A-P-T RESEARCH, INC.
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HAZARDOUS MATERIAL TRANSPORT WITH UNMANNED SYSTEMS

PHASE 1 - EXPLORATION

ET-4: Exploration of the Issues, Development, and Potential Hazards Associated with the Transport of Hazardous Materials by Unmanned and Autonomous Vehicles in Various Modes

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Prepared for:
Pipeline and Hazardous Materials Safety Administration
Office of Hazardous Materials Safety
U.S. Dept. of Transportation
1200 New Jersey Ave., Washington, D. C. 20590

Contract Details:
Contract #: 693JK318C000009, Project #: PH957-18-0024
ET-4: Exploration of the Issues, Development, and Potential Hazards Associated with the Transport of Hazardous Materials by Unmanned and Autonomous Vehicles in Various Modes

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CONTENTS

ACRONYMS

A-P-T	A-P-T Research, Inc.
AAWA	Advanced Autonomous Waterborne Applications
AUVSI	Association for Unmanned Vehicle Systems International
CFR	U.S. Code of Federal Regulations
CFS	Commodity Flow Survey
DOT	U.S. Department of Transportation
FAA	Federal Aviation Administration
FRA	Federal Railroad Administration
HM	Hazardous Materials
IBC	Intermediate Bulk Container
IMO	International Maritime Organization
mpa	MegaPascal
OHMS	Office of Hazardous Materials Safety
PHMSA	Pipeline and Hazardous Materials Safety Administration
SAE	Society of Automotive Engineers
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UITP	Union International des Transports Public (International Union of Public Transport)
UN/NA	United Nations/North American Hazardous Materials Code
UPS	United Parcel Service
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
UxS	Unmanned System

1.0 Introduction

The rapid evolution of the unmanned and autonomous systems industry has outpaced many federal regulatory agencies' ability to develop operations, maintenance, and safety regulatory frameworks in a timely manner. Realizing this shortfall, the Pipeline and Hazardous Materials Safety Administration (PHMSA) Office of Hazardous Materials Safety (OHMS) authorized this research to prepare for the inevitability of Hazardous Materials (HM) shipments with an Unmanned System (UxS). This multi-phased research and development effort will identify risks and potential regulatory requirements associated with removing the human in the loop for HM shipments, while maximizing UxS technologies to improve safe delivery of goods.

Hazardous materials are currently shipped via roads, air, rail, and sea. It is inevitable that all four modes of transportation will see the integration of both autonomous and remotely piloted vehicles. As UxS technologies improve, it is envisioned that removing the human driver or pilot from the controls of a transport vehicle will eventually decrease the number of major incidents. However, the use of UxSs to transport HM introduces new hazards that, if not evaluated and mitigated properly, will likely increase the number of major incidents, especially in the near term.

It is important to ensure that these emerging technologies are introduced safely and ultimately deliver on the promise of lower risk through risk management, sufficient package integrity, and minimizing or preventing fatalities and injuries. Identifying common UxS shipping hazards and pinpointing hazards unique to a particular UxS transport mode allows for targeted analyses, risk assessments, or risk management plans. This will ultimately lead to optimal responsive regulatory changes specific to UxSs.

This research effort will provide PHMSA with a robust roadmap for the safe introduction of UxS transport of HM. The roadmap will be developed through a phased technical approach that will systematically address the three main contributors to risk; probability of a hazardous event, consequence of the event, and hazard mitigation techniques (Figure 1). Exploring the likelihood of a UxS incident, characterizing the consequence of that incident, and standardizing hazard mitigation methods for specific UxS modes of transport will position the agency to safely and seamlessly integrate UxS transport of HM into our national infrastructure.

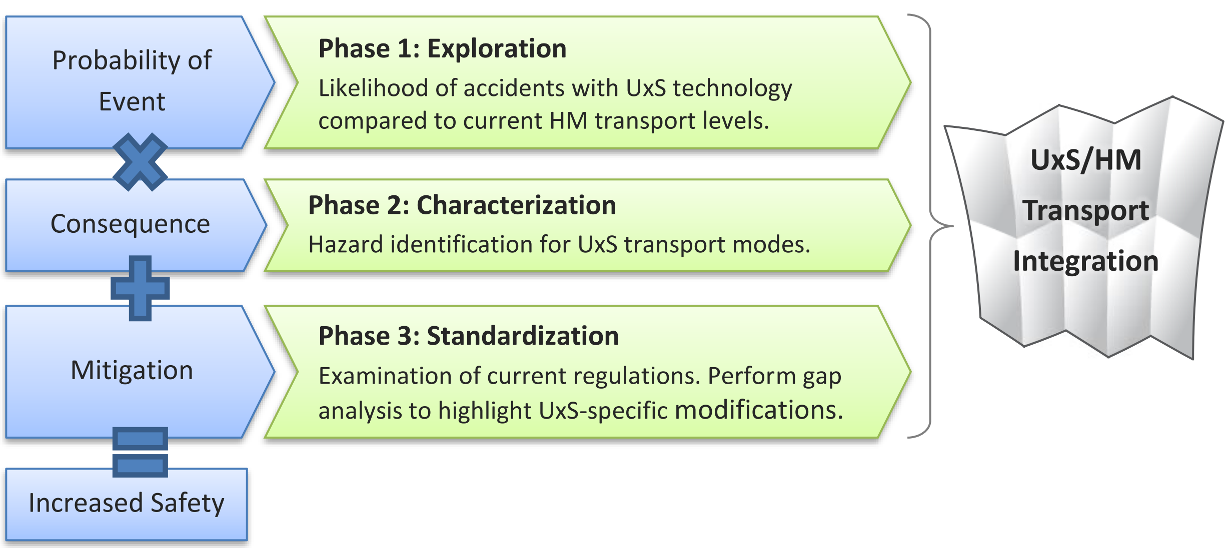

Figure 1: The final roadmap will outline the best approach to increase UxS/HM safety

This report will be the first in a series of three reports documenting the three phases outlined in Figure 1. A final report will combine all findings and present a final roadmap that PHMSA/OHMS can follow to implement HM transport using UxS technology.

2.0 Exploration Phase Description

According to transportation industry publications, 90 percent of trucking accidents are the result of driver error and 60-80 percent of commercial aircraft accidents are the result of pilot error. Assuming UxSs reach their targeted success rates, there is the potential for a significant reduction in injuries or fatalities simply by replacing human operators. The exploration phase of this research and development effort examines the relative likelihood of UxS accidents with particular emphasis placed on specific scenarios, UxS/HM shipment pairings, and situations where there is a clear potential for risk mitigation using existing UxS technology.

Theoretically, it may be possible to transport any HM with any UxS. Moreover, autonomous transport may eventually present lower risk to the public because there is less human in-the-loop interaction, especially if lower exposure routes and schedules are developed. In practice, however, the use of a particular UxS will depend largely on its cargo capacity. To simplify the solution set, this initial exploration phase examines the current methods and quantities of HM shipments and maps those shipments to the most likely mode(s) of UxS transportation currently available. In parallel, the current state of HM shipping is examined to include incident rates, fatality/injury numbers, and frequent hazards associated with all modes of transport. This information will be used as a baseline to compare future risk estimates for HM shipments with UxSs.

This report will document all findings from the exploration phase. Specifically, this report will:

1. Quantify current HM shipping data to include quantities, frequency, and method of HM shipments;
2. List current and developmental UxSs, including aerial vehicles (winged, rotor, lighter than air), ground vehicles (trucks, cars), rail vehicles, and waterborne vehicles (ships, submersibles);
3. Identify the most likely HM payloads for each of the UxSs identified and, conversely, the most likely UxSs for each HM payload; and
4. Baseline current HM shipment incident rates, fatality/injury numbers, and frequent hazards associated with all modes of HM transport with human operators.

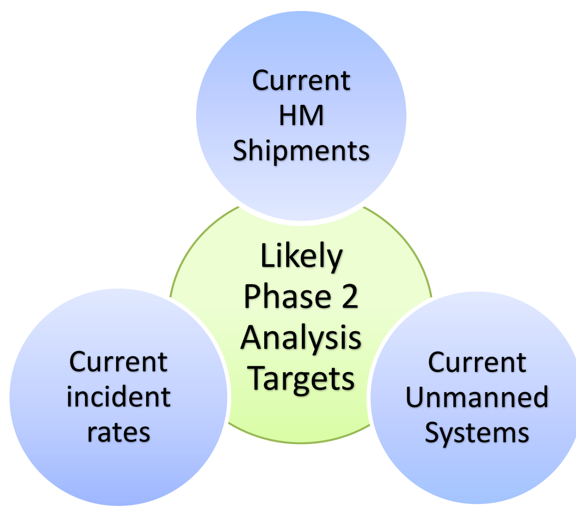

Figure 2: Compiled Phase 1 Results

The results of this exploration phase report will scope the problem of UxS/HM transport and present a clear picture of what UxS transport mode is more mature than another. It will show what types of HM shipments may be paired with a particular UxS. Most importantly, the research will highlight current HM transport modes that present higher incident rates than others.

The results of this analysis will yield a list of UxSs capable of transporting common HMs with an eye toward mitigating the most commonly reported incidents. This targeted list will carry over into Phase 2, the characterization phase, where specific hazards will be identified for each UxS/HM pair.

3.0 Hazardous Material Shipping Statistics

The most comprehensive dataset of hazardous material shipping statistics is the 2012 Commodity Flow Survey (CFS) [1], which is produced through a joint effort by the Bureau of Transportation Statistics and the U.S. Census Bureau, U.S. Department of Commerce. The Survey is conducted every five years as part of the economic census and provides data on the type, origin, destination, value, weight, modes of transportation, and distance shipped of domestic freight shipments. Of particular importance to this research effort is the identification of hazardous material commodities shipped as a function of transport mode.

