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Systems Analysis of Decontamination Options for Civilian Vehicles

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ABSTRACT

The objective of this project, which was supported by the Department of Homeland Security (DHS) Science and Technology Directorate (S&T) Chemical and Biological Division (CBD), was to investigate options for the decontamination of the exteriors and interiors of vehicles in the civilian setting in order to restore those vehicles to normal use following the release of a highly toxic chemical. The decontamination of vehicles is especially challenging because they often contain sensitive electronic equipment, multiple materials some of which strongly adsorb chemical agents, and in the case of aircraft, have very rigid material compatibility requirements (i.e., they cannot be exposed to reagents that may cause even minor corrosion). A systems analysis approach was taken examine existing and future civilian vehicle decontamination capabilities.

First, an assessment was performed to determine the chemical threat to vehicles in terms of types of chemicals likely to be released, contamination levels, and extent of contamination (i.e., contamination locations). Next, the state-of-the-art or expected practices that would be employed currently to decontaminate both the exterior and interior of vehicles were identified. A gaps analysis was then conducted to identify technology, capability, and data gaps for potential decontamination approaches. Finally, a roadmap to fill the identified gaps was developed including an assessment of related resources and near-term or emerging technologies that could be used to decontaminate vehicles focusing on efficacy and material compatibility.

ACKNOWLEDGEMENTS

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NOMENCLATURE

AC	Hydrogen cyanide
BWA	Biological Warfare Agent
CBD	Chemical and Biological Division
CG	Phosgene
CTRA	Chemical Terrorism Risk Assessment
CWA	Chemical Warfare Agent
DHS	Department of Homeland Security
DOE	Department of Energy
GD	Soman
GB	Sarin
HD	Distilled Sulfur Mustard
JPEO	Joint Program Executive Office
SNL	Sandia National Laboratories
S&T	Science and Technology
TIC	Toxic Industrial Chemical
VX	VX (nerve-type CWA)

EXECUTIVE SUMMARY

The objective of this project, which was supported by the Department of Homeland Security (DHS) Science and Technology Directorate (S&T) Chemical and Biological Division (CBD), was to investigate options for the decontamination of the exterior and interior of vehicles in the civilian setting in order to restore those vehicles to normal use following the release of a highly toxic chemical. A systems analysis approach was taken examine existing and future civilian vehicle decontamination capabilities.

First, the chemical threat to vehicles was assessed in terms of the types of chemical agents and the fate and transport of the agents in vehicle interiors and on the exteriors. The chemical threats to aircraft, railcars and emergency vehicles are distinct compared to other assets. Vehicles are made up of a variety of materials (metals, glass, plastics, rubber, natural and synthetic textiles, etc.) that serve structural, mechanical, electronic, and aesthetic functions. Adsorption and infiltration of an agent can result in degradation of vehicle materials and also may lead to unexpected persistence of the agent, even after measures have been taken to decontaminate the vehicle.

With an understanding of the chemical threat to vehicles, the current practices for vehicle decontamination were examined and a gaps analysis was performed. The primary origin of the gaps in vehicle decontamination is the lack of consideration for the whole vehicle function and conditions of use. Specific gaps in the current approach to civilian vehicle decontamination have been identified:

1. Objectives for vehicle decontamination based on vehicle usage.
2. Information on the compatibility of the decontamination process with vehicle materials.
3. Protocols for clearance and return to service that are specific for civilian vehicles (i.e. process to determine if the decontamination objectives have been met).

A roadmap for future approaches to the decontamination of civilian vehicles has been developed. This roadmap integrates several decontamination resources with a focus on conditions of use:

1. Classify the range of vehicle functions, characteristics, and passenger populations. Use this information to establish risk-based and value-based guidelines for setting appropriate decontamination objectives.
2. Leverage related, existing practices for vehicle cleaning and maintenance, and revise for chemical hazard decontamination. These include:
    a. Military vehicle decontamination strategies
    b. Biological weapon agent (BWA) and human biohazard decontamination
    c. Transit facility decontamination strategies
3. Identify, validate and integrate emerging technologies into decontamination approaches for civilian vehicles.

Currently the approach to vehicle decontamination is not specific for vehicles and does not address potential transportation-related hazards. However there are a number of resources and emerging technologies that, along with vehicle specific decontamination objectives, can provide a more strategic and comprehensive approach to civilian vehicle decontamination.

1. INTRODUCTION

The United States Department of Homeland Security (DHS) is committed to using cutting-edge technologies and scientific talent in its quest to make America safer. The DHS Directorate of Science and Technology (S&T) is tasked with researching and organizing the scientific, engineering, and technological resources of the United States and leveraging these existing resources into technological tools to help protect the homeland. The Chemical and Biological Division (CBD) supports this effort by developing plans, procedures, technologies, and methods to enhance rapid recovery from releases of chemical agents, biological agents, and toxic industrial chemicals.

