts ($\chi^2 = 31.42$, $p < 0.0001$) and snowplow operators working a mix of day and night shifts ($\chi^2 = 34.26$, $p < 0.0001$). Snowplow operators with mostly night shifts did not report statistically significant different fatigue ratings than snowplow operators with a mix of day and night shifts ($\chi^2 = 3.13$, $p = 0.5355$).

Table 3. Chi-square test results for fatigue frequency rating by shift time.

Shift Time Comparison	χ^2	*df*	*p*
Day vs. Night	31.4152	4	<0.0001
Day vs. Day & Night	34.2575	4	<0.0001
Night vs. Day & Night	3.1348	4	0.5355

Table 4 displays a series of Fisher tests used to identify statistically significant differences in the overall distribution of self-reported fatigue by shift length. Because of the large number of comparisons, an adjusted critical value was used to determine significance (critical values for the tests below was set at 0.0024). The statistically significant results have an "*" in the right-most column. Shifts longer than 16 h were found to be statistically different in reported fatigue when compared to all other shift lengths. Shifts between 8 and 12 h showed statistically significant differences from shifts that were 12 h ("always" and "most of the time" fatigued rated at approximately half the value seen in shifts that were 12 h) and shifts that were 12 to 16 h ("always" and "most of the time" fatigued rated at approximately one-third the value seen in shifts that were 12 to 16 h).

Table 4. Fisher test results for the overall distribution of fatigue frequency ratings by shift length.

Shift Length Comparison 1	Shift Length Comparison 2	χ^2	p	Statistically Significant
Less than 8 h	8 h	0.0152	0.7599	
Less than 8 h	8 to 12 h	0.0017	0.1962	
Less than 8 h	12 h	<0.0001	0.0171	
Less than 8 h	12 to 16 h	<0.0001	0.0024	
Less than 8 h	16 h	<0.0001	0.0112	
Less than 8 h	More than 16 h	<0.0001	0.0003	*
8 h	8 to 12 h	0.0005	0.3006	
8 h	12 h	<0.0001	0.0325	
8 h	12 to 16 h	<0.0001	0.0025	
8 h	16 h	0.0002	0.0625	
8 h	More than 16 h	<0.0001	<0.0001	*
8 to 12 h	12 h	<0.0001	<0.0001	*
8 to 12 h	12 to 16 h	<0.0001	<0.0001	*
8 to 12 h	16 h	<0.0001	0.0186	
8 to 12 h	More than 16 h	<0.0001	<0.0001	*
12 h	12 to 16 h	<0.0001	0.1361	
12 h	16 h	<0.0001	0.0015	*
12 h	More than 16 h	<0.0001	<0.0001	*
12 to 16 h	16 h	0.0034	0.9738	
12 to 16 h	More than 16 h	<0.0001	0.0003	*
16 h	More than 16 h	0.0006	0.3504	

Fatigue was also assessed for differences by years of experience. In Table 5, the distribution of self-reported fatigue is shown by years of experience. Winter maintenance operators with less than 1 year of experience reported never feeling fatigued at 2 to 8 times the rate of winter maintenance operators with more experience. Winter maintenance operators with 6 or more years of experience reported feeling "always" fatigued at approximately 2 to 4 times the rate of winter maintenance operators with 5 years or less of experience. A chi-square test showed experience in winter operations impacted the frequency of self-reported fatigue ($\chi^2 = 78.96$, $df = 16$, $p < 0.0001$).

Table 5. Percentage of fatigue by years of experience.

Fatigue Frequency	<1 Year Experience	1 to 5 Years' Experience	6 to 10 Years' Experience	11 to 15 Years' Experience	>15 Years' Experience
Always	1%	2.54%	4.61%	4.53%	4.99%
Most of the time	2%	7.83%	11.24%	10.19%	12.26%
Half of the time	16.38%	15.66%	22.77%	22.26%	16.58%
Sometimes	64.66%	65.56%	55.62%	58.11%	63.61%
Never	16.38%	8.41%	5.76%	4.91%	2.56%

3.3. Equipment-Related Factors Associated with Fatigue

Table 6 reports snowplow operators' responses on their ratings of fatigue during winter emergencies being affected by equipment-related vibration, noise, reduced visibility, and other factors associated with in-cab equipment. Participants responded very similarly for vibration, noise, and in-cab equipment. Nearly 50% of winter maintenance operators reported that vibration, noise, and in-cab equipment never caused fatigue while driving. Few operators reported these factors often lead to driver fatigue. Unlike the other equipment-related factors, more than one-quarter of the snowplow operators stated that reduced visibility made them "always" (9.81%) fatigued or fatigued "most of the time" (16.38%) while driving.