The 2012 CFS data were first filtered to identify only HM shipments. The 13 different transport modes used in the CFS were aggregated into the four representative modes; highway, waterborne, rail, and air transport. These became the basis for examination as part of this research. Highway transport includes trucks, for-hire trucks, parcel/USPS/courier, private trucks, truck and rail, and truck and water. Waterborne transport includes water, deep sea, inland water, and multiple waterways. Rail transport includes rail, and rail and water. Finally, air transport includes air, and truck and air. Pipeline transport is outside the scope of this task. Lastly, shipping weights for each hazardous commodity from the CFS were aggregated and sorted by tonnage shipped.

The following tables provide a comprehensive list of HM shipped for each representative mode of transport. Only the commodities in the top 98% of shipments (as a function of tonnage shipped) are listed in each table. Standard U.S. hazard classifications as well as the United Nations/North American (UN/NA) shipping numbers are listed for each hazardous material [2][3][4].

Table 1. Most prevalent HM moved by highway

UN/NA Code	Hazard Class	Description of Hazardous Materials	Tons Transported (thousands)	Quantity per Shipment
1203	3	Gasoline includes gasoline mixed with ethyl alcohol, with not more than 10% alcohol	1,471,084	66.43%
1993	3	Flammable liquids, including anti-freeze, liquid, combustible liquid, compounds, cleaning liquid, tree killing, diesel fuel, fuel oil (no. 1, 2, 4, 5, or 6), or plastic solvent.	377,781	17.06%
1202	3	Diesel fuel, including gas oil or heating oil, light	80,402	3.63%
3257	9	Elevated temperature liquid, at or above 100 ˚c and below its flash point (including molten metals, molten salts)	32,195	1.45%
1075	2.1	Petroleum gases, liquefied or liquefied petroleum gas	30,075	1.36%
1830	8	Sulfuric acid with more than 51 percent acid, including hydrogen sulfate, or matting acid	14,072	0.64%
1824	8	Sodium hydroxide solution, including lye	13,566	0.61%
1863	3	Fuel, aviation, turbine engine, including jet fuel	13,128	0.59%
1066	2.2	Nitrogen, compressed	12,854	0.58%

UN/NA Code	Hazard Class	Description of Hazardous Materials	Tons Transported (thousands)	Quantity per Shipment
1999	3	Tars, liquid including road oils and cutback bitumens, including road asphalt	12,426	0.56%
1791	8	Hypochlorite solutions, including potassium hypochlorite, solution or sodium hypochlorite, solution	11,369	0.51%
1013	2.2	Carbon dioxide, including mine rescue equipment containing carbon dioxide	11,085	0.50%
1072	2.2	Oxygen, compressed	9,665	0.44%
1005	2.3	Ammonia, anhydrous	9,284	0.42%
1987	3	Alcohols, including denatured alcohol	9,091	0.41%
1170	3	Ethanol or ethyl alcohol or ethanol solutions or ethyl alcohol solutions	7,113	0.32%
1006	2.2	Argon, compressed	6,703	0.30%
1978	2.1	Propane, see also petroleum gases, liquefied	6,417	0.29%
2672	8	Ammonia solutions, relative density between 0.880 and 0.957 at 15 ˚c in water, with more than 10 percent but not more than 35 percent ammonia, including aqua ammonia	4,503	0.20%
2794	8	Batteries, wet, filled with acid, electric storage	4,350	0.20%
2448	4.1	Sulfur, molten	3,783	0.17%
1910	8	Calcium oxide, including lime, unslaked or quicklime	3,777	0.17%
3082	9	Environmentally hazardous substance, liquid, including hazardous waste, liquid, marine pollutants, liquid or solid, or other regulated substances, liquid	3,725	0.17%
3475	0	Ethanol and gasoline mixture or ethanol and motor spirit mixture or ethanol and petrol mixture, with more than 10% ethanol	3,512	0.16%
1263	3	Paint including paint, lacquer, enamel, stain, shellac solutions, varnish, polish, liquid filler, liquid lacquer base, and paint related material including paint thinning, drying, removing or reducing compound	3,274	0.15%
1956	2.2	Compressed gas or nonliquefied gases	3,169	0.14%
1017	2.3	Chlorine	2,829	0.13%
1268	3	Petroleum distillates or petroleum products	2,757	0.12%
1789	8	Hydrochloric acid, including muriatic acid, spirits of salt	2,721	0.12%
331	1.5D	Explosive, blasting, type b or agent blasting, type b, including ammonium nitrate-fuel oil mixture containing only prilled ammonium nitrate and fuel oil	2,562	0.12%

Table 2. Most prevalent HM moved by water

UN/NA Code	Hazard Class	Description of Hazardous Materials	Tons Transported (thousands)	Percentage of Total
1203	3	Gasoline includes gasoline mixed with ethyl alcohol, with not more than 10% alcohol	195,397	43.47%
1993	3	Flammable liquids, including anti-freeze, liquid, combustible liquid, compounds, cleaning liquid, tree killing, diesel fuel	78,913	17.56%
1863	3	Fuel, aviation, turbine engine, including jet fuel	25,687	5.71%
1824	8	Sodium hydroxide solution, including lye	18,708	4.16%
2398	3	Methyl tert-butyl ether	17,648	3.93%
1268	3	Petroleum distillates or petroleum products	16,568	3.69%
1267	3	Petroleum crude oil	11,936	2.66%
1270	3	Petroleum oil	11,264	2.51%
1011	2	Butane see also petroleum gases, liquefied	8,684	1.93%
1918	3	Isopropylbenzene	8,669	1.93%
1964	2	Hydrocarbon gas mixture, compressed, including nonliquefied hydrocarbon gas	8,207	1.83%
1005	2	Ammonia, anhydrous	7,070	1.57%
1202	3	Diesel fuel, including gas oil or heating oil, light	6,363	1.42%
2055	3	Styrene monomer, stabilized	5,800	1.29%
1223	3	Kerosene	5,030	1.12%
3257	9	Elevated temperature liquid, at or above 100 ˚c and below its flash point (including molten metals, molten salts)	4,966	1.10%
1972	2	Methane, refrigerated liquid (cryogenic liquid) or natural gas, refrigerated liquid (cryogenic liquid)	4,923	1.10%
1547	6	Aniline	4,018	0.89%

Table 3. Most prevalent HM moved by rail

UN/NA Code	Hazard Class	Description of Hazardous Materials	Tons Transported (thousands)	Percentage of Total
1170	3	Ethanol or ethyl alcohol or ethanol solutions or ethyl alcohol solutions	20,178	10.54%
1987	3	Alcohols, including denatured alcohol	19,068	9.96%
1824	8	Sodium hydroxide solution, including lye	15,454	8.07%
1830	8	Sulfuric acid with more than 51 percent acid, including hydrogen sulfate, or matting acid	15,376	8.03%

UN/NA Code	Hazard Class	Description of Hazardous Materials	Tons Transported (thousands)	Percentage of Total
1993	3	Flammable liquids, including anti-freeze, liquid, combustible liquid, compounds, cleaning liquid, tree killing, diesel fuel, fuel oil (no. 1, 2, 4, 5, or 6), or plastic solvent	12,580	6.57%
1805	8	Phosphoric acid solution	11,191	5.85%
3082	9	Environmentally hazardous substance, liquid, including hazardous waste, liquid, marine pollutants, liquid or solid, or other regulated substances, liquid	7,394	3.86%
3257	9	Elevated temperature liquid, at or above 100 ˚c and below its flash point (including molten metals, molten salts, etc.)	6,771	3.54%
1863	3	Fuel, aviation, turbine engine, including jet fuel	6,338	3.31%
2448	4	Sulfur, molten	5,743	3.00%
1789	8	Hydrochloric acid, including muriatic acid, spirits of salt, or white acid	4,708	2.46%
1075	2	Petroleum gases, liquefied or liquefied petroleum gas	4,546	2.37%
1017	2	Chlorine	4,434	2.32%
1005	2	Ammonia, anhydrous	3,962	2.07%
1040	2	Ethylene oxide or ethylene oxide with nitrogen up to a total pressure of 1 mpa (10 bar) at 50 ˚c	3,960	2.07%
1013	2	Carbon dioxide, including mine rescue equipment containing carbon dioxide	3,562	1.86%
1942	5	Ammonium nitrate, with not more than 0.2% total combustible material, including any organic substance, calculated as carbon to the exclusion of any other added substance	3,452	1.80%
1307	3	Xylenes	3,447	1.80%
1010	2	Butadienes, stabilized or butadienes and hydrocarbon mixture, stabilized containing more than 40% butadienes	3,074	1.61%
1268	3	Petroleum distillates or petroleum products	2,337	1.22%
1814	8	Potassium hydroxide, solution or potassium hydroxide, liquid	2,254	1.18%
3077	9	Environmentally hazardous substance, solid, including hazardous waste, solid or other regulated substances, solid	2,246	1.17%
1689	6	Sodium cyanide, solid	2,242	1.17%
3475	0	Ethanol and gasoline mixture or ethanol and motor spirit mixture or ethanol and petrol mixture, with more than 10% ethanol	2,032	1.06%
1964	2	Hydrocarbon gas mixture, compressed, including nonliquefied hydrocarbon gas	2,021	1.06%
2312	6	Phenol, molten	1,768	0.92%
1978	2	Propane see also petroleum gases, liquefied	1,520	0.79%
1086	2	Vinyl chloride, stabilized, including monochloroethylene	1,386	0.72%
2426	5	Ammonium nitrate, liquid (hot concentrated solution)	1,138	0.59%