The objective of this project, sponsored by CBD, was to investigate options for the decontamination of the exterior and interior of vehicles in the civilian setting in order to restore those vehicles to normal use following the release of a highly toxic chemical. The decontamination of vehicles is especially challenging because they often contain sensitive electronic equipment, multiple materials some of which strongly adsorb chemical agents, and in the case of aircraft, have very rigid material compatibility requirements (i.e., they cannot be exposed to reagents that may cause even minor corrosion). A systems analysis approach was taken examine existing and future civilian vehicle decontamination capabilities.

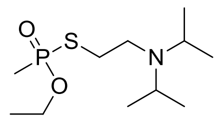
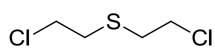
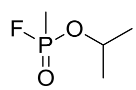
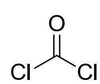
First, an assessment was performed to determine the chemical threat to vehicles in terms of types of chemicals likely to be released, contamination levels, and extent of contamination (i.e., contamination locations). Next, the state-of-the-art or expected practices that would be employed currently to decontaminate both the exterior and interior of vehicles were identified. A gaps analysis was then conducted to identify technology, capability, and data gaps for potential decontamination approaches. Finally, a roadmap to fill the identified gaps was developed assessment of related resources and near-term or emerging technologies that could be used to decontaminate vehicles focusing on efficacy and material compatibility.

2. CHEMICAL THREAT TO VEHICLES

A general scenario of a chemical threat to civilian vehicles could involve the exposure of aircraft, railcars, or emergency vehicles, either intentionally or accidentally, to either chemical warfare agents (CWAs) or toxic industrial chemicals (TICs). Any of the civilian vehicles considered here could become incidentally contaminated if they are in the path of a plume from a release targeted elsewhere (e.g. emergency vehicles contaminated in a wide area outdoor release). However in some cases, the vehicle may be the actual target of the chemical attack (e.g. subway cars or airplanes). Regardless of whether the vehicle was the intended target or not, the decontamination objectives and methods would primarily be driven by the vehicle type and usage. A detailed threat assessment according to specific vehicle type and chemical hazard drawn from on the Chemical Terrorism Risk Assessment (CTRA)[1] will be described in a classified appendix.

A large body of literature addresses a number of relevant issues concerning CWAs and TICs (chemical properties, reactivity, toxicity, medical response, detection methods, decontamination methods, etc.)[2-5]. The goal of this report is to specifically address the decontamination of chemical hazards specifically for civilian vehicles. With this goal in mind, a few prototypical chemical hazards have been chosen as working examples that will be used to illustrate the decontamination strategies discussed. Mustard (HD), sarin (GB) and VX are archetypical CWAs and hydrogen cyanide (AC) and phosgene (CG) are standard examples of commonly used TICs. The structures and physical properties (physical state, vapor pressure, and reactivity) of these chemical hazard prototypes are described in Table 1. The reader is referred to the literature for a broader picture of chemical threat and decontamination methods.

Table 1. Examples of chemical agents that would require decontamination in civilian vehicles. For comparison, the vapor pressure of water is 17.5 mmHg (mp = 0 °C, bp = 100 °C at 1 atm).

			molecular structure	**physical state** (at 25 °C)	**vapor pressure** mm Hg(at 20 °C)	**water solubility** (# g /100 g Soln)
VX	VX	nerve		liquid mp = -39 °C bp = 298 °C	0.0007	3.0 (at 25 °C)
Mustard	HD	blister		liquid mp = 14.5 °C bp = 218 °C	0.072	0.92 (at 22 °C) limited
Sarin	GB	nerve		liquid mp = -56 °C bp = 158 °C	2.1	miscible
Hydrogen Cyanide	AC	blood	H−C≡N	gas/liquid mp = -13.4 °C bp = 25.6 °C	740	miscible
Phosgene	CG	choking		gas mp = -128 °C bp = 8.2 °C	1215	limited

Hazardous chemicals are often released as aerosols or vapors, causing an initial acute inhalation hazard. Agents with low boiling points (≤ 25 ˚C) can be gases near room temperature, as is the case for AC, CG and several other TICs. After vaporous release, these low-boiling agents would continue to be inhalation hazards inside a vehicle until the gas is dispersed to a concentration below a toxic threshold. At the other end of the spectrum, agents that are liquids at room temperature with high boiling points and low vapor pressures, such as HD and VX, are classified as persistent agents. After aerosol or vaporous release and subsequent condensation on the exterior and interior of a vehicle, a persistent agent could pose long-term cutaneous and ingestion hazards, along with an inhalation hazard upon slow evaporation. While GB is not typically considered to be a persistent agent, especially compared to HD and VX, condensation of the agent on vehicle surfaces would similarly result in cutaneous and ingestion hazards in addition to a continuous inhalation hazard. All of these chemical agents interact with vehicle materials, which may alter the fate and transport of the contaminant. Agent is absorbed into porous vehicle materials and drawn by capillary action into material seams and crevices. Adsorption and infiltration of an agent may result in degradation of vehicle materials and can lead to unexpected persistence of the agent, even after measures have been taken to decontaminate the vehicle.

