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Whole-body Vibration Assessment of the M1070 Heavy Equipment Transporter

Volume 1

By

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An evaluation of all new tactical vehicles and aircraft is required to assess potential whole-body vibration (WBV) health hazards to crewmembers. As requested by the U.S. Army Environmental Hygiene Agency (USAEHA), a health hazard assessment (HHA) was performed by the U.S. Army Aeromedical Research Laboratory (USAARL) on the M1070 Heavy Equipment Transporter System (HETS). The HETS was tested on three cross-country courses at Aberdeen Proving Ground (APG), MD, by the U.S. Army Combat Systems Test Activity (USACSTA), in coordination with the Response and Tolerance Branch of USAARL. The M1070 HETS was tested with a M1000 trailer in a loaded and unloaded configuration. The loaded configuration was obtained by placing an M1 tank on the bed of the M1000 trailer. The unloaded configuration consisted of a M1070 tractor with an empty M1000 trailer. While operating the HETS in its intended operational environment, the front passenger was exposed to an overall risk assessment code of 5. This consisted of an overall assignment of hazard severity category IV and hazard probability level D.

Volume 1 describes the tests and discusses the results. Volume 2 contains Appendix B, the data plots and graphs.

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Introduction

It is a requirement of Army Regulation (AR) 40-10, Health hazard assessment program in support of the Army materiel acquisition process, that an evaluation for potential whole-body vibration (WBV) health hazards be conducted on all new tactical vehicles and aircraft to survey the risk to their crewmembers. In support of this program, the U.S. Army Environmental Hygiene Agency (USAEHA) requested the U.S. Army Aeromedical Research Laboratory (USAARL) to perform a health hazard assessment (HHA) on the M1070 heavy equipment transporter system* (HETS) truck.

The HETS, shown in Figure 1, is an all-wheel drive (8x8) commercial vehicle manufactured by the Oshkosh Truck Corporation*. The M1070 HETS was built to fill the need of transporting the M1 Abrams main battle tank (MBT). The HETS is powered by a Detroit Diesel 8V-92TA diesel engine* generating 500 hp and has a 5-speed automatic Allison transmission*. The HETS is capable of attaining a maximum speed of 52 km/h and has a range of 724 km.