Table 6. Frequency of equipment-related factors that cause fatigue during winter emergencies.

Factor	Always	Most of the Time	Half of the Time	Sometimes	Never
Vibration	1.27%	4.71%	7.95%	36.76%	49.32%
Noise	1.45%	5.28%	7.87%	37.70%	49.15%
Visibility	9.81%	16.38%	15.77%	40.45%	27.41%
In-cab Equipment	0.78%	2.19%	6.58%	41.93%	49.30%

3.3.1. Equipment-Related Vibration

Table 7 shows the ratings for types of equipment related to vehicle vibration. Non-automatic chains and the front plow had the most ratings associated with the development of fatigue while driving. For these equipment types, at least one-quarter of snowplow operators rated the equipment as "sometimes" or "always" increasing fatigue while driving. Air-suspension seats, air-cushioned seats, rubber-encased blades, and blade-float devices were rated as decreasing fatigue while driving. For these equipment types, 18% to 30% of snowplow operators felt they "sometimes" or "always" decreased fatigue while driving.

Table 7. Impact of vibration from equipment on fatigue.

Vibration-Related Equipment	Always Increases	Sometimes Increases	Never Impacts	Sometimes Decreases	Always Decreases
Air-suspension seat	1%	9%	59%	16%	14%
Air-cushioned seat	1%	9%	64%	14%	13%
Automatic tire chains	4%	7%	78%	5%	7%
Non-automatic tire chains	7%	18%	63%	6%	7%
Rubber-encased blades	1%	6%	66%	13%	13%
Blade float device	1%	5%	76%	9%	9%
Segmented blades	1%	6%	80%	6%	7%
Belly plow	2%	13%	72%	6%	7%
Wing plow	3%	17%	66%	8%	7%
Tow plow	2%	9%	80%	4%	6%
Front Plow	3%	22%	63%	6%	6%

Table 8 displays the results of t-tests evaluating the average rating for how vibrations from each type of equipment impacted the development of fatigue while driving (termed fatigue impact). Snowplow operators indicated air-suspension seats (M = 2.6656), air-cushioned seats (M = 2.7021), rubber-encased blades (M = 2.6868), and blade float devices (M = 2.8876) all statistically significantly decreased their perceived fatigue while driving. However, snowplow operators reported that non-automatic tire chains (M = 3.1077) and the front plow (M = 3.1071) increased their perceived levels of fatigue while driving.

3.3.2. Equipment-Related Noise

The equipment-related noise reported to have the largest impact on fatigue was music or the radio turned on or off (see Table 9). Approximately 50% of snowplow operators stated having music or the radio on decreased their fatigue while driving ("sometimes" at 26% or "always" at 24%). Conversely, just under half the snowplow operators stated having music or the radio turned off increased fatigue while driving ("sometimes" at 31% or "always" at 14%). Other noises that decreased fatigue while driving included the CB radio (20% of snowplow operators rated as "sometimes" or "always" decreased fatigue) and the DOT radio (27% of snowplow operators rated as "sometimes" or "always"). Noise from the plow or engine increased fatigue in snowplow operators (35% and 36%, for the noise types, respectively, rated as "sometimes" or "always").

Table 8. Statistical analyses for vibration-related equipment and levels of fatigue (rating of 1 = always decreases; 5 = always increases).

Vibration-Related Equipment	*n*	Average Rating	*df*	*t*	*p*	Significance
Air-suspension seat	1794	2.6656	1793	−16.31	<0.0001	*
Air-cushioned seat	1363	2.7021	1362	−13.19	<0.0001	*
Automatic tire chains	393	2.9644	392	−0.98	0.3300	
Non-automatic tire chains	956	3.1077	955	3.79	0.0002	*
Rubber-encased blades	843	2.6868	842	−11.02	<0.0001	*
Blade float device	1083	2.7867	1082	−9.99	<0.0001	*
Segmented blades	1023	2.8876	1022	−5.45	<0.0001	*
Belly plow	633	2.9874	632	−0.43	0.6684	
Wing plow	1279	3.0094	1278	0.43	0.6684	
Tow plow	388	2.9691	387	−0.94	0.3494	
Front Plow	1765	3.1071	1764	5.69	<0.0001	*

Table 9. Impact of noise from equipment on fatigue.