UN/NA Code	Hazard Class	Description of Hazardous Materials	Tons Transported (thousands)	Percentage of Total
2209	8	Formaldehyde, solutions, with not less than 25 percent formaldehyde	1,074	0.56%
2280	8	Hexamethylenediamine, solid	894	0.47%
3256	3	Elevated temperature liquid, flammable, with flash point above 37.8 ˚c, at or above its flash point	884	0.46%
1011	2	Butane see also petroleum gases, liquefied	866	0.45%
1247	3	Methyl methacrylate monomer, stabilized	775	0.40%
2067	5	Ammonium nitrate-based fertilizer (hazard class 5.1)	744	0.39%
1280	3	Propylene oxide	732	0.38%
2015	5	Hydrogen peroxide, stabilized or hydrogen peroxide aqueous solutions, stabilized with more than 60 percent hydrogen peroxide	721	0.38%
1270	3	Petroleum oil	720	0.38%
1381	4	Phosphorus, white dry or phosphorus, white, under water or phosphorus white, in solution or phosphorus, yellow dry or phosphorus, yellow, under water or phosphorus, yellow	624	0.33%
1018	2	Chlorodifluoromethane or refrigerant gas r22	600	0.31%
1999	3	Tars, liquid including road oils and cutback bitumens	537	0.28%
1100	3	Allyl chloride	536	0.28%
1910	8	Calcium oxide, including lime, unslaked or quicklime	510	0.27%
1831	8	Sulfuric acid, fuming with 30 percent or more free sulfur trioxide, including nordhausen acid, or oleum	493	0.26%
3267	8	Corrosive liquid, basic, organic	484	0.25%
1303	3	Vinylidene chloride, stabilized	482	0.25%
2031	8	Nitric acid other than red fuming, with more than 20 percent nitric acid	364	0.19%
2810	6	Toxic, liquids, organic, including compounds, tree killing, liquid or compounds, weed killing, liquid	360	0.19%
1077	2	Propylene see also petroleum gases, liquefied	356	0.19%
1114	3	Benzene, or benzol	298	0.16%
1357	4	Urea nitrate, wetted with not less than 20 percent water	294	0.15%

Table 4. Most prevalent hazardous materials moved by air

UN/NA Code	Hazard Class	Description of Hazardous Materials	Tons Transported (thousands)	Percentage of Total
3082	9	Environmentally hazardous substance, liquid, including hazardous waste, liquid, marine pollutants, liquid or solid, or other regulated substances, liquid	11	28.21%
1263	3	Paint including paint, lacquer, enamel, stain, shellac solutions, varnish, polish, liquid filler, liquid lacquer base, and paint related material including paint thinning, drying	6	15.38%

UN/NA Code	Hazard Class	Description of Hazardous Materials	Tons Transported (thousands)	Percentage of Total
12	1.4S	Cartridges for weapons, inert projectile or cartridges, small arms	4	10.26%
3268	9	Air bag inflators, or air bag modules, or seat-belt pretensioners.	4	10.26%
1046	2	Helium, compressed	3	7.69%
1266	3	Perfumery products with flammable solvents	3	7.69%
3090	9	Lithium battery	3	7.69%
1197	3	Extracts, flavoring, liquid	2	5.13%
1993	3	Flammable liquids, including anti-freeze, liquid, combustible liquid, compounds, cleaning liquid, tree killing, diesel fuel, fuel oil (no. 1, 2, 4, 5, or 6), or plastic solvent	2	5.13%
331	1.5D	Explosive, blasting, type b or agent blasting, type b, including ammonium nitrate-fuel oil mixture containing only prilled ammonium nitrate and fuel oil	1	28.21%

3.1 MAXIMUM SHIPMENT WEIGHTS FOR ROADWAY

Ninety-eight percent of all HM shipped (as a function of tonnage shipped) in the U.S. consists of just 74 commodities. These commodities run the gamut from pressurized gasses to dry powders and molten products. Each commodity must be handled, containerized, and shipped according to specific regulations outlined in the U.S. Code of Federal Regulations (49 CFR), Subpart B - Table of Hazardous Materials and Special Provisions (§§172.101 – 172.102) [5].

To estimate typical shipment weights, allowable packaging criteria was assigned to each commodity based on the Hazardous Materials Tables found in 49 CFR, Subpart B, §§172.101-172-102. For gasses, a wide range of cylinder design criteria was specified. For liquid commodities, containers ranged from small steel jerricans to large tank trailers. The sheer number of different sizes, shapes, and packaging material of containers approved for shipping the 74 selected commodities complicated the process of matching HM shipments with a suitable UxS. Nevertheless, a large number of containers were identified and mapped to each commodity. The volume and empty weight of each container was recorded. Densities for each of the 74 commodities were estimated and used to compute the final (filled) weight of each container. This provided estimated weight ranges for each package size for each specific commodity.

Table 5 shows a short list of standard container sizes approved for transporting gasoline (UN/NA Code 1203). It is important to note that not all approved DOT container classes could be mapped to a commercially available container. Some container class requirements have been superseded by updated requirements and manufacturers no longer offer containers built to older specifications. Cargo tanks and portable tanks will most likely continue to be pulled by a standard semi-truck (on highways) or train engine so the total weights of those approved containers is not critical to this effort.

Table 5. Approved containers and approximate container weights for gasoline

Approved DOT Container Class for Gasoline	Tare Weight (lbs)	Average Volume (ft3)	Commodity Weight (lbs)	Total Weight (lbs)	Comments
IBC - 31A/B/N	284.0	24.1	1179.1	1463.1	
	400.0	40.1	1965.1	2365.1	
	640.0	73.5	3602.7	4242.7	
IBC - 31H	127.0	36.8	1801.4	1928.4	
IBC - 31HZ †	-	-	-	-	
Steel Drum - 1A	30.0	7.4	360.3	390.3	55 Gallon Drum
	30.0	4.0	196.6	226.6	
	26.0	2.7	131.0	157.0	
	17.0	2.1	104.9	121.9	
	14.0	1.9	91.7	105.7	
	10.0	0.7	32.7	42.7	5 Gallon Pail
	0.9	0.1	6.6	7.5	Paint Can
Aluminum Drum - 1B †	-	-	-	-	
Other Metal - 1N †	-	-	-	-	
Plastic Drum - 1H	21.5	7.4	360.3	381.8	
Steel Jerrican - 3A	0.9	0.1	6.5	7.4	1 Gallon
	9.5	0.7	34.6	44.0	5.28 Gallons
Plastic Jerrican - 3H	1.6	0.3	16.4	18.0	2.5 Gallons
	2.6	0.7	32.7	35.3	5 Gallons
Aluminum Jerrican - 3B †	-	-	-	-	
Plastic Liner in Drum - 6H †	-	-	-	-	
Glass, Porcelain, Stoneware Liner in Drum - 6P †	-	-	-	-	
Cargo Tanks - MC 300-307, MC 310-312, MC 330-331 ‡	-	-	-	-	
Cargo Tanks - 406, 407, 412 ‡	-	-	-	-	
Portable Tanks - 51, 56, 57, 60 ‡	-	-	-	-	

† No commercial product was readily found with this specification.

‡ Cargo and portable tanks are pulled by standard semi-trucks or train engines regardless of commodity weight.

From Table 5 it is shown that approved containers of gasoline can range in weight from 7.4 lbs for a 1-gallon steel jerrican to 4,242.7 lbs for an Intermediate Bulk Container (IBC). It is likely that any UxS, with the exception of small unmanned aerial vehicles, will be able to transport gasoline based on the wide range of container sizes available. It is important to note that a sample set of containers were identified for this research in order to return a significant range of container sizes. There are hundreds of container shapes and sizes available to ship each commodity.

Table 6 lists each of the top 30 commodities shipped by highway and the minimum and maximum container weights (up to but not including cargo tanks).

This process was repeated for each of the remaining commodities specifically for highway transport. The other three modes of transport had clearly defined maximum shipping quantities; therefore, the process of quantifying maximum/minimum shipment weights was unnecessary for rail, water, and air transport modes.

Table 6. Min and max container weights of the top 30 commodities shipped by highway

UN/NA Code	Hazard Class	Description of Hazardous Material	Approximate Filled Weight (lbs)	
			Min (lbs)	Max (lbs)
1203	3	Gasoline includes gasoline mixed with ethyl alcohol, with not more than 10% alcohol	8	4,243
1993	3	Flammable liquids, including anti-freeze, liquid, combustible liquid, compounds, cleaning liquid, tree killing, diesel fuel, fuel oil (no. 1, 2, 4, 5, or 6), or plastic solvent	8	4,243
1202	3	Diesel fuel, including gas oil or heating oil, light	9	5,045
3257	9	Elevated temperature liquid, at or above 100˚c and below its flash point (including molten metals, molten salts, etc.)	-	-
1075	2.1	Petroleum gases, liquefied or liquefied petroleum gas	2	280
1830	8	Sulfuric acid with more than 51 percent acid, including hydrogen sulfate, or matting acid	13	7,480
1824	8	Sodium hydroxide solution, including lye	14	7,594
1863	3	Fuel, aviation, turbine engine, including jet fuel	8	4,312
1066	2.2	Nitrogen, compressed	3	317
1999	3	Tars, liquid including road oils and cutback bitumens, including road asphalt	10	5,425
1791	8	Hypochlorite solutions, including potassium hypochlorite, solution or sodium hypochlorite, solution	11	5,736
1013	2.2	Carbon dioxide, including mine rescue equipment containing carbon dioxide	5	1,237
1072	2.2	Oxygen, compressed	3	317
1005	2.3	Ammonia, anhydrous	3	330
1987	3	Alcohols, including denatured alcohol	8	4,404
1170	3	Ethanol or ethyl alcohol or ethanol solutions or ethyl alcohol solutions	8	4,263
1006	2.2	Argon, compressed	3	317
1978	2.1	Propane see also petroleum gases, liquefied	3	895
2672	8	Ammonia solutions, relative density between 0.880 and 0.957 at 15 ˚c in water, with more than 10 percent but not more than 35 percent ammonia, including aqua ammonia	9	4,726
2794	8	Batteries, wet, filled with acid, electric storage	-	-
2448	4.1	Sulfur, molten	16	4,907
1910	8	Calcium oxide, including lime, unslaked or quicklime	29	1,564
3082	9	Environmentally hazardous substance, liquid, including hazardous waste, liquid, marine pollutants, liquid or solid, or other regulated substances, liquid	11	6,111

UN/NA Code	Hazard Class	Description of Hazardous Material	Approximate Filled Weight (lbs)	
			Min (lbs)	Max (lbs)
3475	0	Ethanol and gasoline mixture or ethanol and motor spirit mixture or ethanol and petrol mixture, with more than 10% ethanol	8	4,267
1263	3	Paint including paint, lacquer, enamel, stain, shellac solutions, varnish, polish, liquid filler, liquid lacquer base, and paint related material including paint thinning, drying, removing or reducing compound	12	6,424
1956	2.2	Compressed gas, or nonliquefied gases	3	317
1017	2.3	Chlorine	4	293
1268	3	Petroleum distillates or petroleum products	9	5,093
1789	8	Hydrochloric acid, including muriatic acid, spirits of salt, or white acid	5	6,098
331	1.5D	Explosive, blasting, type b or agent blasting, type b, including ammonium nitrate-fuel oil mixture containing only prilled ammonium nitrate and fuel oil	-	1,522

3.2 MAXIMUM SHIPMENT WEIGHTS FOR RAIL, AIR, AND WATER

U.S. Code 49 CFR, Subpart B, §§172.101-172-102 specifically presents the maximum commodity weights allowed on passenger and cargo aircraft as well as passenger rail. There are no restrictions on cargo rail transport.