3. CHEMICAL HAZARD DECONTAMINATION METHODS

The purpose of decontamination is to attenuate or eliminate the risk of exposure to chemical agent. The agent may be physically removed through physical decontamination methods, or may undergo reaction into a less hazardous substance through chemical decontamination methods. It should be noted that while the remediation is often an active process, natural attenuation can also contribute to the remediation effort through passive chemical and physical processes. In general, the selection of the decontamination method for any type of asset is dependent on remediation objectives which may include health-based clearance goals and asset restoration goals. Setting decontamination objectives is critical to a successful remediation effort. Not only do the objectives inform the selection of a decontamination strategy at the outset of the effort, but they play a crucial role the clearance process before the asset is restored to service. During the clearance phase, a determination is made whether the decontamination objectives have been met and if the asset is safe for use. While chemical and physical decontamination methods can be applied to a number of different types of assets and chemical hazards, they will be described here only as they relate to vehicles.

3.1. Chemical decontamination

Chemical methods for decontamination aim to alter the molecular structure of the hazardous agent through chemical reaction with the decontaminate reagent to produce reaction products that are less toxic than the parent compound. Chemical decontamination agents include reactive chemicals (oxidants, nucleophiles), catalysts (metal complexes, enzymes) and sources of directed energy (UV radiation). The broad range of reagents and reaction pathways by which a chemical agent may be detoxified are reviewed extensively in the literature[2]. In chemical decontamination, the macroscopic or bulk interactions of the reagents are equally important to the efficacy of chemical decontamination as the molecular reactivity. For example, the form in which a decontaminant is applied to the hazard (e.g. in aqueous solution, as a gas, in a foam, or with an organic solvent) has a significant impact on the fraction of productive molecular interactions between chemical agent and decontaminant. Similarly, the "contact time", or the length of time a chemical hazard is treated with the decontaminant, determines the extent of the decomposition reaction. Contact time is often a factor in the decontaminant formulation. For example, a decontamination gel may be designed to both stick to surfaces (increasing contact time) and solubilize chemical agent (increasing molecular interactions). The overall scheme used in chemical decontamination, including the reagent, the formulation and the application method, is referred to as the decontamination system.

Highly reactive decontamination agents such as hypochlorites and strong bases are very effective at attenuating chemical hazards. However, these reactive agents may also be quite corrosive. Vehicles are made up of a variety of materials (metals, glass, plastics, rubber, natural and synthetic textiles, etc.) that serve structural, mechanical, electronic, and aesthetic functions. Most chemical decontaminants react with these materials to some degree depending on the concentration and the contact time. Even a benign decontaminant like water can prove deleterious to the electronic components of a vehicle. Adsorption and reactivity of the agent and decontaminant with the vehicle materials could potentially degrade the function of the material and therefore compromise the vehicle system as a whole. Material compatibility is an important consideration in choosing chemical decontamination methods.

3.2. Physical decontamination

Physical decontamination is the physical removal of chemical agent by washing, evaporation, and dispersal, or by more sophisticated means including adsorption and sequestration into applied powders and coatings. The properties of the agent, especially the vapor pressure and the aqueous solubility, are determinant in whether physical decontamination methods can be effective. For example, HD would be difficult to remove through water washing because of its insolubility, and VX may be difficult to remove with evaporation or dispersion because of its high boiling point and low vapor pressure. Since physical decontamination only dilutes or relocates the chemical hazard, additional decontamination steps may be required. For example, water run-off and stripped adsorbent paint are collected during the decontamination of a vehicle exterior and may be subjected to further chemical decontamination. An important factor in physical decontamination is the interactions of the agent with the vehicle materials which may lead to persistence of agent even after measures have been taken to decontaminate the vehicle. Physical decontamination may afford some advantages in terms of material compatibility by avoiding the use of corrosive chemicals; however the challenge in assuring the complete removal, in combination with the potential need for additional chemical decontamination after removal, may outweigh the benefits of physical decontamination methods.

4. CURRENT PRACTICE FOR VEHICLE DECONTAMINATION

Although broad-application decontamination methods have recently undergone significant developments, very little attention has been given specifically to civilian vehicle decontamination of chemical hazards. Generic guidance available for hazard decontamination in civilian vehicles is to use dilute bleach and detergent. In the event of a chemical incident, military technologies would likely be referenced for vehicle decontamination. Specifically, DF200 (a.k.a. Sandia Foam, Modec Decon Formula, EasyDECON), which is currently in use for the remediation of military facilities, vehicles, and equipment, has also been commercialized through MODEC for civilian applications[6]. DF200 is a peroxide-based, broad-spectrum decontaminant that works against toxins, chemical, and biological agents, and has been reported to have promising material compatibility compared to other corrosive chemical decontaminants (e.g. hypochlorites, hydroxides)[7]. An isolated, yet very relevant set of studies by Denys Amos and coworkers describes an investigation into the adsorption and desorption of chemical agents in a Landrover[8-10]. Through a combination of computational and experimental work, Amos compares active and passive processes for removing chemical contamination from vehicles. The conclusion of these studies reiterates that (a) the many different materials in a vehicle desorb contaminate at widely different rates, and (b) weathering (wind, sunlight, warm temperatures) can potentially reduce the exposure risk below minimum levels, although active processes were still recommended. In general, there is a deficiency of validated and exercised approaches for civilian vehicle decontamination.

