Recommendations to Improve Passenger Railcar Safety During Electric Micromobility Vehicle Fires

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Executive Summary

Developments in lithium-ion battery powered electric micromobility vehicles (EMV) have led to both a surge in their utility and popularity, as well public safety concerns due to high profile incidents involving fires started by EMV. On October 3, 2024, The Fire Safety Research Institute (FSRI) conducted experiments in a passenger railcar to examine the impact of thermal runaway-initiated EMV fires on tenability and egress conditions for passengers.

Selected EMV included 3 different types commonly used by first and last-mile passenger rail commuters. Four experiments were conducted with one vehicle each: standing e-scooter (compliant), e-bicycle (compliant), and 2 seated e-scooters (non-compliant). The e-scooter and e-bicycle were placed in locations likely to be used by passengers (nearby overhead luggage space, and designated bicycle rack, respectively). The seated e-scooters were placed in the only space large enough to accommodate a seated scooter in the current railcar configuration.

The railcar was instrumented to measure temperature and smoke conditions to assess occupant tenability during the time the passengers would be egressing the railcar. Video cameras were installed to monitor fire progress and to assess visibility during fire development. This summary discusses the results from these experiments.

During thermal runaway, the battery packs suddenly vented a flammable gas mixture with little audible warning. The burning gases then ignited in a fireball, followed by a flame plume driven by the Lithium-ion Battery (LiB) in thermal runaway. Shortly after ignition, the combustible vehicle components became involved, followed by fire spreading to the interior finish of the railcar.

Estimated times for potential occupant incapacitation were determined for asphyxiant and thermal exposures using fire safety engineering industry standard fractional effective dose (FED) model calculations. FED calculations provide a means to estimate the available safe egress time (ASET), or the amount of time available for occupants to safely exit a space, in a specific fire scenario. The calculations utilize gas concentrations, heat fluxes and temperatures measured during the experiments. The fractional effective doses calculated for these experiments indicate a greater risk of incapacitation due to asphyxiant gas exposure than thermal exposure for occupants more than 3 m (10 ft) from the EMV fires.

Tenability with respect to asphyxiant gases filling the entire railcar was compromised most quickly in the first seated scooter experiment, with FED > 0.3 at 3 minutes and 37 seconds after gas ignition. The slowest time to compromise tenability occurred during the e-bike experiment, where the entire railcar became untenable within 7 minutes and 8 seconds. The median time until compromised tenability at a standing elevation was 4 minutes and 54 seconds. It is critical to understand that these times are based only on heat and smoke generated from the EMV. The railcar was protected against fire extension from the EMV to the surface finish materials so that multiple experiments could be achieved. Involvement of the surface finish in fire in a real incident could potentially produce faster times to incapacitation.

Occupants within 3 m (10 ft) of an EMV could be potentially incapacitated by thermal exposure from the emitted fireball and fire plume within 20 to 60 seconds, based on the standing e-scooter experiment. Similar flaming was observed from the seated e-scooters, but their position further from passenger locations limited measured thermal exposure. In all experiments, thermal exposure was not significant enough to cause incapacitation further than 3 m (10 ft) from the vehicle (e.g., the midpoint and endpoints of the railcar).

Visibility diminished to zero prior to combustion byproducts presenting a risk of incapacitation by asphyxiation or thermal exposure for occupants. Given the rapid growth of the LiB fires, visibility was lost end-to-end in the railcar between 1 minute and 48 seconds and 4 minutes and 6 seconds from fire ignition (median 3 minutes and 12 seconds). Visibility is critical consideration as reduced visibility is known to reduce egress speed.

Determination of whether an evacuation can be performed safely requires comparison of ASET, which must be longer than the required safe egress time (RSET), or the amount of time that it is expected to take for occupants to exit a specific space. Quantification of RSET was not within the scope of these experiments, but limited passenger railcar evacuation literature is available to estimate RSET.

According to studies conducted by the John A. Volpe National Transportation Systems Center (Volpe Center) [1], it may be possible to evacuate an 84-person railcar in approximately 1 minute and 41 seconds under ideal conditions where passengers are able to exit unimpeded to an adjacent railcar or onto a level platform. An estimated 4 minutes, and 14 seconds are needed under less-than-ideal conditions where it is necessary to egress to a right of way (ROW). Both estimates should be considered best-case scenarios for available egress time; These egress estimates do not include factors involved in pre-movement decision making, or factors affecting movement such as waning visibility caused by smoke, difficulty opening unfamiliar doors, mobility impaired passengers, fire location blocking egress paths, time to stop the train if occupants cannot escape to an adjacent railcar, etc.

Given the speed of EMV fire growth and the development of smoke conditions, it is anticipated that:

- Most if not all passengers will be exposed to smoke from the EMV fire before exiting the railcar.
- Under ideal egress conditions and typical EMV fire development, passengers may be able to escape without incapacitation.
- Under less-than-ideal egress conditions, passengers will be egressing during untenable conditions.