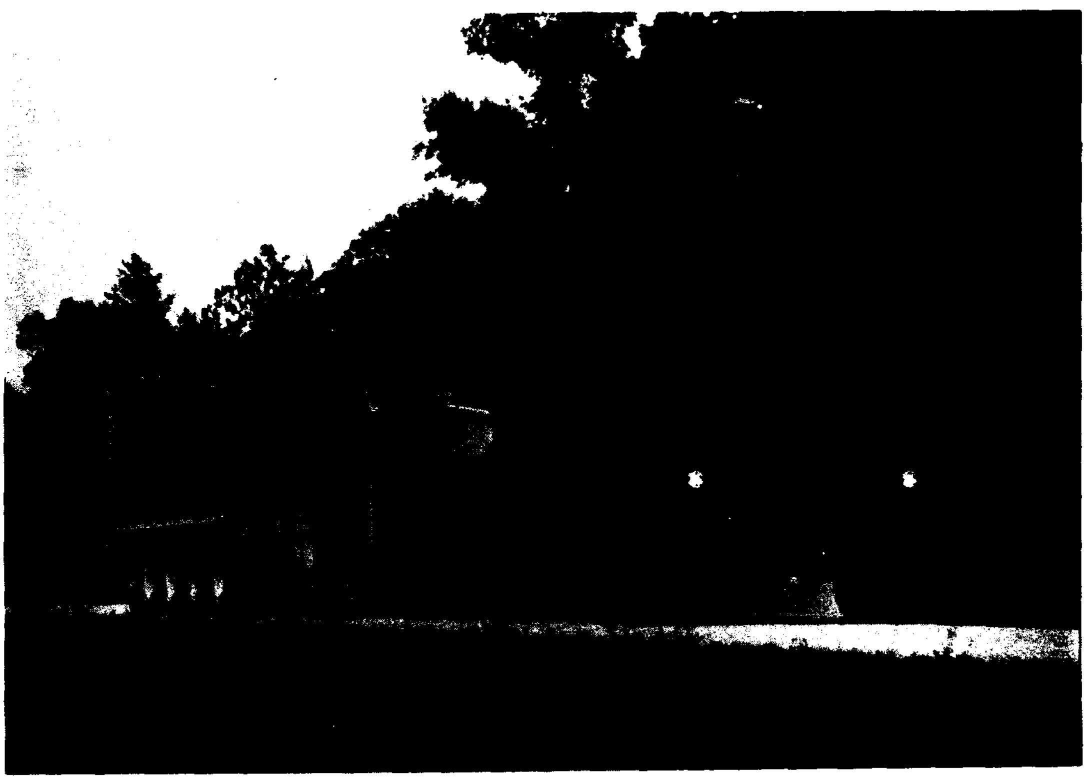

Figure 1. M1070 heavy equipment transporter.

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* See manufacturers' list.

The HETS has a typical configuration consisting of a fully covered cab, a crew capacity of five, and is designed to tow the M1000 semitrailer. The standard M1070 HETS is equipped with two winches, each having a 25-ton load capacity. The nominal load on the fifth wheel of the vehicle is 20,866 kg. The HETS has a curb weight of 18,598 kg and is transportable in the C-5A and C-17 transport aircraft. The physical characteristics of the M1070 HETS, combined with vehicle speed, load, terrain, and crewmember position, result in a unique WBV signature whose measurement and evaluation are the subject of this report.

The methods for measuring and analyzing WBV are found in the International Organization for Standardization's (ISO) guideline entitled "Guide for the evaluation of human exposure to whole-body vibration (ISO 2631)." ISO 2631 is reflected in MIL-STD-1472D, "Human engineering design criteria for military systems, equipment and facilities." The relative severity of the processed WBV signatures are interpreted using the risk assessment codes (RAC) found in AR 40-10. As a set, these publications define the methods and criteria used in evaluating the WBV signatures of the M1070 HETS.

ISO 2631 identifies three criteria for the evaluation of human exposure to WBV which can be described in terms of intensity, frequency, direction, and duration. These criteria are the preservation of comfort, the preservation of working efficiency, and the preservation of health and safety. They are known formally as the reduced comfort boundary (RCB), fatigue-decreased proficiency boundary (FDPB), and health and safety exposure limit (HSEL), respectively.

The RACs, as described in AR 40-10, Appendix B, require the classification of a health hazard according to its severity and probability. Processing vibration signatures using ISO-2631 results in measurements of vibration severity, but does not yield a measure of the probability of occurrence. Therefore, RACs also are used and are obtained by combining vibration severity with the probability that the test condition will occur in a real life scenario. For vibration, RACs would be determined for each vibration amplitude at each direction and frequency.

Methods

The WBV data on the M1070 HETS were collected at Aberdeen Proving Grounds (APG), Maryland. A test matrix was developed that represented the planned operating environment of the M1070 HETS with respect to terrain type and vehicle speed (Table 1).

Table 1.

Test matrix for WBV testing of the M1070 HETS.

	Test courses					
Speed (mph)	Paved road		Cross-country #2		Secondary road	
	Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded
5			X	X		
10			X	X	X	
15			X	X	X	X
20					X	X
25	X	X			X	X
30	X	X				X
35	X	X				
40	X	X				

Experimental conditions

The M1070 HETS was tested over three courses with a M1000 trailer in a loaded and unloaded configuration. Exact characterizations of the three test tracks can be obtained from APG. The loaded configuration was obtained by placing an M1 tank on the bed of the M1000 trailer. The unloaded configuration consisted of a M1070 tractor with an empty M1000 trailer.

The HETS was tested with vehicle speeds ranging from 5 to 40 mph. Specific vehicle speeds were selected in order to mirror likely employment scenarios for each test course. On the cross-country #2 course, the HETS was tested at 5, 10, and 15 mph for both the loaded and unloaded case. Secondary course test speeds were 15, 20, and 30 mph for the loaded case, and 20, 25, and 30 mph for the unloaded case. On the paved course, the HETS was tested at 30, 35, and 40 mph for both the loaded and unloaded configuration.

Instrumentation

Seat pad accelerations were obtained in the X-, Y-, and Z-axes for the driver, front-seated passenger, and the two rear seated passengers located on the road-side seat and the curb-side seat. The rear-seated center passenger location accelerations were not measured. Three Endevco* model 2265C-25 accelerometers, in a triaxial arrangement, were attached to disks placed between the seat pad and the subject's buttocks. Each of the accelerometers were connected to a signal conditioner which provided excitation, amplification, calibration, and low pass filtering. The accelerometers were low pass filtered at 100 Hz using a six-pole Butterworth filter. A diagram of the data acquisition system is included as Figure 2.