4.1. Gap analysis of the current vehicle decontamination practices

A vehicle is a unique type of asset compared to a facility or a piece of equipment. The types of civilian vehicles considered for this study include an array of modes of transport, passenger populations, and functions. This variety in usage of vehicles should give rise to different decontamination objectives, tailored strategies for decontamination, and specific concepts of operations for restoring each type of vehicle to service. Civilian vehicle decontamination is not currently given this level of attention. The origin of the gaps in vehicle decontamination is the lack of consideration for the whole vehicle function and conditions of use.

Objectives for the decontamination of a vehicle should be set prior to the remediation process and should be based on the conditions of use of the vehicle. The chemical hazard posed in a vehicle is a combination of the toxicity of the agent and the exposure routes of passengers. In addition to the chemical hazard, further hazards may be present depending on how the contamination and remediation impacted the function of the vehicle materials. The conditions of use of a vehicle strongly control the overall hazard exposure of an at-risk population. Precise decontamination objectives should address all potential hazards, and would inform the initial decision point where the determination of whether a vehicle should undergo decontamination for restoration of service, or should be processed for disposal. Ideally the objectives established at the outset of the remediation would be revisited after decontamination to determine if the goals have been met. Currently there is no process or protocol in the civilian sector to determine, (a) whether a vehicle has been cleared of agent, and (b) if the vehicle is still fully functional and operationally safe.

With remediation objectives in place, a decontamination strategy would be chosen to meet the objectives set. In this approach a decontamination strategy must, first, be effective at attenuating the activity of the chemical contaminant in a vehicle, and second, be compatible with the vehicle materials and function. Currently, data to inform the selection of a decontamination strategy toward these two goals are severely lacking. Of the information that is available, it often does not address the vehicle as a whole. The susceptibilities of aircraft-type polymers to CWAs have been screened, however the authors explicitly note that this assessment did not evaluate the impact of CWAs on material performance or overall system function[11]. Experimental research using panel tests to determine the effectiveness and impact of decontaminants on a variety of building materials is ongoing[12]. The current method for field testing decontamination strategies is based on the clearance of surrogate coupons distributed in a testing vehicle. As with the material panel testing, these coupon field tests provide only a limited amount of information on the efficacy and impact on the whole vehicle. Unanswered questions on various decontamination strategies remain: How do chemical agents infiltrate the vehicle and adsorb to vehicle materials? Do the decontaminants infiltrate and adsorb to the same extent as the chemical agent? How corrosive is the decontamination process to the assembled vehicle materials? Does the contamination or the decontamination process compromise vehicle function? Information on the impact on whole-vehicle materials and function is needed in order to strategically select a decontamination strategy to meet remediation objectives.

Another gap is the need for validated sampling and analytical detection protocols for chemical clearance certification. Once a vehicle has undergone the decontamination process, the levels of chemical agent in the vehicle must be re-characterized. This again ties into the decontamination objectives since a clearance determination is a partial confirmation that the decontamination objectives have been met. For vehicles, since the objectives should be broader than simply attenuating the chemical hazard, additional testing methods and technologies for the restoration process are needed.

The specific gaps in the current approach to civilian vehicle decontamination can be summarized as follows:

1. Objectives for vehicle decontamination based on vehicle usage.
2. Information on the compatibility of the decontamination process with vehicle materials.
3. Protocols for clearance and return to service that are specific for civilian vehicles (i.e. process to determine if the decontamination objectives have been met).

5. ROADMAP FOR CHEMICAL HAZARD DECONTAMINATION IN CIVILIAN VEHICLES

Preparing and executing a decontamination plan for civilian vehicles calls for a holistic approach that encompasses multiple factors that is centered on the conditions of use of a civilian vehicle. The conditions of use are the circumstances and activities that result in exposure to a harmful agent. A hazard is a function of the intrinsic harmfulness (i.e. chemical agent toxicity, vehicle material malfunction) and the *conditions of use*. A roadmap for future approaches to the decontamination of civilian vehicles integrates several decontamination resources with a focus on vehicle conditions of use:

1. Delineate the range of vehicle functions, characteristics, and passenger populations. Use this information to establish risk-based and value-based guidelines for setting appropriate decontamination objectives.
2. Leverage related, existing practices for vehicle cleaning and maintenance, and revise for chemical hazard decontamination. These include:
    a. Military vehicle decontamination strategies
    b. Biological weapon agent (BWA) and human biohazard decontamination
    c. Transit facility decontamination strategies
3. Identify, promote and integrate emerging technologies into decontamination approaches for civilian vehicles.