Noise-Related Equipment	Always Increases	Sometimes Increases	Never Impacts	Sometimes Decreases	Always Decreases
Noise from plow	4%	31%	54%	6%	6%
Noise from engine	5%	31%	56%	5%	4%
Music/radio turned on	0%	4%	45%	26%	24%
Music/radio turned off	14%	31%	47%	5%	3%
CB radio	2%	7%	71%	11%	9%
Department of Transportation (DOT) radio	4%	10%	60%	17%	10%
Audible alerts	2%	8%	68%	12%	10%

Table 10 reports the results of *t*-tests that evaluated how the average ratings of fatigue were affected by equipment-related noise. Noise-related equipment that was found to decrease perceived fatigue while driving included the music/radio turned on (M = 2.3044), CB radio (M = 2.8171), DOT radio (M = 2.8097), and audible alerts from snow/ice/safety equipment (M = 2.7929). Noise-related equipment found to increase perceived levels of fatigue while driving included noise from the plow or engine (M = 3.2182 and M = 3.2734, respectively) and having the music/radio turned off (M = 3.4794).

Table 10. Statistical analyses for equipment-related noise and levels of fatigue (rating of 1 = always decreases; 5 = always increases).

Equipment-Related Noise	*n*	Average Rating	*df*	*t*	*p*	Significance
Noise from plow	1884	3.2182	1883	11.23	<0.0001	*
Noise from engine	1880	3.2734	1879	14.99	<0.0001	*
Music/radio turned on	1820	2.3044	1819	−32.97	<0.0001	*
Music/radio turned off	1771	3.4794	1770	22.20	<0.0001	*
CB radio	924	2.8171	923	−7.31	<0.0001	*
DOT radio	1823	2.8097	1822	−9.15	<0.0001	*
Audible alerts	1405	2.7929	1404	−9.89	<0.0001	*

3.3.3. Equipment-Related Visibility

Few types of visibility-related equipment were rated as having a strong impact on decreasing fatigue while driving (see Table 11). Antiglare glass was rated by 22% of snowplow operators as "sometimes" (13%) or "always" (9%) decreasing fatigue while driving. However, several types of equipment were rated as "sometimes" increasing fatigue while driving. These types of equipment included exterior strobe lights (33%), exterior flashing lights (31%), interior vehicle lighting (18%), and windshield wipers (30%). Most often, snowplow operators reported visibility-related equipment never impacted their feelings of fatigue while driving (ranged between 51% and 84% of snowplow operators).

Table 11. Impact of visibility-related equipment on fatigue.

Visibility-Related Equipment	Always Increases	Sometimes Increases	Never Impacts	Sometimes Decreases	Always Decreases
Antiglare glass	2%	12%	65%	13%	9%
Exterior strobe lights	7%	33%	51%	5%	4%
Exterior flashing lights	6%	31%	54%	5%	4%
Interior vehicle lighting	2%	18%	69%	7%	4%
Auxiliary exterior lighting	2%	15%	71%	6%	5%
Windshield wipers	4%	30%	57%	5%	4%
Heated mirrors	0%	2%	82%	7%	9%
Heated windshield	0%	2%	84%	6%	7%
Heated windows	1%	3%	84%	5%	8%
Snow deflector	1%	6%	80%	6%	6%

Table 12 shows the results of *t*-tests evaluating how the average ratings of fatigue were affected by visibility-related equipment. Several types of equipment were found to decrease perceived levels of fatigue while driving. These included antiglare glass ($M = 2.8543$), heated mirrors ($M = 2.7790$), heated windows ($M = 2.8360$), heated windshield ($M = 2.6306$), and snow deflectors ($M = 2.6656$). Visibility-related equipment rated as increasing perceived levels of fatigue while driving included exterior strobe lights ($M = 3.3310$), exterior flashing lights ($M = 3.3001$), interior vehicle lighting ($M = 3.0718$), and windshield wipers ($M = 3.2604$).