Filtered acceleration signals from the signal conditioner were connected to an EMR* model 372-03 pulse code modulation (PCM) encoder. The encoder multiplexed the incoming analog signals which then were sampled at 416.67 Hz per channel. The incoming analog signal was sampled using a sample-and-hold amplifier, digitized using a 10-bit successive approximation analog-to-digital converter, and then converted to a nonreturn-to-zero level (NRZ-L) code for transmission. The encoded PCM data then was input to a Conic* model CTL 510 transmitter for transmission at 237 MHz to the remote data handling facility. The signal conditioner, encoder, and transmitter were mounted on the back of the HETS cab during the entire test.

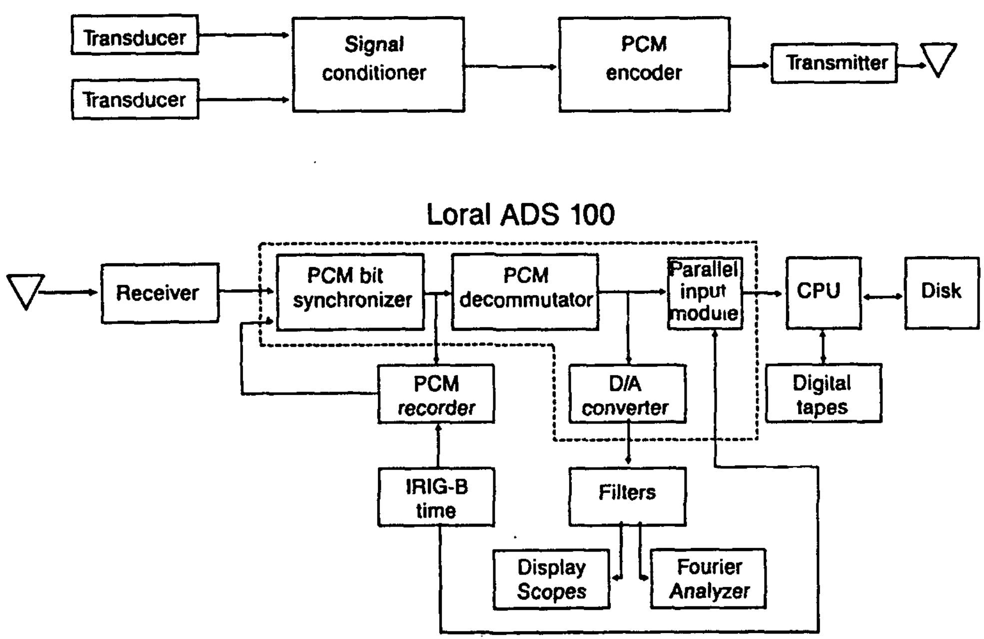

Figure 2. Data acquisition system.

The transmitted NRZ-L code was received by a Scientific Atlanta* series 420S receiver and passed into a Loral Instrumentation* ADS-100 system. The input buffer and PCM bit synchronizer modules recovered the serial pulse train from the data link noise and disturbances. The pulse train was recorded on a Honeywell* model 101 PCM tape recorder along with voice annotation of the individual test runs and an IRIG-B time code. Simultaneously, the PCM pulse train was passed to a PCM decommutator and demultiplexed into 16-bit words.

From this point, the pulse train was sent to both a digital-to-analog (D/A) converter and a parallel input module. The D/A converter passed the pulse train through a filter, external to the ADS-100 system, for real time display and Fourier analysis. The parallel input module was used to input digital IRIG-B time code into the ADS-100. The pulse train passed out of the ADS-100 system from the input module to the host computer, a Hewlett-Packard* (HP) model 21MX-E series minicomputer. The data were stored temporarily on the HP system disk and later transferred to digital tape to provide a permanent storage medium. The ADS-100 system was independent of the host control: however, software residing on the minicomputer controlled the handshaking between the ADS-100 and the HP21MX-E during data acquisition.