5.1. Set decontamination objectives

Civilian vehicles differ based on the passenger population, function, and usage. Using these features, guidelines for setting decontamination objectives are described here. First, the three vehicle types considered in this report, which include rail cars, aircraft, and automotive vehicles, were further classified by function. Various categories of risk and value for each vehicle class were then evaluated relative to the other vehicles (Table 2). This characterization of vehicles by conditions of use leading to exposure, along with the value of the vehicle, facilitate the initial decision point to determine whether a vehicle should be disposed of, or decontaminated and restored to service. Subsequently, these guidelines would form the basis for the decontamination objectives and clearance standards that would be required for return to service.

Table 2. Relative rankings of risk and value for the restoration of a variety of civilian vehicles. This type of information can serve as guidelines for setting decontamination objectives. (red = more important, green = less important)

		risk-based guidelines			value-based guidelines	
		passenger exposure duration	health of passenger population	consequence of malfunction	criticality of operation restoration	uniqueness/ expense to replace
rail car:	passenger train	medium	diverse pop	medium	low	medium
	cargo train	NA	NA	low	medium	medium
	subway	medium	diverse pop	medium	low	medium
aircraft:	passenger	long	diverse pop	high	medium	high
	cargo plane	NA	NA	medium	medium	high
emergency vehicle:	ambulance	short	poor health	low	high	low
	fire truck	short	good health	low	high	low
	police car	medium	good health	low	high	low

5.1.1. Risk-based guidelines

A risk-based guideline considers the conditions of use of a vehicle and the resulting likelihood that passengers may be exposed to follow-on hazards after of the decontamination process. The relative magnitudes of the resulting consequences are also evaluated. A risk-based guideline accounts for the efficacy of the decontamination process including how complete the elimination of chemical agent is, and the impact on the vehicle of being exposed to both the chemical agent and decontaminant. Risk-based guidelines evaluated for each vehicle type include:

Passenger exposure This guideline considers number of passengers, the length of time the average passenger spends in the vehicle and the associated exposure route during that passenger residence.

- Ambulances and fire trucks are small-volume, open-air systems that transport a handful of passengers over a short distance (approx 0-30 min). Police cars are also open-air systems that transport only a few passengers; however the average residence time may be longer (0-90 min).
- Passenger trains and subways are relatively open-air systems that serve a larger, diverse population (elderly, children, men and women) with intermediate residence times (0-90 min).
- Passenger aircraft are closed systems with re-circulating atmospheres that serve a larger, diverse population (elderly, children, men and women) who have longer residence times (>90 min).
- Cargo trains and cargo planes only have small crews, which minimizes this factor.

Health of passenger population This guideline considers the distribution of health of the passengers in each vehicle type. A population with good health and fitness who are exposed to chemical hazard will have reduced consequences compared to a population that includes children, elderly, and sick people.

- Firefighters (fire trucks) and police officers (police cars) are generally healthy, fit adults (age 20-55 yr).
- Passenger trains, subways and passenger aircraft serve diverse populations with a wide range of health and fitness (elderly, children, men and women). Inadvertent ingestion of chem agent is also more likely in children.
- Ambulances, by definition, transport people in poor health.
- Cargo trains and cargo planes only have small crews, which minimizes this factor.

Consequence of malfunction The structural, mechanical or electronic function of the vehicle may be compromised from exposure to chemical agent or decontaminate. This guideline considers the consequences for passengers or cargo in the event of vehicle malfunction.

- Passenger airplanes have the largest consequence associated with malfunction because there is a large passenger population and a very low margin for operation error. Cargo planes similarly have low margin for error but do not transport passengers, therefore the consequences of malfunction are ranked slightly lower.
- Passenger trains and subways transport a large passenger population and have a moderate tolerance for vehicle error (i.e. malfunction is not always devastating) resulting in an intermediate consequence level. Cargo trains are ranked with low consequence since they are ground transportation without passengers.
- Malfunction of commercial planes and railcars may have secondary economic consequences due to loss of public confidence in the service.
- Operational error in emergency vehicles would not be likely to have devastating consequences because they have few passengers and are ground transportation. Malfunction of life-sustaining equipment is included in the overall operability of emergency vehicles.

5.1.2. Value-based guidelines

A value-based objective is related to the criticality or priority that the vehicle operations be restored. Information included in these guidelines may inform the initial decision point to determine whether the vehicle is worth the restoration effort (dispose vs. re-issue). Unlike the risk-based guidelines, the value-based guidelines are independent of the chemical scenario. Value-based guidelines evaluated for each vehicle type include:

Criticality of operation restoration

- Subway and passenger trains are considered low priority for restoration because they have mostly local impact and there are alternative means of transportation for the passenger population.
- Passenger aircraft and cargo trains and planes serve a larger geographical region (planes may be international) and slow restoration may result in large economic impact.
- Emergency vehicles are considered high priority because of their importance in continuity in crisis management.

Uniqueness and expense to replace The monetary cost of a vehicle, including the cost of sensitive electronic equipment, is a direct measure of the value of a vehicle[13]. A related characteristic is the uniqueness, or the number of vehicles of that type that are in operation elsewhere and are available to replace the damaged vehicle.