The following two tables list the maximum allowable shipments of HM through rail, Table 7, and air, Table 8, for both passenger and cargo shipping configurations.

Table 7. Maximum allowable shipment weights for passenger and cargo rail cars

UN/NA Code	Hazard Class	Description of Hazardous Material	Max. Shipment Weight (lbs)	
			Passenger (lbs)	Cargo
1170	3	Ethanol or ethyl alcohol or ethanol solutions or ethyl alcohol solutions	8.7	None
1987	3	Alcohols, including denatured alcohol	1.8	None
1824	8	Sodium hydroxide solution, including lye	3.3	None
1830	8	Sulfuric acid with more than 51 percent acid, including hydrogen sulfate, or matting acid	3.3	None
1993	3	Flammable liquids, including anti-freeze, liquid, combustible liquid, compounds, cleaning liquid, tree killing, diesel fuel, fuel oil (no. 1, 2, 4, 5, or 6)	110.2	None
1805	8	Phosphoric acid solution	22.4	None
3082	9	Environmentally hazardous substance, liquid including hazardous waste, liquid, marine pollutants, liquid or solid, or other regulated substances, liquid	None	None
3257	9	Elevated temperature liquid, at or above 100˚c and below its flash point (including molten metals, molten salts, etc.)	Forbidden	None
1863	3	Fuel, aviation, turbine engine, including jet fuel	1.8	None
2448	4.1	Sulfur, molten	Forbidden	None

UN/NA Code	Hazard Class	Description of Hazardous Material	Max. Shipment Weight (lbs)	
			Passenger (lbs)	Cargo
1789	8	Hydrochloric acid, including muriatic acid, spirits of salt, or white acid	2.6	None
1075	2.1	Petroleum gases, liquefied or liquefied petroleum gas	Forbidden	None
1017	2.3	Chlorine	Forbidden	None
1005	2.3	Ammonia, anhydrous	Forbidden	None
1040	2	Ethylene oxide or ethylene oxide with nitrogen up to a total pressure of 1 mpa (10 bar) at 50˚c	Forbidden	None
1013	2.2	Carbon dioxide, including mine rescue equipment containing carbon dioxide	165.3	None
1942	5	Ammonium nitrate, with not more than 0.2% total combustible material, including any organic substance, calculated as carbon to the exclusion of any other added substance	55.1	None
1307	3	Xylenes	9.5	None
1010	2	Butadienes, stabilized or butadienes and hydrocarbon mixture, stabilized containing more than 40% butadienes	Forbidden	None
1268	3	Petroleum distillates, or petroleum products	2.1	None
1814	8	Potassium hydroxide, solution or potassium hydroxide	4.7	None
3077	9	Environmentally hazardous substance, solid, including hazardous waste, solid or other regulated substances	None	None
1689	6	Sodium cyanide, solid	11.0	None
3475	0	Ethanol and gasoline mixture or ethanol and motor spirit mixture or ethanol and petrol mixture, with more than 10% ethanol	8.7	None
1964	2	Hydrocarbon gas mixture, compressed, including nonliquefied hydrocarbon gas	Forbidden	None
2312	6	Phenol, molten	Forbidden	None
1978	2.1	Propane see also petroleum gases, liquefied	Forbidden	None
1086	2	Vinyl chloride, stabilized, including monochloroethylene	Forbidden	None
2426	5	Ammonium nitrate, liquid (hot concentrated solution)	Forbidden	None
2209	8	Formaldehyde, solutions, with not less than 25 percent formaldehyde	11.9	None
2280	8	Hexamethylenediamine, solid	55.1	None
3256	3	Elevated temperature liquid, flammable, with flash point above 37.8˚c, at or above its flash point	Forbidden	None
1011	2	Butane see also petroleum gases, liquefied	Forbidden	None
1247	3	Methyl methacrylate monomer, stabilized	10.4	None
2067	5	Ammonium nitrate-based fertilizer (hazard 5.1)	55.1	None
1280	3	Propylene oxide	1.9	None
2015	5	Hydrogen peroxide, stabilized or hydrogen peroxide aqueous solutions, stabilized with more than 60 percent hydrogen peroxide	Forbidden	None

UN/NA Code	Hazard Class	Description of Hazardous Material	Max. Shipment Weight (lbs)	
			Passenger (lbs)	Cargo
1270	3	Petroleum oil	1.8	None
1381	4	Phosphorus, white dry or phosphorus, white, under water or phosphorus white, in solution or phosphorus, yellow dry or phosphorus, yellow, under water or phosphorus, yellow	Forbidden	None
1018	2	Chlorodifluoromethane or refrigerant gas r 22	165.3	None
1999	3	Tars, liquid including road oils and cutback bitumens, including road asphalt	Forbidden	None
1100	3	Allyl chloride	Forbidden	None
1910	8	Calcium oxide, including lime, unslaked or quicklime	55.1	None
1831	8	Sulfuric acid, fuming with 30 percent or more free sulfur trioxide, including nordhausen acid, or oleum	Forbidden	None
3267	8	Corrosive liquid, basic, organic	1.5	None
1303	3	Vinylidene chloride, stabilized	2.7	None
2031	8	Nitric acid other than red fuming, with more than 20 percent nitric acid	Forbidden	None
2810	6	Toxic, liquids, organic, including compounds, tree killing, liquid or compounds, weed killing, liquid	2.6	None
1077	2	Propylene see also petroleum gases, liquefied	Forbidden	None
1114	3	Benzene, or benzol	9.7	None
1357	4	Urea nitrate, wetted with not less than 20 percent water, by mass	2.2	None

Table 8. Maximum allowable shipment weights for passenger and cargo aircraft

UN/NA Code	Hazard Class	Description of Hazardous Material	Max. Shipment Weight (lbs)	
			Passenger (lbs)	Cargo (lbs)
3082	9	Environmentally hazardous substance, liquid, including hazardous waste, liquid, marine pollutants, liquid or solid, or other regulated substances, liquid	None	None
1263	3	Paint including paint, lacquer, enamel, stain, shellac solutions, varnish, polish, liquid filler, liquid lacquer base, and paint related material including paint thinning, drying, removing or reducing compound	2.8	83.3
12	1.4S	Cartridges for weapons, inert projectile or cartridges, small arms	55.1	220.5
3268	9	Air bag inflators, or air bag modules, or seat-belt pretensioners.	55.1	220.5
1046	2	Helium, compressed	165.3	330.7
1266	3	Perfumery products with flammable solvents	41.7	166.7
3090	9	Lithium battery	Forbidden	77.2
1197	3	Extracts, flavoring, liquid	13.9	166.7
1993	3	Flammable liquids, including anti-freeze, liquid, combustible liquid, compounds, cleaning liquid, tree killing, diesel fuel, fuel oil (no. 1, 2, 4, 5, or 6), or plastic solvent	166.7	611.1

UN/NA Code	Hazard Class	Description of Hazardous Material	Max. Shipment Weight (lbs)	
			Passenger (lbs)	Cargo (lbs)
331	1.5D	Explosive, blasting, type b or agent blasting, type b, including ammonium nitrate-fuel oil mixture containing only prilled ammonium nitrate and fuel oil	Forbidden	Forbidden

For waterborne transport, weight restrictions for HM transported by passenger ships are based on the number of passengers and the length of the ship. There are also restrictions on whether HM cargo is allowed above or below deck. However, there are no weight restrictions on cargo ship transport of HM. Since waterborne transport limitations are based on passenger count and ship characteristics (which are unknown at this point in time), this analysis assumes there are no restrictions for waterborne transport; however, special care was taken when pairing unmanned waterborne vehicles with hazardous commodities if the unmanned waterborne vehicle can carry passengers.

4.0 Unmanned System Maturity

The unmanned systems industry is expanding at an exponential rate. Companies and their products are entering the market on a daily basis hoping to cash in on the autonomous vehicle market. Likewise, companies building autonomous systems are going out of business just as fast due to lack of funding or poor market analysis. This market flux makes it difficult to predict, with 100% certainty, the exact UxS that will be the first applicant to transport HM. However, current UxSs in each representative mode of transport have similar features and functionality that exist (or are shared) between manufacturers. For example, there may be several variations of autonomous semi-trucks, but all have a similar load capacity, tracking system, and autonomous navigation implementations.

Data for this UxS research came from multiple sources. AUVSI’s Unmanned Systems and Robotics Database [6] was a primary source. Industry magazines such as AUVSI’s “Unmanned Systems,” UxS organizational groups, and corporate press releases also provided avenues for viewing the innovations, issues, and progress being made and allowed for further research.

For each mode of transport, a comprehensive list of currently available, as well as developmental UxSs, suitable for HM transport are presented. Information such as system maturity, level of autonomy, and payload capacity is listed for each system.

The maturity and level of autonomy for a particular system will guide the hazard analysis and risk assessment in Phase 2 of this effort.