Table 12. Statistical analyses for visibility-related equipment and levels of fatigue (rating of 1 = always decreases; 5 = always increases).

Vibration-Related Equipment	*n*	Average Rating	*df*	*t*	*p*	Significance
Antiglare glass	1167	2.8543	1166	−6.11	<0.0001	*
Exterior strobe lights	1837	3.3310	1836	16.88	<0.0001	*
Exterior flashing lights	1826	3.3001	1825	15.64	<0.0001	*
Interior vehicle lighting	1811	3.0718	1810	4.31	<0.0001	*
Auxiliary exterior lighting	1764	3.0295	1763	1.76	0.0786	
Windshield wipers	1885	3.2604	1854	14.58	<0.0001	*
Heated mirrors	1760	2.7790	1759	−14.46	<0.0001	*
Heated windshield	1554	2.6306	1553	−17.58	<0.0001	*
Heated windows	951	2.8360	950	−8.19	<0.0001	*
Snow deflector	1794	2.6656	1793	−16.31	<0.0001	*

3.3.4. In-Cab Equipment

Snowplow operators rated several types of in-cab equipment and their impact on fatigue while driving (see Table 13). For each type of in-cab equipment, two-thirds of snowplow operators felt there was "never" an impact on fatigue while driving (ranged from 65% to 84%). Placement and number of equipment controls sometimes increased fatigue while driving for 21% and 18% of snowplow operators, respectively. LCD displays also affected levels of fatigue while driving: placement of LCD displays sometimes increased fatigue for 20% of snowplow operators, and light from LCD displays increased fatigue for 24% of snowplow operators. The percentages of snowplow operators rating "always increases," "sometimes decreases," or "always decreases" were fairly consistent across each type of equipment.

Table 13. Impact of in-cab equipment on fatigue.

In-Cab Equipment	Always Increases	Sometimes Increases	Never Impacts	Sometimes Decreases	Always Decreases
Placement of equipment controls	2%	21%	69%	5%	3%
Number of equipment controls	2%	18%	72%	5%	3%
Mobile phone	1%	4%	83%	8%	4%
Presence of a collision avoidance system	1%	5%	82%	5%	8%
Assistance via a lane departure warning system	1%	8%	78%	6%	7%
Back-up cameras	2%	5%	81%	6%	6%
HUDs	1%	10%	79%	5%	4%
Placement of interior LCD displays	3%	20%	70%	5%	3%
Light from LCD displays (other than back-up cameras)	4%	24%	65%	5%	3%

Table 14 reports the results of *t*-tests evaluating how the average ratings of fatigue were affected by in-cab equipment. The adjusted alpha was equal to 0.0045. In-cab equipment associated with a decreased perceived level of fatigue while driving included a mobile phone (M = 2.8901), presence of a collision avoidance system (M = 2.8584), assistance to stay within lane (M = 2.9155), and back-up cameras (M = 2.9080). In-cab features rated as increasing perceived levels of fatigue while driving included the placement and number of equipment controls (M = 3.1336 and M = 3.1086, respectively) and placement of and light from LCD displays (M = 3.1372 and M = 3.1937, respectively).

Table 14. Statistical analyses for in-cab equipment and levels of fatigue (rating of 1 = always decreases; 5 = always increases).

In-Cab Equipment	N	Average Rating	df	t	p	Significance
Placement of equipment controls	1842	3.1336	1841	8.45	<0.0001	*
Number of equipment controls	1832	3.1086	1831	6.96	<0.0001	*
Mobile phone	1456	2.8901	1455	−7.49	<0.0001	*
Presence of a collision avoidance system	551	2.8584	550	−5.13	<0.0001	*
Assistance via a lane departure warning system	521	2.9155	520	−2.88	0.0041	*
Back-up cameras	511	2.9080	510	−3.28	0.0011	*
HUDs	648	2.9923	647	−0.32	0.7497	
Placement of interior LCD displays	1115	3.1372	1114	6.85	<0.0001	*
Light from LCD displays (other than back-up cameras)	1301	3.1937	1300	9.68	<0.0001	*

4. Discussion

Similar to the results from Camden et al., the vast majority of snowplow operators reported feeling fatigued at some point while operating a snowplow during a winter emergency [3]. In both studies, snowplow operators most frequently reported they "sometimes" felt fatigued while driving. However, 12% to 15% of snowplow operators reported feeling fatigued "most of the time" or "always" while driving.