Analysis

Triaxial seat pad vibration data were processed using the methods prescribed in ISO 2631 for broadband signals using third-octave analysis with weighting. Digitized acceleration signals from the X-, Y-, and Z-axis from both the driver and passenger seat pad accelerometers were read into a Dolch* model 486 portable computer. A USAARL-developed automated analysis program was used to produce tabular and graphic plots of the acceleration data. These plots (Appendix B) were used to identify vibration exposure limits which occurred under projected normal daily operating conditions.

The exposure data then were classified using the RACs from AR 40-10. The RACs require classification of the health hazard according to the hazard severity and probability. Since the ISO 2631 standard does not use RACs, the severity of the hazard reasonably may be estimated from worst-case exposure before the onset of the HSEL for each vibration frequency and direction. An indicator which may be used for the assessment of hazard severity is the duration of safe exposure (DSE). The DSE is defined as the length of time a person can be exposed to WBV before reaching the HSEL. Thus, a long DSE indicates tolerable WBV, whereas a short DSE indicates severe WBV. In order to translate the DSEs to RACs, Table 2 was used to define the category (I-IV) of exposure.

Table 2.

Hazard severity classification.

Attribute	Category	WBV duration of safe exposure
Catastrophic	I	Less than 5 minutes
Critical	II	Between 5 and 30 minutes
Marginal	III	Between 30 minutes and 4 hours
Negligible	IV	More than 4 hours

Hazard severity categories are defined as:	
Category I	Catastrophic: Hazard may cause death or total loss of a bodily system.
Category II	Critical: Hazard may cause severe bodily injury, severe occupational illness, or major damage to a bodily system.
Category III	Marginal: Hazard may cause minor bodily injury, minor occupational illness, or minor damage to a bodily system.
Category IV	Negligible: Hazard would cause less than minor bodily injury, minor occupational illness, or minor bodily system damage.

The operational environments of the HETS determine the likelihood of occurrence, or probability level, of exposure to WBV. These levels, identified in AR 40-10 as levels A through E, with their corresponding descriptions, are listed in Table 3. The probability levels for each test condition relevant to the WBV signatures in the HETS are listed in Table 4. Table 4 also gives the weighted probability calculated using a coding of 50 - 10 for probability level A - E, respectively. This is divided by the total of the coded probability level for each mission percentage time, and multiplied by the mission percentage. Weighted probabilities A' - E' were found using natural breaks in the sorted weighted probabilities with $A'>7$, $3<B'<7$, $1<C'<3$, and $D'<1$ percent. No weighted probability is given for E' although test engineers at APG suggested this would cover those times the HETS was operated in a bobtail configuration.

Table 3.

Hazard probability classification.

Attribute	Level	Specific individual item	Fleet or inventory
Frequent	A	Likely to occur frequently	Continuously experience
Probable	B	Will occur several times in the life of an item	Will occur frequently
Occasional	C	Likely to occur sometime in the life of an item	Will occur several times
Remote	D	Unlikely but possible to occur in the life of an item	Unlikely but can be reasonably expected to occur
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced	Unlikely to occur, but possible

Table 4.

Hazard probability classification with test operating conditions.

Terrain	Percentage of mission time	Configuration	Speed (mph)	Probability	Probability level	Weighted probability	Weighted probability level
Secondary road	50	Loaded	10	Frequent	A	13.158	A'
			15	Frequent	A	13.158	A'
			20	Frequent	A	13.158	A'
			25	Probable	B	10.526	A'
	5	Unloaded	15	Frequent	A	1.316	C'
			20	Frequent	A	1.316	C'
			25	Frequent	A	1.316	C'
			30	Probable	B	1.053	C'
Paved road	28	Loaded	25	Frequent	A	7.368	A'
			30	Frequent	A	7.368	A'
			35	Frequent	A	7.368	A'
			40	Probable	B	5.895	B'
	2	Unloaded	25	Probable	B	0.444	D'
			30	Probable	B	0.444	D'
			35	Frequent	A	0.556	D'
			40	Frequent	A	0.556	D'
Cross-country	14	Loaded	5	Probable	B	4.000	B'
			10	Frequent	A	5.000	B'
			15	Frequent	A	5.000	B'
	1	Unloaded	5	Probable	B	0.308	D'
			10	Probable	B	0.308	D'
			15	Frequent	A	0.385	D'

Hazard severity categories and hazard probability levels are used to find the RACs for each test condition. Using Table 5, the RACs are found at the intersection of the Hazard Category and Probability Level, here using the primed levels. The overall RAC for the vehicle is determined by averaging and rounding the individual RACs.