4.1 UNMANNED SYSTEM MATURITY LEVEL

Communication links, ephemeral data collection and analysis, sensor integration, and how a particular system translates all of this into safe motion all suggest a system maturity level. For this analysis, current UxSs will be assigned a maturity level (1 to 5) based on where the vehicle is positioned between idea inception and operational use. The following criteria were used to assign a maturity rating for each system:

Table 9. Maturity levels for current UxS designs

Maturity Level	Definition
1	System is at the design phase and is at least two years from initial testing
2	System design has been solidified and a prototype has been made but has not been tested
3	System design has been through initial testing and issues are being addressed
4	System has been through a robust testing program and is seeing limited real-world testing
5	System is regularly performing in real-world situations

4.2 LEVEL OF AUTONOMY

It is important to differentiate between various levels of autonomy when describing an autonomous system. For example, a passenger car with adaptive cruise control and lane departure sensors still needs a driver to navigate the roads. A passenger car that drives between two points with no human input has a much higher level of autonomy. Ultimately, a system that has completely removed the human-in-the-loop and has passed a robust testing program should prove to be more consistent than a human-piloted vehicle.

Some industries have generated a standardized list of autonomy levels specific to their mode of transport. The Society of Automotive Engineers (SAE International) released guidelines that define six levels of automation [7]. A self-driving vehicle must meet all criteria at a particular level of automation before it can be considered to operate at that level.

Table 10. SAE autonomy levels for cars and trucks

SAE Autonomy Level	Definition
0	The performance by the driver of the entire driving task, even when enhanced by active safety systems
1	The sustained and operational design domain-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the driving task (but not both simultaneously) with the expectation that the driver performs the remainder of the driving task
2	The sustained and operational design domain-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the driving task with the expectation that the driver completes the object and event detection and response subtask and supervises the driving automation system
3	The sustained and operational design domain-specific performance by an automated driving system of the entire driving task with the expectation that the driving task fallback-ready user is receptive to automated driving system-issued requests to intervene, as well as to driving task performance relevant system failures in other vehicle systems, and will respond appropriately
4	The sustained and operational design domain-specific performance by an automated driving system of the entire driving task and driving task fallback without any expectation that a user will respond to a request to intervene
5	The sustained and unconditional (i.e., not operational design domain-specific) performance by an automated driving system of the entire driving task and driving task fallback without any expectation that a user will respond to a request to intervene

The United States and eight other countries have tasked the United Nations' International Maritime Organization (IMO) to start mapping international regulations for autonomous shipping [8]. At this time, no concrete levels of autonomy have been defined for maritime vessels. Other entities such as Lloyd's Register [9] and the Norwegian Forum for Autonomous Ships [10] have all proposed autonomy levels for vessels; however, the shipping industry has broadly adopted autonomous definitions from the automotive and aviation industries.

Table 11. Autonomy levels for ships

Marine Autonomy Level	Definition
0	Not defined
1	A ship that can benefit from a remote operator’s assistance (Driver Assistance)
2	A ship capable of being partly or periodically left unattended (Partial Automation)
3	A ship with an automated drive system that can self-drive providing an operator can step in as required (Conditional Automation)
4	As with the previous level, but capable of self-driving if an operator does not step in (High Automation)
5	A ship that can self-drive totally unmanned in the same conditions and with the same capability as if it were manned (Full Automation)

The Federal Railroad Administration (FRA) released a request for information and comment on the future of automation in the railroad industry in 2018 [11]. The request included reference to the SAE levels of autonomy but suggested that they be modified slightly to account for fixed guideway systems which are easier to ensure public safety. The FRA lists the International Association of Public Transport (UITP) grades of automation for fixed guideway systems as a potential starting point for an approved description of autonomy grades.

Table 12. UITP autonomy levels for rail

UITP Autonomy Grades	Definition
0	On-sight train operation, similar to a streetcar running in mixed traffic
1	Manual train operation where a train operator controls starting and stopping, operation of doors and handling of emergencies or sudden diversions
2	Semi-automatic train operation where starting and stopping is automated, but the train operator or conductor controls the doors, drives the train if needed and handles emergencies
3	Driverless train operation where starting and stopping are automated but a train attendant or conductor controls the doors and drives the train in case of emergencies
4	Unattended train operation where starting and stopping, operation of doors and handling of emergencies are fully automated without any on-train staff

Autonomy levels do not currently exist for the aircraft sector. While it might be tempting to apply a generic unmanned system scale similar to National Institute of Standards and Technology’s Autonomy Levels for Unmanned Systems Framework [12], general scales are typically much more detailed than a five or six level scale generated for other transport sectors. The level of detail in generic unmanned system scales makes it difficult to accurately estimate the autonomy level of UASs, especially when little detail is available for a particular system. In this research effort, an autonomy level scale for aircraft has been developed by APT that will closely follow the SAE scale.

Table 13. Autonomy levels for aircraft

UAS Autonomy Grades	Definition
0	The performance by the pilot of the entire flight, even when augmented by active safety systems
1	The sustained and operational design domain-specific execution by a flight automation system of partial motion control subtasks of the flight task (i.e., will takeoff and/or land with no pilot input) with the expectation that the pilot performs the remainder of the driving task
2	The sustained and operational design domain-specific execution by a flight automation system of all vehicle motion control subtasks of the flight task with the expectation that the pilot completes the object and event detection and response subtask and supervises the flight automation system
3	The sustained and operational design domain-specific performance by an automated flight system of the entire flight task with the expectation that the flight task fallback-ready pilot is receptive to automated flight system-issued requests to intervene, as well as to flight task performance relevant system failures in other vehicle systems, and will respond appropriately
4	The sustained and operational design domain-specific performance by an automated flight system of the entire flight task without any expectation that a user will respond to a request to intervene
5	The unrestricted (i.e., not operational design domain-specific) performance by an automated flight system of the entire flight task without any expectation that a user will respond to a request to intervene

4.3 AVAILABILITY MATRIX

Since all modes of transport share the same maturity scale and similar autonomy levels, a general UxS availability matrix can be generated as a tool to help visualize the autonomy and maturity of any system. Table 14 shows an availability matrix with the maturity scale increasing along the horizontal axis and the level of autonomy increasing along the vertical axis.

All UxSs designated with a dark blue color will be examined as part of Phase 2. These systems are mature enough and/or have sufficient autonomy to likely be used for HM transport in the near-term (2-5 years) if conditions warrant. The three orange boxes represent systems that are on the cusp of employability where they are still in development and/or their autonomy isn't mature enough to warrant significant hazard analyses for safety evaluation. These systems may be available in the next 5-8 years. Lastly, systems designated as gray neither are mature enough nor do they have significant autonomy to warrant analysis. These systems are not viewed as viable to transport HM within the next ten years.

Table 14. General UxS availability matrix

		System Maturity				
System Autonomy		1	2	3	4	5
	5					
	4					
	3					
	2					
	1					

4.4 UNMANNED GROUND VEHICLES

There are hundreds of systems that fall under the umbrella of UGVs. Most, however, are built for a very specific purpose that does not include material transport. As an example, there are many UGVs designed to inspect the inside or outside of pipelines. These vehicles typically cannot carry more than a camera and have no reported payload weights. Other systems are designed for training purposes where a simple tablet on wheels projects an instructor's face to students in a classroom setting.

As part of this effort, a complete list of currently available American made UGVs was produced. Any system that was specific to a particular industry (such as pipeline inspection), or systems that are designed to operate autonomously in a warehouse setting (autonomous fork lifts) were culled from the list. Many entries in the list included multiple variants of the same system. In this case, the largest or latest system identified was retained and the other entries were deleted. The remaining systems were organized into one of four distinct categories: last-mile, auto, trucking, and other.

Figure 3. Amazon Scout package delivery system

Last-mile UGVs are designed to take small to medium sized packages (up to tens of pounds) short distances (typically less than a few miles). These vehicles typically have a small cargo compartment and are programmed to operate autonomously on city sidewalks to deliver packages to their final destination. Systems were also identified that have a payload capacity of greater than 10 lbs and have the appropriate wheelbase to navigate concrete sidewalks and pavement but may not be designed specifically for logistics. These systems could very easily be fitted with a cargo compartment and programmed to deliver HM in a last-mile delivery operation.

Boston Dynamics

Figure 4. Boston Dynamic's Spot UGV

Autos are standard automobiles including passenger vans that carry both people and cargo. Developers will typically retrofit a currently available platform with the appropriate number of sensors to facilitate autonomous operation. In some instances, a vehicle will be designed for a specific purpose such as a college campus shuttle van to carry up to 15 people. In all cases, there is the capability for this type of system to transport HM.

Trucking is a more traditional HM shipping configuration where the semi-tractor is used as the power plant that attaches to and pulls any type of tanker or trailer. All system autonomy is contained in the semi-tractor. This allows the autonomous semi-tractor to haul any type of cargo, including HM.

The last UGV category, ***other***, is reserved specifically for all systems produced by Boston Dynamics, Inc. Boston Dynamics produces a range of four legged systems that operate like any traditional four-legged animal. Their designs are very efficient at hauling cargo for military personnel in a lead-and-follow configuration. It is conceivable that any one of Boston Dynamic's systems could be used to transport HM. For this reason, Boston Dynamic's Spot UGV remains on the short list of UGVs for this effort and represents its own category.

The following table, Table 15, lists 30 UGV systems that could reasonably be used to transport HM either in a last-mile or long-distance highway transport configuration. The table is sorted by category, maturity level, and then by level of autonomy. References for the systems listed in the table, unless otherwise noted, came from the AUVSI's Unmanned Systems and Robotics Database referenced above.