The snowplow operators in this study reported similar shifts compared to those in Camden et al. [3]. The majority of snowplow operators worked day and night shifts (56% in Camden et al. [3] and 58% in the current study). However, 67% of snowplow operators in Camden et al. [3] reported shift lengths longer than 12 h compared to 28% of snowplow operators in this study. The current study found snowplow operators with shifts lasting 16 h or longer reported statistically significant higher levels of fatigue compared to all other shift lengths. This fatigue may be the result of sleep debt (lack of sleep over one or more days), sustained activity over a long period of time, or some combination.

4.1. Equipment-Related Vibration

Sustained, low-frequency vibrations contribute to the development of fatigue [7,9,10]. These results were supported by snowplow operators' opinions from Camden et al. [3] and the current study. Approximately 50% of the snowplow operators in the current study reported that vibrations caused fatigue at some point. One method to reduce sustained, low-frequency vibrations is to upgrade or improve the snowplow's suspension. Previous research found that air-ride truck suspensions produced statistically significant reductions in vehicle vibrations [44,45]. Snowplow operators provided dozens of comments in Camden et al. [3] that suggested an improved truck suspension would reduce vibration-causing fatigue.

A snowplow blade float device may be another countermeasure to reduce sustained, low-frequency vibrations. A blade float device attaches to the snowplow and automatically adjusts the pressure and position of the plow based on the roadway. Although there is no published research examining the effectiveness of a blade float device in reducing fatigue, snowplow operators in this study indicated they reduced fatigue by a statistically significant amount. They also may help alleviate the fatigue snowplow operators associated with the front plow. However, some snowplow operators may override the float device to get more downward pressure on the snowplow blade to make the road as clear as possible. In this scenario, the snowplow operator would create higher levels of vibrations than intended with the float device.

Rubber-encased snowplow blades also reduce sustained vibrations and noise [14]. Results from this study confirmed that snowplow operators believed that rubber-encased blades reduced fatigue. Schneider et al. examined the costs associated with the purchase, replacement, and installation of various snowplow blades [46]. They found that rubber-encased blades may not be cost-effective given the high purchase and replacement costs. However, Schneider et al. did not factor in benefits associated with reduced snowplow operator fatigue (e.g., increased productivity and crash costs) from the use of rubber-encased blades. These added benefits may improve the cost–benefit of rubber-encased blades.

Snowplow operators in the current study indicated that an air-ride/vibration dampening seat may be an effective solution to reduce fatigue associated with vibration. This finding is supported by the comments provided in Camden et al. [3] and Peterson [47]. Additionally, several other studies demonstrated the importance of an operator's seat in reducing vibrations [11,12]. Blood et al. found that air-ride seats reduced low-frequency vibrations compared to a traditional seat [11]. On the other hand, Blood et al. found that electromagnetically active seats reduced vibration by 30% over air-ride seats; however, both types of vibration-reducing seats reduced vibrations compared to a traditional seat [12].

4.2. Equipment-Related Noise

Previous research has found that, similar to vibration, noise can adversely impact fatigue [16,17]. In particular, low-frequency, continuous noise has consistently been found to increase self-reported fatigue and driver behaviors associated with fatigue [18–21]. Snowplow operators in the current study reported that noise from the engine and plow increased fatigue. This is likely why Camden et al. found that noise was an important source of fatigue in winter road maintenance operations [3]. One solution to reduce noise-related fatigue is to increase cabin insulation. There were over 180 comments in Camden et al. to reduce noise with increased cab insulation [3]. Additionally, Peterson recommended increased cab insulation as an effective countermeasure to exterior snowplow noise [47].

However, prior research has demonstrated that every noise does not necessarily increase fatigue [17]. Unlike low-frequency sound, high-frequency, intermittent sound increases alertness and vigilance [23–25]. Snowplow operators in the current study indicated that alerts (i.e., high-frequency, intermittent sound) from snow, ice, or safety equipment decreased fatigue.