Table 5.

RAC determination.

	Hazard probability levels				
Hazard category	A	B	C	D	E
I	1	1	1	2	3
II	1	1	2	3	4
III	2	3	3	4	5
IV	3	5	5	5	5

Results

The duration of exposure to reach the HSEL was calculated for all 216 data sets. The minimum durations for HSELs were found for each position, terrain, speed, and load for each of the four seating positions--driver, front passenger, roadside passenger (RS), and curb-side passenger (CS)--and are shown in Tables 6, 7, 8, and 9, respectively. These tables are arranged in order of increasing levels of DSE. Since the HETS requires 10 hours of total mission time in any 24-hour period, the exposure limits of less than 10 hours were flagged for assessment. The DSE is determined from the time required to reach the HSEL (Appendix B) according to ISO-2631. The RACs shown are a measure of the hazard severity of the test condition and are based on the DSE, course terrain, and speed.

The worst case exposure limits were determined from each seating position's lowest DSE. The DSEs below 10 hours were found only for the front passenger seating position under unloaded conditions. Two cases were flagged for assessment: a DSE of 8 hours 4 minutes at a vehicle speed of 15 mph on cross-country terrain (Appendix B, run number 14), and a DSE of 8 hours 52 minutes at a vehicle speed of 30 mph on paved roads (Appendix

B, run number 20). Both DSEs occurred in the Z axis at frequencies of 2.0 and 3.9 Hz, respectively. The hazard severity assigned to these two conditions were found to be Category IV from the DSE ranges of Table 2. Weighted hazard probabilities for these two conditions were combined with hazard categories using Table 5 to yield RACs of 5. With only two test conditions yielding RACs of 5, this vehicle is assigned an overall RAC of 5.

Table 6.

Driver seat HSEL for minimal exposure times with respect to axis, vibration frequency, vehicle speed, and test course.

Determination of hazard severity					Determination of probability level					Overall RAC
DSE (h:m)	Axis	Hz	Hazard severity	Hazard category	Test course	Configuration	Speed (mph)	Hazard probability	Probability level	
8:52	Z	3.9	Negligible	IV	Paved	Unloaded	30	Remote	D'	5
10:22	Z	1.6	Negligible	IV	CC #2	Unloaded	15	Remote	D'	5
13:18	Z	2.5	Negligible	IV	CC #2	Unloaded	20	Remote	D'	5
14:00	Z	2.0	Negligible	IV	Secondary	Loaded	20	Frequent	A'	3
15:18	Z	2.0	Negligible	IV	Secondary	Loaded	15	Frequent	A'	3
16:45	Z	2.5	Negligible	IV	Paved	Loaded	25	Frequent	A'	3

Table 7.

Front passenger seat HSEL for minimal exposure times with respect to axis, vibration frequency, vehicle speed, and test course.

Determination of hazard severity					Determination of probability level					Over-all RAC
DSE (h:m)	Axis	Hz	Hazard severity	Hazard category	Test course	Configuration	Speed (mph)	Hazard probability	Probability level	
8:04	Z	2.0	Negligible	IV	CC #2	Unloaded	15	Remote	D'	5
11:02	Z	3.9	Negligible	IV	Secondary	Unloaded	30	Remote	C'	5
12:08	Z	2.5	Negligible	IV	Paved	Loaded	25	Frequent	A'	3
14:33	Z	5.0	Negligible	IV	Paved	Unloaded	40	Probable	B'	5
15:52	Z	2.5	Negligible	IV	Secondary	Loaded	20	Frequent	A'	3
16:25	Z	2.0	Negligible	IV	CC #2	Loaded	15	Occasional	B'	5

Table 8.

Roadside passenger seat HSEL for minimal exposure times with respect to axis, vibration frequency, vehicle speed, and test course.

Determination of hazard severity					Determination of probability level					Over-all RAC
DSE (h:m)	Axis	Hz	Hazard severity	Hazard category	Test course	Configuration	Speed (mph)	Hazard probability	Probability level	
12:30	Z	1.6	Negligible	IV	CC #2	Unloaded	15	Remote	D'	5
15:41	Z	3.9	Negligible	IV	Paved	Unloaded	30	Remote	D'	5
16:37	Z	5.0	Negligible	IV	CC #2	Unloaded	20	Remote	D'	5
16:37	Z	5.0	Negligible	IV	Paved	Loaded	40	Frequent	A'	3
17:13	Z	2.5	Negligible	IV	Secondary	Loaded	20	Frequent	A'	3
19:45	Z	2.0	Negligible	IV	CC #2	Loaded	15	Occasional	B'	5

Table 9.