Table 15. Potential UGV platforms for HM transport

System Name	Company	Maturity Level	Level of Autonomy	Payload Capacity (lbs)
Auto				
PROBOT©V2	Roboteam [13]	5	1	1,500
R1 prototype	Nuro [14]	4	5	800
EZ10	EasyMile [15]	4	4	2,700
Udelv	Udelv [16]	4	4	800
Auro	Auro Robotics [17] (in collaboration with Ridecell) [18]	3	4	800
O-R3	OTSAW Digital Inc.	3	2	100†
Last-Mile				
GRP 4400	American Robot Company	5	1	550
RMP440 SE	Segway Robotics, Inc.	5	1	400
Super Mega Bot	Inspectorbots	5	1	250
Eclipse Rover MTK	Eclipse Rover	5	1	100
Amazon Scout	Amazon	4	3	100†
SameDay Bot	DEKA/FedEx	4	3	100†
AT Panther	Advanced Tactics, Inc.	4	2	22
Marble Courier	Marble	4	2	100†
Scorpion	NXT Robotics	4	1	250
Seekur	Adept MobileRobots	4	1	154
Forerunner RDV	RE2, Inc.	4	1	25†
M6	Aion Robotics	4	1	25†
INTELLOS A-UGV	Sharp Electronics Corporation	3	3	50†
RS1 (Base Platform)	Howe and Howe Technologies, Inc.	3	1	50†
Trucking				
Direct Vehicle to Vehicle (V2V) communications	Daimler Trucks North America (DTNA) [19]	5	1	78,000 GVW
N/A	Peleton Technology [20]	5	1	78,000 GVW

System Name	Company	Maturity Level	Level of Autonomy	Payload Capacity (lbs)
Tesla Semi	Tesla [21]	5	1	80,000 GVW
Mercedes Benz Future Truck 2025	Daimler Trucks [22]	4	3	80,000 GVW
Embark	Embark	4	3	80,000 GVW
N/A	Waymo (Subsidiary of Alphabet) [23]	4	2	78,000 GVW
Uber Freight	Uber Advanced Technologies Group [24]	4	1	78,000 GVW
Volvo VNL 670 model	Volvo AB [25]; [26]	4	1	78,000 GVW
Ike	Ike	3	5	78,000 GVW
Other				
Spot	Boston Dynamics, Inc.	4	2	100

† Estimated

Maturity levels and level of autonomy were assigned subjectively using Table 9 and Table 10 as guidance. In many cases, websites, and videos of the system in operation were used to assess the level of autonomy and maturity level. For sales purposes, these sites are generally overly optimistic on the promises they make about their systems. Nevertheless, many of these companies have made and are making great progress on providing a transport system with significant autonomy.

One thing to note about the available UGVs is that the most mature products typically have the lowest level of autonomy. This is an indication that the UGV industry is still relatively new at this point. It is not unreasonable, though, to assume that many of these systems will be fully autonomous (autonomy level 5) within the next decade.

4.5 UNMANNED RAIL VEHICLES

An exhaustive search for potential unmanned rail vehicles returned no unmanned rail systems beyond people-movers in industrial centers or airports. The rail industry is looking into ways of integrating autonomous functions into current rail systems for cargo transport but does not seem to be working towards completely replacing human engineers in the near to medium term.

While there were no unmanned rail systems identified for HM transport, there are findings about what might be necessary for autonomous rail transport of HM at the conclusion of this document that may help guide future efforts to safely automate rail.

4.6 UNMANNED WATERBORNE VEHICLES

Figure 5. Kongsberg Maritime's YARA Birkeland USV

A thorough search of all global underwater and surface vehicles returned over 280 systems. It was important for this mode of transport to include all countries in the UUV/USV search since two of the most mature shipping systems are being developed in Norway and Finland. All UUVs were culled from the list since the vast majority of these systems were designed and built for underwater exploration and have very little or no cargo capacity. Of the 69 remaining USVs, only four are being designed and built for logistics transport. All other systems are being designed for military purposes, environmental research, mine clearing, or communications. Table 16 lists the four systems identified for transporting HM cargo.

Table 16. Potential USV platforms for HM transport

System Name	Company	Maturity Level	Level of Autonomy	Payload Capacity (lbs)
YARA Birkeland	Kongsberg Maritime AS (Norway)	5	3	7,054,792
Sea Machine	Sea Machines Robotics (United States)	4	5	2,000
4D's USV	4D Tech Solutions (United States)	4	4	400
AAWA Program	Rolls-Royce (Finland)	4	4	N/A

Of the four systems, the YARA Birkeland from Kongsberg Maritime and Rolls-Royce's Advanced Autonomous Waterborne Applications (AAWA) initiative are the two systems capable of transporting significant cargo. Sea Machines Robotics initially started creating a new USV but shifted focus to providing existing shipbuilders (or retrofitting current vehicles) with their autonomous platform. 4D Tech Solutions offers a USV that looks much like a pontoon boat and is designed to lift and haul up to 400 lbs. While this is not ideally suited for HM cargo shipping, the platform can be used to transport cargo for short distances, if required.

The maritime industry is aware that complete autonomy of a ship is possible; however, given that there are only two serious (albeit high profile) companies working on completely autonomous ships, the reality of USV fleets traversing the world's oceans seems to be a long-term goal. The YARA Birkeland will run routes no more than 12 nautical miles from the coast between three different ports in southern Norway. The ship is currently being built and expects to enter limited service in 2020. Rolls-Royce is taking a phased approach to introducing a fully autonomous vessel. Phase one is a vessel with a reduced crew with remote support in 2020. Phase two is a remote controlled unmanned coastal vessel in 2025. Phase three is a remote controlled unmanned ocean-going ship in 2030. Lastly, a completely autonomous ocean-going ship will be introduced in 2035.

4.7 UNMANNED AERIAL VEHICLES

Research uncovered over 321 unique UAVs available in the U.S. alone. Designs range from fixed wing planes retrofitted with autonomous flight systems to ultra-small quad-copter style platforms. A large majority of the quad-copter style UAVs had very little payload capacity. Other UAVs with slightly larger payload capacity could only fly within sight of an operator. For a UAV to be employed for HM transport, Beyond Line Of Sight (BLOS) capability would most likely be required. Applicable UAVs were selected based on the ability to transport 10 pounds or more and have BLOS functionality.

Many entries in the list included multiple variants of the same system. In this case, the largest payload capacity or latest UAV was retained, and the other entries were excluded. The remaining UAVs were organized into one of three distinct categories: fixed-wing, rotary wing, and human transport.

Figure 6. Workhorse Group's HorseFly has been selected by UPS as a package delivery system

Fixed-wing vehicles are specifically designed to maximize the duration of flight and payload capacity. These vehicles have very long ranges but require runways for takeoff and landing.

Rotary-wing vehicles rely on rotary blades to provide lift. Rotary-wing UAVs are preferred for package delivery since they can take-off and land in a vertical configuration without the need for runways.

There is one current UAV that is being specifically designed for autonomous ***human transport***. VIMANA Global, Inc., is designing a four-person UAV that will have vertical lift/landing capability but will transition to fixed wing flight after reaching a certain altitude. While there are other companies developing personal transport vehicles, this particular vehicle is being specifically developed using full autonomy. Given the ambitious goals of this particular UAV, it is no surprise that the vehicle is still in the development stage and has yet to take flight. This category will also have the added complication of regulatory restrictions for HM on passenger rated vehicles.

Table 17 lists 18 UAVs that are most likely to be capable of autonomously delivering HM in the next several years. References for the systems listed in the table, unless otherwise noted, came from the AUVSI's Unmanned Systems and Robotics Database referenced above.

Table 17. Potential UAV platforms for HM transport

System Name	Company	Maturity Level	Level of Autonomy	Payload Capacity (lbs)
Fixed wing				
AV-2 / 32 HTOL SFE	DroneTech UAV Corp	4	3	40
ALBATROSS 2.2	UAVOS, Inc.	4	3	617
Centaur (DA42 MPP), OPA	Aurora Flight Sciences Corporation [27]	4	3	800

System Name	Company	Maturity Level	Level of Autonomy	Payload Capacity (lbs)
Resolute Eagle	PAE ISR	4	3	65
RS-20	American Aerospace Technologies, Inc.	4	3	65
T-20	ARCTURUS UAV	4	3	75
Bat 4	Martin UAV	3	3	20
AirStrato Explorer	ARCA Space Corporation	3	2	100
Archimede (Sky Arrow U)	International Aviation Supply	2	2	330
Human Transport				
VIMANA VTOL AAV	VIMANA Global, Inc.	1	4	900
Rotary Wing				
s1	Near Earth Autonomy, Inc.	4	3	15
Avenger	Leptron Unmanned Aircraft Systems	4	3	10
ASV 150-EC	Aero Surveillance, Inc.	3	3	66
DP-14 Hawk	Dragonfly Pictures, Inc.	3	3	430
Carrier Hx8 Power	Harris Aerial LLC	3	3	99
HorseFly	Workhorse Group [28]	3	3	10
Aluminum Falcon	Elroy Air [29]	3	3	150
Cargo Aerial Vehicle (CAV)	The Boeing Company	2	3	500

While there is a tremendous number of UAVs available on the world market, it is evident that transporting payload is taking a backseat to gathering data through cameras and other sensors based on the payload specifications, flight envelopes, and overall design characteristics of many UAVs. Only the Boeing Company and United Parcel Service (UPS) partners are designing a UAV specifically for heavy lift cargo and package delivery respectively.

5.0 Hazardous Material Incident Rates

The goal of transitioning to autonomous transport is to realize a reduction in incidents in order to make transport safer to the general public. To this end, it is important to understand and quantify the current level of risk in transporting HM for all modes of transport. The current level of risk will serve as a baseline to compare risk results based on the use of UxSs.

To define a risk baseline, all incidents listed in the PHMSA OHMS Incident Reports Database Search [30] for the past ten years were examined. The incident list for each mode of transportation was filtered to show only ***serious incidents*** that occurred while the HM was ***in transit***. This distinction was made since autonomous vehicles will presumably be loaded and unloaded by humans. The loading and unloading phase will not benefit from autonomous vehicles unless the act of loading and unloading becomes autonomous. Autonomous loading and unloading of HM are outside the scope of this task.