- Emergency vehicles can cost tens of thousands of dollars depending on their function. (e.g. police car ~ $ 30 K; ambulance ~ $ 100 K; fire truck ~ $ 50-250 K, all fully equipped).
- Depending on its usage, a railcar can cost $ 1-3 M (this includes both freight cars and subway cars).
- An airplane can cost $ 50-300 M (737 aircraft and 747 freighter aircraft, respectively).
- Manufacturing lead times are long, and excess inventories are minimal for both rail cars and airplanes, which results in a relative increase in the value of the vehicles.

The civilian vehicles considered in this report represent a many conditions of use and passenger populations. The decontamination guidelines described here are intended to construct a framework to examine the unique considerations of each vehicle type. The risk- and value-based guidelines are relative amongst the vehicles described and do not necessarily apply in a broader context (i.e. to different hazard scenarios, or to other vehicles such as ships). Decontamination objectives set by these guidelines will address the issues needed to safely restore a vehicle to service.

5.2. Leverage related topic areas and resources

Although there are currently no approaches that specifically address the decontamination of civilian vehicles from chemical hazards, there are a number of topic areas and resources with some degree of application to the problem. A rigorous approach to vehicle decontamination will leverage the relevant aspects of all available resources. Topics and resources related to chemical hazard decontamination in civilian vehicles are described here and summarized in Table 3.

5.2.1. Military chemical hazard decontamination strategies

Strategies to decontaminate military equipment after exposure to chemical hazards have continually been under development since the advent of chemical warfare during WWI. Since that time a number of equipment decontamination technologies have been developed, standardized and improved upon (see timeline, Figure 1)[14-16]. As in the civilian setting, technology development for military decontamination has also been driven by material compatibility. This is reflected in the move away from corrosive chemical decontaminants over time. In an ongoing initiative, the Joint Program Executive Office (JPEO) for Chemical and Biological Defense has a plan to acquire new broad spectrum decontamination technologies. The JPEO decontaminant acquisition program is discussed further in the emerging technologies section (5.3.2).

Although these military decontamination systems are often employed for vehicles, the objectives for decontamination in a military setting are often battle oriented with the goal of maintaining continuity of operations and ensuring mission success. Furthermore, the occupant populations using military vehicles are at the peak of health and fitness, are typically trained in chemical defense, and possess protective equipment. This indicates that the decontamination doctrine and strategies employed in the military are not directly applicable to civilian vehicles. Nonetheless, military technologies may be leveraged for civilian vehicle decontamination once the agent attenuation and the impact on vehicle materials and functions meet civilian requirements.

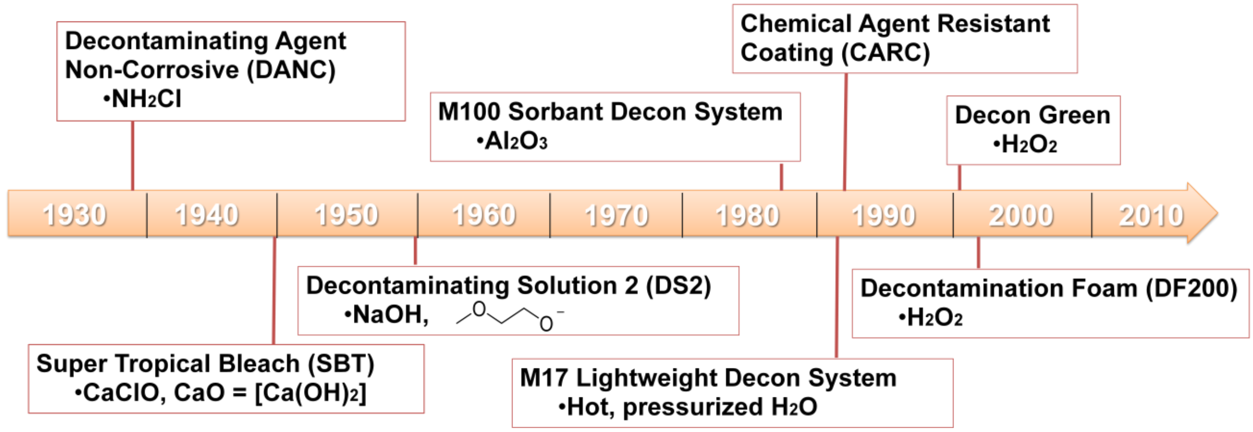


Figure 1. Timeline of military implementation of chemical and biological decontamination technologies.

5.2.2. Decontamination of biological agents and biohazards

Although biological hazards pose very different risk from chemical hazards in terms of toxicity and exposure, the decontamination strategies for each are similar. A scenario involving intentional release of a biological warfare agent (BWA), such as anthrax, is analogous to the chemical release scenario discussed. The impact on vehicle materials of BWAs is minimal, although there are similar concerns for the impact of the decontamination process on materials and function. There are also a number of other naturally manifested biohazard scenarios that have driven decontamination research and technology development. For example, decontamination of an aircraft after a passenger is discovered to be carrying an infectious disease, such as tuberculosis. Another example of biohazard decontamination which is very commonplace is cleaning bodily fluids from emergency vehicles. The broad biohazard threat space has led to the development a number of civilian decontamination strategies with varying levels of sophistication that could also be utilized in the to decontaminate chemical hazards arena.