Curb side passenger seat HSEL for minimal exposure times with respect to axis, vibration frequency, vehicle speed, and test course.

Determination of hazard severity					Determination of probability level					Over-all RAC
DSE (h:m)	Axis	Hz	Hazard severity	Hazard cate-gory	Test course	Configu-ration	Speed (mph)	Hazard proba-bility	Prob-ability level	
10:12	Z	2.0	Negligible	IV	CC #2	Unloaded	15	Remote	D'	5
13:23	Z	3.9	Negligible	IV	Secondary	Unloaded	30	Occasional	C'	5
14:07	Z	5.0	Negligible	IV	Paved	Unloaded	40	Remote	D'	5
15:41	Z	3.9	Negligible	IV	Paved	Loaded	35	Frequent	A'	3
16:45	Z	2.5	Negligible	IV	Secondary	Loaded	20	Frequent	A'	3
20:17	Z	2.0	Negligible	IV	CC #2	Loaded	15	Probable	B'	5

Discussion

Whole-body vibration exposures for the M1070 HETS that were less than the required 10-hour operational period were found for only two conditions. Both these conditions were in the unloaded configuration and occurred on cross-country and paved terrain. These scenarios were projected to have a low probability of occurrence which resulted in a weighted probability level of D, or remote, for both instances. The hazard category was identified as IV with both DSEs being greater than 4 hours. The hazard probability of D, combined with the hazard category of IV, resulted in an overall RAC of 5 implying a low risk level with a decision making authority residing with the program manager (AR 40-10).

The two hazardous WBV exposure conditions that were found occurred at the front seat positions only. The driver position received a DSE of less than 10 hours on the paved terrain, and the front seat passenger received a DSE of less than 10 hours for cross-country terrain. No hazardous WBV exposures were found for the rear seated passengers under loaded conditions--a configuration likely to occur when the M1 tank crew would be riding in the HETS passenger compartment.

The frequency of the hazardous WBV exposures were found to be 1.0 Hz and 3.9 Hz for the driver and front seat passenger, respectively. This trend for a large vibration amplitude at low frequencies was seen in most of the HETS vibration signatures. This low-level frequency response is unusual for heavy equipment with most off-road vehicles showing resonant WBV peaks in the 4-8 Hz range. A potential explanation for this low frequency content is that the seating/suspension system could be very soft resulting in a very low resonant frequency.

The WBV experienced by the vehicle crewmen differed for seating position. The front seat positions typically showed data with lower HSELs as compared to the rear seat passenger positions for most of the data trials. A review of the plotted data of Appendix B shows that the rear seated passengers typically had lower amplitude low frequency components and higher amplitude high frequency components. This implies that the rear seating systems are stiffer than the front seat positions showing less gain in the low frequency bands and more transmission in the higher frequency bands.

Conclusions

While operating the HETS in its intended operational environment, the front passenger was exposed to an overall RAC of 5. This consisted of an overall assignment of hazard severity category IV and hazard probability level D. It is recommended that exposure to WBV be restricted to:

a. Paved surface at vehicle:

(1) Unloaded trailer configuration: not more than 9 hours continuous operation in any 24-hour period speeds less than 30 mph.

(2) Loaded trailer configuration: not more than 12 hours continuous operation in any 24-hour period speeds less than 25 mph.

b. Cross-country terrain:

(1) Unloaded trailer configuration: not more than 8 hours continuous operation in any 24-hour period at vehicle speeds less than 15 mph.

(2) Loaded trailer configuration: not more than 15 hours continuous operation in any 24-hour period at vehicle speeds less than 15 mph.

c. Secondary terrain:

(1) Unloaded trailer configuration: not more than 11 hours continuous operation in any 24-hour period at vehicle speeds less than 30 mph.

(2) Loaded trailer configuration: not more than 14 hours continuous operation in any 24-hour period at vehicle speeds less than 20 mph.

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Appendix A.

Manufacturers' list.

Conic/Loral Data Systems
9020 Balboa Avenue
San Diego, CA 92123

EMR/Fairchild Weston Systems
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Sarasota, FL 33578

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