Each incident description was read and examined to determine whether the failure mode was human failure-induced, mechanical failure, failure of the container, weather related, or if shipping requirements were intentionally violated. In each case, the subjective determination was made whether employment of an autonomous system could have prevented the incident. Any duplicate entries in the database were removed. Results of this analysis are summarized in the following table:

Table 18. HM incident categorization

Transport Mode	Incident Cause					Total Incidents	Potential UxS Prevention
	Human	Mechanical	Container	Weather	Violation		
Ground Vehicles	1942	399	96	87	5	2529	1910
Waterborne Vehicles	2	0	4	1	0	7	4
Rail Vehicles	66	290	13	1	0	370	142
Aerial Vehicles	18	0	26	0	8	52	4

As Table 18 shows, there is significant opportunity to reduce the number of human induced incidents. The most significant finding is that there is a potential of reducing incidents involving ground vehicles by 75%. Although not all incidents result in human injury or death, a 75% reduction would most certainly reduce the average number of casualties.

While researching the incident database, several themes emerged for each mode of transport. The following paragraphs discuss observations made as it applies to the overall safety of currently manned transport systems.

5.1 GROUND VEHICLES

Autonomy will immediately address common causes of trucking incidents such as driver fatigue, driver medical emergencies, distractions such as reaching for items in the cab, poor visibility, animal strikes (potentially), and vehicle rollover due to driving too close to shoulders. Other incident scenarios may be harder to address with autonomy such as head-on collisions with passenger vehicles crossing the median and intentional suicide attempts. Phase 2 of this research and development project will highlight these scenarios and suggest mitigation techniques that autonomous vehicle developers may want to incorporate into their designs.

Other common causes of HM incidents with ground vehicles are poor packaging and load shifting due to inadequate strapping. Some tie-down straps are sufficient to keep loads from shifting during normal driving conditions but fail when drivers have to use extreme maneuvers to avoid an accident. The act of avoiding an accident can cause a secondary incident due to shifting loads. While autonomy may not be able to mitigate poor packaging and load shifting scenarios, there are mitigation techniques that may assist in reducing the likelihood of an accident.

5.2 WATERBORNE VEHICLES

Waterborne vessels have historically been a very safe method of HM transport. In fact, there have been only seven total incidents in the past ten years. Two of the incidents may have been miss-categorized as "in transit" where they should have been "unloading." None of the remaining five incidents were caused by human error. On the contrary, three of the incidents were caught and mitigated by on-board personnel during the voyage. One incident was caused by bad weather where two cargo containers were lost in the heavy seas.

5.3 RAIL VEHICLES

There are two main causes for HM incidents with rail vehicles; missing or defective containment hardware and derailments. A large number of spills are caused by loose bolts on tank hatches or leaking valves. Autonomy may be able to detect these types of incidents faster and reduce the consequence of a spill but may not be able to eliminate this subset of incidents. It is also questionable whether derailments can be reduced by autonomous systems unless the entire rail system is equipped with automated sensors communicating with the rail vehicle.

5.4 AERIAL VEHICLES

Most of the incidents for air transport indicate either shipping violations or damaged/insufficient packaging. In each case, smoke, fire, or fumes were detected by passengers or crew which triggered a response. Most flights are diverted to the nearest airport without incident. The key to autonomous aerial transport of HM may be the ability of the vehicle to detect a release in time to land safely without the HM causing complete vehicle failure in flight.

6.0 Unmanned System/Hazardous Material Shipment Pairing

To limit the solution set of UxSs transporting HM, the top 98% of HM shipments (as a function of tonnage shipped) for each mode of travel are paired with the most mature UxSs available regardless of the UxS level of autonomy. These UxS/HM pairings are the most likely to achieve operational use as of the publication of this report. Reducing the scope of this analysis to the most suitable UxS/HM pairings will focus the hazard analysis performed as part of Phase 2 while ensuring that a large majority of potential HM transport scenarios influence the overall roadmap for PHMSA/OHMS.

The relative suitability of each unmanned autonomous mode of transportation is captured in the following tables. These modes include Ground Vehicles for which there are three subcategories: automobiles, last-mile vehicles, and trucks. Additionally, the waterborne vehicles and unmanned aerial vehicles are evaluated. The relative suitability used in this document employ Harvey Balls [31], round ideograms used for comparison, and are displayed as a legend in Table 19. The colors in the tables correlate to the general UxS availability matrix identified in Table 14.

Table 19. Relative suitability ideogram legend

Ideogram	Suitability Usage
	An empty cell indicates there is no suitability associated with the transport mode and the commodity
○	The open circle indicates minimal suitability between the vehicle and the commodity. While the vehicle may be able to carry the commodity mass, there is a very low likelihood that this vehicle would be used to carry the commodity
◑	The half-closed circle indicates the vehicle can carry a significant portion of the commodity's range of containerized mass and has a significant likelihood of use to carry the commodity
●	The closed circle indicates the vehicle can carry any allowed mass of the commodity and is highly likely to carry the commodity

Table 20, Table 21, and Table 22 visually highlight which UxSs are most likely to be transporting HM in the near term and match each system with potential HM for transport.

Table 20. UGV and HM commodity transport suitability

UN/NA Code	Description of Hazardous Materials	PROBOT©V2	***R1 prototype***	EZ10	***Udelv***	Auro	O-R3	Spot (other)	GRP 4400	RMP440 SE	Super Mega Bot	Eclipse Rover	***Amazon Scout***	***SameDay Bot***	AT Panther	Marble Courier Robot	Scorpion	Seekur	Forerunner RDV	M6	INTELLOS A-UGV	RS1	Direct V2V	Peleton	Tesla Semi	Future Truck 2025	***Embark***	Waymo	Uber Freight	Volvo VNL 670 model	***Ike***
1203	Gasoline includes …	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1993	Flammable liquids…	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1202	Diesel fuel…	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
3257	Elevated temperature liquid	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●
1075	Petroleum gases, …	●	●	●	●	●	●	◐	●	●	◐	◐	●	●	◐	◐	◐	◐	◐	◐	◐	◐	●	●	●	●	●	●	●	●	●
1830	Sulfuric acid …	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	○	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1824	Sodium hydroxide solution	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	○	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1863	Fuel, aviation, …	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1066	Nitrogen, compressed	●	●	●	●	●	●	○	●	●	◐	◐	●	●	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1999	Tars, liquid including road …	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	○	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1791	Hypochlorite solutions, …	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	○	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1013	Carbon dioxide, …	●	◐	●	◐	◐	◐	○	◐	◐	◐	◐	●	●	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1072	Oxygen, compressed	●	●	●	●	●	●	◐	●	●	◐	◐	●	●	◐	◐	◐	◐	◐	◐	◐	◐	●	●	●	●	●	●	●	●	●
1005	Ammonia, anhydrous	●	●	●	●	●	●	◐	●	●	◐	◐	●	●	◐	◐	◐	◐	◐	◐	◐	◐	●	●	●	●	●	●	●	●	●
1987	Alcohols…	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	●	●	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1170	Ethanol or ethyl …	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
1006	Argon, compressed	●	●	●	●	●	●	◐	●	●	◐	◐	●	●	◐	◐	◐	◐	◐	◐	◐	◐	●	●	●	●	●	●	●	●	●
1978	Propane see also …	●	◐	●	◐	◐	◐	○	◐	◐	◐	◐	●	●	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
2672	Ammonia solutions…	◐	◐	◐	◐	◐	◐	○	◐	◐	◐	◐	◐	◐	◐	○	◐	◐	○	○	○	○	●	●	●	●	●	●	●	●	●
2794	Batteries, wet, …	◐	◐	◐	◐	◐	◐	◐	◐	◐	◐	◐	●	●	◐	◐	◐	◐	◐	◐	◐	◐	●	●	●	●	●	●	●	●	●

UN/NA Code	Description of Hazardous Materials	PROBOT©V2	*R1 prototype*	EZ10	*Udelv*	Auro	O-R3	Spot (other)	GRP 4400	RMP440 SE	Super Mega Bot	Eclipse Rover	*Amazon Scout*	*SameDay Bot*	AT Panther	Marble Courier Robot	Scorpion	Seekur	Forerunner RDV	M6	INTELLOS A-UGV	RS1	Direct V2V	Peleton	Tesla Semi	Future Truck 2025	*Embark*	Waymo	Uber Freight	Volvo VNL 670 model	*Ike*
2448	Sulfur, molten	◑	◑	◑	◑	◑	◑	○	◑	◑	◑	◑	◑	◑	○	○	◑	◑	○	○	○	○	●	●	●	●	●	●	●	●	●
1910	Calcium oxide…	●	◑	●	◑	◑	◑	○	◑	◑	◑	◑	◑	◑		○	◑	◑	○	○	○	○	●	●	●	●	●	●	●	●	●
3082	Environmentally hazardous	◑	◑	◑	◑	◑	◑	○	◑	◑	◑	◑	◑	◑	○	○	◑	◑	○	○	○	○	●	●	●	●	●	●	●	●	●
3475	Ethanol and gasoline …	◑	◑	◑	◑	◑	◑	○	◑	◑	◑	◑	◑	◑	◑	○	◑	◑	○	○	○	○	●	●	●	●	●	●	●	●	●
1263	Paint including paint, …	◑	◑	◑	◑	◑	◑	○	◑	◑	◑	◑	●	●	○	○	◑	◑	○	○	○	○	●	●	●	●	●	●	●	●	●
1956	Compressed gas …	●	●	●	●	●	●	◑	●	●	◑	◑	●	●	◑	◑	◑	◑	◑	◑	◑	◑	●	●	●	●	●	●	●	●	●
1017	Chlorine	●	●	●	●	●	●	◑	●	●	◑	◑	●	●	◑	◑	◑	◑	◑	◑	◑	◑	●	●	●	●	●	●	●	●	●
1268	Petroleum distillates …	◑	◑	◑	◑	◑	◑	○	◑	◑	◑	◑	◑	◑	◑	○	◑	◑	○	○	○	○	●	●	●	●	●	●	●	●	●
1789	Hydrochloric acid, …	◑	◑	◑	◑	◑	◑	○	◑	◑	◑	◑	◑	◑	◑	○	◑	◑	○	○	○	○	●	●	●	●	●	●	●	●	●
331	Explosive, blasting, type b	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●