5.2.3. Chemical threat and decontamination in transit facilities

Transit facilities are associated with a number of the civilian vehicles of interest in this study (e.g. train and subway stations, airports). Significant efforts have been invested modeling chemical scenarios in airports and subway systems. Various mitigation strategies are then applied to the airport scenarios in order to understand their feasibility and potential impact on the scenario consequences. Examples of the types of mitigation strategies investigated include medical countermeasures, responsive countermeasures, sampling and contamination characterization strategies, decontamination approaches, and restoration efforts. A separate objective of this project was to conduct a systems analysis to investigate methods that could be utilized in a subway system to rapidly and efficiently mitigate the effects of a release of toxic chemicals. This portion of the project is described in a separate report[17]. It is easy to imagine how chemical and material hazards in the transit facility would pose a risk of transfer to the vehicle, and vice versa. Because of this, both the vehicle and its transit facility would need to be cleared of hazard before either could be restored to service. As a result, the decontamination objectives of both the vehicle and the facility are highly correlated.

Table 3. Resources and topics related to decontamination of chemical hazards in civilian vehicles. Relevant aspects of each are listed as well as important distinctions form chemical hazard decontamination in civilian vehicles.

	Relevant aspects	Important distinctions
Military vehicle decontamination strategies	• addresses vehicle decontamination • aimed at chemical hazards	• decontamination objectives are battle oriented • population is fit and healthy • personal protective equipment is employed
BWA decontamination	• BWA decontamination agents and systems are often effective on chemical agents	• also lacking in vehicle-specific protocol • BWAs have very different vehicle material interactions
Natural biohazard decontamination	• common practice in emergency vehicles • protects a broad population	• the simplicity of these methods may not be rigorous enough for chemical hazards
Transit facility decontamination	• the same passenger population as the associated vehicle • both the transit vehicle and facility must be cleared of hazard for restoration to service	• facility decontamination does not have the same requirements for material compatibility and restoration of safe function

5.3. Integrate emerging technologies

Developments in decontamination technologies have been extensively reviewed and are published in numerous technical reports, conference proceedings and open literature articles. A very brief summary of emerging decontamination technologies is reported here. The research and development of decontamination technologies has matured to the stage where particular use cases can be evaluated. Nonetheless, methodologies specific to vehicles have yet to be a focus in the development. With many of the near-term technologies at the application and field testing stages, it is the ideal opportunity for them to be evaluated for vehicle decontamination to see if they measure up to the rigid material compatibility requirements.

5.3.1. Chemical and physical decontamination

Oxidants:

- **Decon Green™** is a broad-spectrum, peroxide-based, aqueous decontaminant that is considered to be "environmentally friendly" while retaining its effectiveness against HD, GD, and VX. Material compatibility has been tested against painted and metal surfaces with favorable results. Decon Green™ is licensed to Strategic Technologies Enterprises, Inc. (STE), a subsidiary of STERIS Corp[18,19].

- **L-Gel** is gel formulation of oxone™ (potassium peroxymonosulfate) that adheres to non-horizontal surfaces (e.g. walls) while it oxidizes CWAs. L-gel was developed at Lawrence Livermore National Laboratory. L-gel is also effective against HD, GD, and VX on airplane-relevant materials (e.g. steel, painted metal, indoor-outdoor carpet)[20].

Directed energy:

- **Electrostatic Decontamination System** (EDS), which was developed by Clean Earth Technologies, is an oxidizing decontamination solution that is activated by UV light. EDS is effective against CWAs and TICs on hard an porous surfaces "without adversely affecting materials"[21].
- **Electrostatically Charged Aerosol Decontamination** (ECAD) is a reagent delivery system that produces an aerosol fog of electrically charged droplets of decontamination liquid. This systems aims to be effective against both chem and bio agents, to not damage materials and equipment, and to not require post-application cleanup[22].
- **Atmospheric plasma systems** produce excited, dissociated or ionized gases (i.e. reactive oxygen species) for oxidative decontamination of CWAs. Plasma systems are touted to be more compatible with wiring, electronics, and plastics compared to wet chemistry decontamination systems, although extended exposure still can be corrosive. Emerging plasma-based technologies include Binary Ionization Technology (BIT™) developed by Titan Corp.[23], Atmospheric Pressure Plasma Jet (APPJ) and the Plasma Decon Chamber developed at Los Alamos National Laboratories and are currently licensed to APJeT[24,25].

Reactive metal ion materials:

- **FAST-ACT™**, which is licensed to NanoScale Corp., is a sorbent material made of oxidizing nanoparticles (e.g. titanium dioxide or magnesium dioxide) which effectively adsorbs and destroys both CWAs and TICs. FAST-ACT is advertised as "non-corrosive" however there are no further details on material compatibility[26].
- Metal organic frameworks and zeolites are being investigated for their ability to adsorb and react with CWAs[27].
- A number of small-molecule M(II) and M(III) metal complexes have been shown to catalyze the degradation of VX and HD[28]. Specifically, PARTEQ innovations, has developed a number of catalysts for the decomposition of organophosphorus agents e.g. alcoholysis of G agents with a Cu(II) complex, and of VX with La(III) complexes[29].