The current study also found that the use of a CB or DOT radio reduced fatigue. A communication device (regardless if it is a CB radio, DOT radio, or cell phone) would allow the snowplow operator to converse with others and, thus, provide stimulation in monotonous conditions. This result somewhat contradicts the snowplow operators' opinions in Camden et al., which found that 62% of snowplow operators believed that conversations on a CB/DOT radio or cell phone were rarely effective or never effective at reducing fatigue [3]. However, the results from the current study support previous research with heavy-vehicle [48,49] and light-vehicle drivers [50–52]. In all of these studies, the use of a CB radio or cell phone conversation decreased subjective ratings of fatigue; however, the effects often lasted less than 30 min. It is also important to note that some states ban cell phone use while driving. Thus, it is not feasible or recommended to have a cell phone conversation while operating the snowplow during a winter emergency.

According the snowplow operators in the current study, music or a radio (or lack thereof) had the largest impact on snowplow operator fatigue. Operators indicated that fatigue increased when the radio was turned off, whereas fatigue decreased when the radio was on. Similar to the CB radio, these results somewhat contradict Camden et al. [3], which found that snowplow operators frequently used music or the radio to mitigate fatigue. However, those same snowplow operators reported that music or the radio was only "sometimes" effective in reducing fatigue. However, other research has shown that listening to music or the radio may be effective in reducing fatigue for some individuals for a limited amount of time [25,26].

4.3. Visibility-Related Equipment

Snowplow operators in the current study and in Camden et al. [3] indicated that visibility was an important source of fatigue. Nearly 75% of participants in the current study reported that reduced visibility caused fatigue at some point. Reduced visibility may be associated with cognitive overload conditions. Previous research has shown that eye strain and discomfort from reduced visibility and glare increased subjective ratings of fatigue for some individuals [27–29]. For these reasons, Peterson recommended improving the lighting and visibility of winter maintenance vehicles [47].

Several studies identified ways to improve visibility and reduce glare in winter road maintenance vehicles. Bullough and Rae concluded there were three important lighting factors associated with improved visibility in winter road maintenance operations: light location, light beam spread, and light color [36]. Auxiliary lights should be placed outside of the snowplow operator's line of sight (i.e., locate lights on the passenger side of the vehicle) [37–39]. Exterior lights should have narrow-beam spread bulbs (i.e., spot lights) [39–41]. Some research suggested that longer wavelength light (e.g., amber and red) reduced the amount of reflected light from warning lights; however, the effects from light color were limited compared to placement and beam spread [36]. Snowplow operators in the current study reported that warning lights increased fatigue. A possible solution to the brightness of warning lights is to install dimmable warning lights with a dimmer switch inside the cab. This would allow snowplow operators to use a nighttime setting for the forward-facing warning lights at night when other vehicles are not around the snowplow.

Another way to improve visibility is with LED bulbs. Muthumani et al. found that snowplow operators preferred LEDs compared to traditional halogen bulbs for all exterior lighting [39]. These snowplow operators reported that LED lights produced greater visibility similar to daylight.

In addition to lighting, winter weather can restrict a snowplow operator's visibility. Blowing snow or snow/ice buildup on the windshield has the potential to reduce visibility. Thus, it is critical that winter road maintenance vehicles have equipment that prevents snow from spraying up from the plow. Thompson and Nakhla found that snow deflectors with an angle less than 50° eliminated 50% of the accumulating snow on a vehicle's windshield by reducing the amount of snow blown over the plow [53]. This study also found that snow deflectors reduced fatigue.

Windshield wipers are equally important for maintaining visibility during winter road maintenance operations. The current study found that traditional windshield wipers increased fatigue. This is likely because traditional windshield wipers did not adequately remove snow and ice, especially during heavy precipitation. One previous study found that heated windshield wipers may be effective at removing snow and ice buildup; however, snowplow operators offered mixed reviews of this technology [46].

A heated windshield offers another method to eliminate snow and ice buildup on the windshield. Heated windshields use built-in heated strips to melt snow and ice. Traditionally, most vehicles use heated air blown on the interior of the windshield to melt snow and ice. Snowplow operators in the current study reported that traditional defrost systems were ineffective in heavy snow. Additionally, the traditional defrost system heats the cab, which results in increased fatigue. One solution common in winter road maintenance operations is to blow cold air through the defrost system. Although a cold windshield is likely to reduce the amount of snow and ice sticking to the windshield, extended exposure to cold temperatures coupled with fatigue has been found to decrease cognitive functioning [54]. Alternatively, the current study found that a heated windshield reduced fatigue. Although no other studies have previously examined the effectiveness of heated windshield in reducing fatigue, Thomas et al. found that heated windshields were very effective at preventing snow and ice buildup in winter road maintenance operations [55].