Table 21. USV and HM commodity transport suitability

UN/NA Code	Description of Hazardous Materials	YARA Birkeland	Sea Machine	4D's USV	AAWA Program
1203	Gasoline includes gasoline mixed …	●	●	●	●
1993	Flammable liquids …	●	●	●	●
1863	Fuel, aviation, …	●	●	●	●
1824	Sodium hydroxide solution, …	●	●	●	●
2398	Methyl tert-butyl ether	●	●	●	●
1268	Petroleum distillates, …	●	●	●	●
1267	Petroleum crude oil	●	●	●	●
1270	Petroleum oil	●	●	●	●
1011	Butane, …	●	●	●	●
1918	Isopropylbenzene	●	●	●	●
1964	Hydrocarbon gas mixture, …	●	●	●	●
1005	Ammonia, anhydrous	●	●	●	●
1202	Diesel fuel, including gas oil …	●	●	●	●
2055	Styrene monomer, stabilized	●	●	●	●
1223	Kerosene	●	●	●	●
3257	Elevated temperature liquid, …	●	●	●	●
1972	Methane, refrigerated liquid …	●	●	●	●
1547	Aniline	●	●	●	●

Table 22. UAV and HM commodity transport suitability

UN/NA Code	Description of Hazardous Materials	AV-2 / 32 HTOL	ALBATROSS 2.2	Centaur (DA42)	Resolute Eagle	RS-20	T-20	Bat 4	AirStrato Explorer	Sky Arrow U	s1	Avenger	ASV 150-EC	DP-14 Hawk	Carrier Hx8 Power	HorseFly	Aluminum Falcon	CAV	VIMANA VTOL
3082	Environmentally hazardous substa…	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
1263	Paint including paint, …	◑	●	●	◑	◑	◑	◑	●	●	◑	◑	◑	●	●	◑	●	●	●
12	Cartridges for weapons, inert …	◑	●	●	◑	◑	◑	◑	◑	●	◑	◑	◑	●	◑	◑	◑	●	●
3268	Air bag inflators, or air bag …	◑	●	●	◑	◑	◑	◑	◑	●	◑	◑	◑	●	◑	◑	◑	●	●
1046	Helium, compressed	◑	●	●	◑	◑	◑	◑	◑	●	◑	◑	◑	●	◑	◑	◑	●	●
1266	Perfumery products with flammab …	◑	●	●	◑	◑	◑	◑	◑	●	◑	◑	◑	●	◑	◑	◑	●	●
3090	Lithium battery	◑	●	●	◑	◑	◑	◑	●	●	◑	◑	◑	●	●	◑	●	●	
1197	Extracts, flavoring, liquid	◑	●	●	◑	◑	◑	◑	◑	●	◑	◑	◑	●	◑	◑	●	●	●
1993	Flammable liquids, …	◑	●	●	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	●
331	Explosive, blasting, type b or agent…	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

7.0 Exploration Phase Findings

Identifying the most likely HM shipments through UxSs seemed challenging at the outset of this effort. There are hundreds of HMs, thousands of shipping container possibilities, and thousands of UxSs in various states of maturity and autonomy. However, after examining each component and applying physics and engineering judgement, the combinations reduced to a manageable set of HM shipping possibilities.

The first significant finding was that 98% of all hazardous commodities shipped (as a function of tonnage shipped) is made up of only 74 unique commodities. It comes as no surprise that many of these commodities share similar packaging requirements and are shipped via multiple transport modes. As an example, gasoline is the most shipped commodity for both roadway and water transport modes. This further reduced the number of unique packaging possibilities for each commodity.

Once the commodities and package weights were well understood, focus shifted to examining the current state of unmanned systems. The second significant finding of this effort was that logistics and cargo transport is not the focus the UxS industry in general. Communication, surveillance, mine sweeping, weapons delivery, and general data gathering are the leading requirements for UxS design and development. This effort identified only 52 out of 783 UxSs that are either being designed specifically for cargo transport or have the potential to transport HM (based on cargo capacity and platform flexibility). Although 52 UxSs may seem like too few to start preparing a roadmap for HM transport, the systems being developed are, in some instances, quite mature. Once one system is fielded and is proven to offer significant reduction in shipping costs, many more UxS platforms will quickly be fielded.

Research on current incident rates uncovered a third significant finding on the potential for reducing the number of HM incidents using UxSs. Of the four transport modes examined, autonomy may mitigate up to 75% and 38% of all highway and rail incidents respectively. Based on the analysis conducted, targeting UGVs for HM transport on U.S. highways offers the best opportunity for PHMSA to realize a reduction in HM incidents.

Based on the compiled findings of this Exploration Phase, it is suggested that the following actions be taken for each of the four transport modes:

Highway – This transport mode is considered low-hanging-fruit for reducing HM shipping incidents for three reasons. First, autonomy in the trucking industry could potentially reduce up to 200 human induced incidents per year. This number represents nearly 67% of all serious incidents across all transport modes. Second, the number of commodities shipped by highway is second only to rail and the vast majority of HM shipments (as a function of weight) are transported via highway. Lastly, UGVs, especially semi-tractors and last-mile vehicles, are mature enough that they are being aggressively tested. Semi-tractors are currently being tested in a platooning configuration where a lead truck is driven by a human and additional trucks autonomously follow the lead truck (albeit with a safety driver in the cab). The trucking industry has been testing platooning for several years and 16 states currently allow platooning on their highways. Based on the capacity to transport HM and the maturity levels of UGVs, it is highly likely that highway transport of HM will be requested in the near future.

Two vehicles from each of the three UGV categories (auto, last-mile, and trucking) along with Boston Dynamic’s Spot UGV will be examined as part of Phase 2. These include:

- udelv UGV (auto)
- Nuro’s R1 Prototype (auto)
- Amazon Scout (last-mile)
- DEKA’s SameDay Bot (last-mile)
- Embark’s UGV (trucking)
- Ike’s UGV (trucking)
- Boston Dynamic’s Spot (other)

Figure 7. udelv Inc's UGV currently delivers cargo to customers in three different U.S. test cities

Water – The maritime industry is working diligently on USV/UUVs for remote sensing, communications, and border patrol activities. Cargo transport is being addressed primarily by Kongsberg Maritime from Norway, and Rolls-Royce in Finland. When these two systems are mature enough to reach U.S. ports, the platforms will have been through an extensive and lengthy testing period. All international and national shipping regulations will have also been addressed. Even then, there is no evidence that the U.S. will use these systems to haul HM. In addition, waterborne transport is a historically safe mode of transporting HM with only five total serious incidents in the past ten years. None of the five incidents were caused by human error and would not have been mitigated by autonomous navigation of the vessels.

Based on the limited number of USVs under development, the relatively small quantity of HM shipped by water in the U.S. (as compared to highway and rail), and the relative safety of the transport mode, there is little probability that HM will be transported by USV/UUVs in the near to intermediate term. However, as part of Phase 2, the following two USVs will be examined:

- Kongsberg Maritime's Yara Birkeland
- Sea Machines Robotic's USV

When it does come time to evaluate unmanned systems for water transport, it is critical that a system be in place to detect and mitigate container leakage. Three of the five serious HM incidents were mitigated by the first mate noticing and mitigating container leakage. Removing the human will either increase the severity of HM release or an automated system must be in place to detect and mitigate container leakage in order to achieve an equivalent level of safety.

Rail – The rail industry is working to automate certain functions of existing trains; however, there is no significant push to remove engineers from the cab. There were no unmanned rail systems identified that will be available to move HM in the near to intermediate-term. If autonomous rail systems are developed in the future, there are two distinct hazards that must be addressed to limit HM incidents. The first is train derailments. The majority of serious HM incidents involve the train leaving the tracks and spilling the contents of their tank cars. The second common hazard for rail systems is leaky valves or compartment gaskets/covers. Many serious incidents are reported by third party observers witnessing a leaking tank car. Any improvements through autonomy that include the ability to reduce derailments or detect/mitigate tank car leakage will make HM transport via rail significantly safer.

Air – There are many UASs available that have the potential to transport the small list of HM approved for transport. Based on the financial backing of Boeing's Cargo Aerial Vehicle and Workhorse Group's HorseFly system (funded by UPS), the probability of transporting HM such as paint, paint thinners, lacquer, perfumes, and batteries is significant in the near-term. Hazards and public risk for the following relatively mature systems will be examined as part of Phase 2:

- Uavos Inc's Albatros (fixed wing)
- Aurora Flight Sciences Corp's Centaur (fixed wing)
- Near Earth Autonomy Inc's S1 UAV (rotary wing)
- Leptron Unmanned Aircraft Systems' Avenger (rotary wing)

Figure 8. Leptron's Avenger UAV can carry ten pounds of cargo

8.0 Introduction to Phase 2 – Characterization

The next step in providing a UxS/HM integration roadmap is to examine each mode of transport and identify hazards that autonomy may mitigate along with new hazards that autonomy may introduce. We will start by looking at the 13 specific UxSs transporting specific HM as identified in Phase 1. It is important to remember that hazards identified for a specific UxS will most likely be applicable to other UxSs in the same mode of transport. In the event that the UxS identified in this effort does not reach operational use, the hazards associated with the vehicle will be examined as they may apply to others. As an example, loss of communication with a vehicle is a hazard that applies to most UxSs regardless of the maturity of the design. The UxS/HM pairings identified as part of Phase 1 will be used to guide hazard identification, hazard mitigation, and potential regulatory changes.

Once hazards have been identified and mitigations proposed, risk estimates will be generated for each mode of transport. The resulting risk estimates using UxSs will be compared to the risk tabulated from actual incident rates as part of Phase 1. Reduction or increases in risk will be reported in the final documentation of Phase 2 in preparation for Phase 3.

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