Enzymatic Catalysis:

- The enzymatic hydrolysis of G and V agents by organophosphorus acid anhydrolases (OPAAs) and organophosphorus hydrolase (OPHs), respectively, have been studied extensively for their potential application to chemical decontamination[30,31]. Similarly, hydrolytic dehalogenase has been investigated for hydrolysis of HD[32].
- **DEFENZ™** by GENENCOR is a commercialized formulation of OPAAs and OPHs that is advertized to be "safe for use on shipboard, aircraft and water-hardened sensitive equipment"[33].

Coatings:

- Chemical Agent Resistant Coating (CARC) systems have been applied to military vehicles for a number of years. CARCs are strippable paints that protect a vehicle from CWAs and BWAs by adsorbing the agent[34].
- The next generation of CARC is planned to both absorb and decontaminate CWAs by including enzymes[35] or other additives[36] into the paint. Work on these systems is under development at the UK Defense Science and Technology Laboratories (DSTL)[37].

5.3.2. Decontamination systems

A decontamination system is combination of the decontamination reagent, the formulation, and the application method. Each of the emerging chemical decontaminants described in this report are undergoing additional development of an optimized decontamination system. As discussed earlier (section 5.2.1), the military often leads the way for the development of chemical decontamination technologies. The Joint Program Executive Office for Chemical and Biological Defense (JPEO-CBD) has a plan for evolutionary acquisition of new decontamination technologies with cross-cutting applications to remove or neutralize chemical and biological contamination from personnel, equipment, vehicle interiors/exteriors, fixed facilities and terrain[38]. The JPEO decontamination acquisition programs are:

1. Joint Service Family of Decontamination Systems (JSFDS) which includes
    i. Personnel/Skin Decontamination
    ii. Man-Portable Decontamination
    iii. Transportable Decontamination
    iv. Stationary Decontamination
2. Joint Services Sensitive Equipment Decontamination (JSSED)
3. Joint Services Interior Decontamination (JSID)

The approach taken by the JPEO, which considers the specific characteristics and functions of the asset being decontaminated, can serve as an example for the course of development for civilian vehicle decontamination technologies.

In a non-military initiative, the STERIS Corporation[39] is supporting a major effort to develop decontamination systems based on Vaporized Hydrogen Peroxide (VHP®) for decontamination of chemical and biological hazards. Although vapor-phase hydrogen peroxide was initially investigated for biohazard sterilization applications[40,41], the efficacy of VHP® for decontamination of CWAs, most notably HD and VX, has also been demonstrated[42]. Recently, the VHP® system was modified (mVHP®) to allow the injection of ammonia gas into the peroxide stream. This new formulation has new the decontamination efficacy for GD and improved efficacy for VX[43]. The important distinction in the development of VHP® systems compared to other decontamination systems is that the system development focuses has been on vehicle decontamination. The VHP® system has been field tested on several aircraft interiors[44,45], and has been further investigated for the material compatibility of the decontamination process on typical aircraft materials[46]. There is still work to be done to understand the impact on vehicle function, as well as to establish the standards and protocols for restoration of service. Nonetheless, the vehicle focused R&D for the VHP® system has set a precedent for the development process of all emerging technologies for vehicle decontamination.

6. CONCLUSIONS

The specific requirements in vehicle decontamination are often overlooked in technology development and emergency planning. Specific gaps in the current approach to civilian vehicle decontamination have been identified.

1. Objectives for vehicle decontamination based on vehicle usage.
2. Information on the compatibility of the decontamination process with vehicle materials.
3. Protocols for clearance and return to service that are specific for civilian vehicles (i.e. process to determine if the decontamination objectives have been met).

A roadmap for future approaches to the decontamination of civilian vehicles integrates several decontamination resources with a focus on vehicle conditions of use.

1. Delineate the range of vehicle functions, characteristics, and passenger populations. Use this information to establish risk-based and value-based guidelines for setting appropriate decontamination objectives.
2. Leverage related, existing practices for vehicle cleaning and maintenance, and revise for chemical hazard decontamination. These include:
   a. Military vehicle decontamination strategies
   b. Biological weapon agent (BWA) and human biohazard decontamination
   c. Transit facility decontamination strategies
3. Identify, promote and integrate emerging technologies into decontamination approaches for civilian vehicles.

Currently the approach to vehicle decontamination is not specific for vehicles and does not address potential transportation-related hazards. However there are a number of resources and emerging technologies that, along with vehicle specific decontamination objectives, can provide a more strategic and comprehensive approach to civilian vehicle decontamination.

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APPENDIX A

(U) The appendix to this report includes excerpts from the Chemical Terrorism Risk Assessment related to the chemical threat to vehicles and their transit facilities.

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