4.4. In-Cab Equipment

In-cab equipment may increase or decrease a snowplow operator's workload. Previous research found that high task demands increased subjective ratings of fatigue [56,57]. Similarly, snowplow operators in the current study indicated that lots of equipment controls and hard-to-reach equipment controls increased fatigue. This may suggest that increased task demands (e.g., having more controls to monitor or frequently change position to reach controls) of snowplow operators increases their fatigue.

Snowplow operators also reported that interior LCD monitors increased fatigue. This likely was due to the monitor's brightness and the monitor's glare on the windows. This result supports previous research that found that eye discomfort and strain from glare increased subjective ratings of fatigue [27–29]. To alleviate this fatigue, LCD monitors could be equipped with dimmer switches so brightness levels may be adjusted depending on the lighting conditions.

Several other types of in-cab equipment were found to reduce fatigue, including presence of a collision avoidance system, a lane departure warning system, and a back-up camera. However, the reduction appeared to be rather small. Previous research examining the effectiveness of collision avoidance systems and lane departure warning systems in winter road maintenance operations has been limited. All previous studies were small-scale pilot studies. However, the results of these studies found that snowplow operators believed these types of systems may decrease workload and fatigue [58–61]. Although there was not any previous research investigating the effect of back-up cameras in winter road maintenance vehicles on fatigue, it is possible that the reduced fatigue associated with back-up cameras may be due to decreased workload.

4.5. Limitations

The literature review and questionnaire in this study were extensive; however, several factors provided constraints the reader should consider when interpreting the final recommendations. Although over 2000 winter maintenance operators provided responses to the questionnaire, these winter maintenance operators should not be considered representative of all winter maintenance operators. These winter maintenance operators were a convenience sample. Other winter maintenance operators may have different experiences and opinions regarding fatigue. However, responses on the questionnaire showed a wide variety of opinions regarding fatigue, suggesting a large cross-section of winter maintenance operators.

The questionnaire collected subjective ratings and opinions of fatigue. It is possible objective measures of fatigue (e.g., psychomotor vigilance task, actigraph devices, fatigue-related incidents and crashes, etc.) would result in different recommendations. Despite this limitation, subjective opinions of fatigue are important in understanding the role and magnitude of fatigue in winter maintenance operators.

4.6. Future Recommendations

Future research is needed to collect objective data on the effect of these equipment-factors on snowplow operator fatigue. This could include conducting a naturalistic driving study where snowplow vehicles are equipped with equipment found to reduce operator fatigue. Additional future research should include formal cost–benefit analyses of the equipment solutions to reduce snowplow operator fatigue.

5. Conclusions

Based on the questionnaire responses, snowplow operators reported silence (or a lack of music/talking) as the number one source of fatigue. The other top five sources of winter maintenance operator fatigue due to equipment included bright interior lights, standard windshield wipers, misplaced or insufficient auxiliary lighting, and an old or uncomfortable seat. Other sources of winter maintenance operator fatigue due to equipment were the standard windshield defrost system, limited cabin insulation, traditional snowplows and their blades, nonadjustable warning lights (strobe lights and flashing lights), the placement and type of equipment controls, an old or worn out vehicle suspension system, exterior halogen light bulbs, and traditional tire chains.

Although these equipment factors were found to reduce snowplow operator fatigue, not all of these solutions are feasible and are limited by available technology, costs, anticipated benefits, and agency/state policy. Considering the cost–benefit, the following solutions may be the most promising to mitigate snowplow operator fatigue at a relatively low cost: dimmable interior lighting, LED bulbs for exterior lighting, dimmable warning lights, a CD player or satellite radio in each vehicle, heated windshield, snow deflectors, narrow-beam auxiliary lighting, and more ergonomically designed seats with vibration dampening/air-ride technology.

Author Contributions: M.C.C. and J.S.H. completed the literature review, designed the questionnaire, and wrote the manuscript. S.A.S. completed all analyses and assisted in writing the manuscript. R.J.H. provided invaluable guidance, insight, and support throughout the project.

Funding: This research was funded by Clear Roads, TPF-5(218), project number CR-15.

Conflicts of Interest: The authors declare no conflict of interest. Additionally, the funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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