To improve the safety for rail passengers, FSRI has developed the following recommendations:

1. Consider creating storage areas for the EMV that are separated from the passengers to confine devices and preferably exhaust EMV smoke to the exterior of the railcar.
2. Do not put any EMV where passengers may not be able to egress to an adjacent railcar, i.e. the last railcar.
3. Consider implementing restrictions on maximum EMV battery size to limit potential fire severity.
4. Reduce the egress time by providing early detection and instructive announcements during evacuation that may encourage more time-efficient evacuation behavior
5. Consider a program for inspection and pre-registration of e-vehicles that have been tested by a Nationally Recognized Testing Laboratory (NRTL) to UL 2849 and UL 2271
6. Provide li-ion battery specific training to passenger railroad staff highlighting rapidity of fire development, severity of potential smoke exposures, dependency of passenger exposure on egress time, means of reducing passenger egress time
7. Improve passenger awareness of li-ion battery fire hazards, and personal means of reducing those hazards, by providing printed materials or digitally directing them to educational materials from li-ion battery fire public safety education campaigns such as ULRI’s Take C.H.A.R.G.E. (www.batteryfiresafety.org).

1 Introduction

The first/last mile (FLM) is a term used for the distance a transiting person must travel before boarding and/or after exiting from a transport hub such as a train or bus station. For many travelers, FLM influences their perceptions of public transport and may act as a deterrent to using public transportation [2]. For some travelers, the use of electrical micromobility vehicles (EMV) can be an attractive solution for FLM challenges. EMV come in all sorts of shapes and sizes and can be human or electrically powered or a combination of both. Common EMV include E-bicycles, E-scooters (standing or sitting), segways, E-unicycles, and hoverboards. The use of EMV have many benefits including [3]:

- Increase transportation accessibility
- Reducing traffic congestions
- Improve air quality
- Improved city sustainability
- Lower accident rates

However, one of the challenges to EMV is the transport from station to station on public transportation vehicles. In addition to the issue of storage space for the EMV on public transport vehicles, there is also the question of the risk posed to the passenger on the public transport vehicle if the battery in the EMV were to undergo thermal runaway [4] resulting in a fire and/or explosion during transport.

Most modern EMV rely on lithium-ion battery (LiB) for the energy required to drive the electric motor. There are many advantages to LiB including high energy density, low maintenance, long lasting, and fast charging. Much of the world's populations use LiB powered devices routinely with little thought given to the serious consequence exhibited by a LiB fire.

When a LiB fails and starts a fire, it is typically the result of the battery suffering a thermal runaway. Thermal runaway occurs when exothermic reactions generate heat faster than the heat can dissipate, leading to the reactions running out of control. Thermal runaway can be initiated by physical damage, overheating, and/or failure of the battery management system, which could result in overcharging. When considering thermal runaway, the mechanisms are typically categorized into three forms of abuse: electrical, thermal, and mechanical [5]. Electrical abuse [6] occurs when a LiB is overcharged, over discharged, or short circuits either internally or externally. Thermal abuse [7] results from overheating the battery such as exposure to a fire [8]. Mechanical abuse [9] includes physical damage, such as, crushing a cell in a garbage truck or penetration [10] of a nail into the cell.

The impact of a LIB undergoing thermal runaway in a public transport vehicle was clearly demonstrated by the numerous incidents where batteries in cellphones and laptops overheated to the point of catching fire. The most noteworthy case was the Samsung Galaxy Note 7 where the battery was found to be defective and resulted in the recall of the battery [11]. Unfortunately, the replacement was also found to be defective and that led to the product being withdrawn from the market. In addition, the US Department of Transportation with the Federal Aviation Administration and the Pipeline and Hazardous Materials Safety Administration issued an emergency order to ban all Samsung Galaxy Note 7 smartphone devices from aircraft in the United States [12].

The consequences of a thermal runaway of a LIB in EMV in residential buildings has been reported in many cities around the world [13][14][15][16], most notably, New York City [17]. A recent UL Research Institutes study on full scale experimental study, quantified the impact of seated e-scooter fires in residential buildings[17]. The study forced thermal runaway of the LIB scooter using electrical resistance heaters on five cells in the battery pack. The results showed that e-scooter fires in an unsprinklered home can be fatal to the occupants in a few seconds. Occupants that are in close proximity to the fire could suffer fatal burns or perish from smoke inhalation before they can escape. Other occupants in the home may also perish from smoke inhalation if the scooter compromises the exitway.

In the case of a passenger railcar where there can be more than 50 passengers and there is no automatic fire suppression system, the fire would likely block one of the two means of escape, and it can take more than 1-2 minutes to stop the train (once the conductor activates the emergency braking system), there is a logical concern for the passengers safety. In this study, three different EMV (standing e-scooter, e-bike, and seated e-scooter) were forced into thermal runaway in a 72-passenger railcar to assess the hazard to the passengers posed by a EMV fire.

1.1 Analysis of Tenability During Egress

To perform a life safety analysis for occupants of a particular space, two relevant time scales must be compared: 1) available safe egress time (ASET), or the amount of time available for occupants to safely exit a specific space in specific fire scenarios and 2) required safe egress time (RSET), or the amount of time that it is expected to take for occupants to exit a specific space. For life safety, ASET must be a longer time than RSET. In the scenarios studied in these experiments, ASET needs to be determined for toxic combustion byproducts that may incapacitate by asphyxiation and for thermal exposure from the EMV fires.

1.2 Estimation of Available Safe Egress Time

When assessing the impact of the toxic smoke on the occupants, fractional effective dose (FED) is often used to evaluate the cumulative effect of the toxic products (CO) in the smoke and the occupants increased respiration rate caused by heightened CO_2 concentrations. An occupant's actual FED depends on the escape route, travel speed, and local gas concentration. An FED=0.3 is often used in fire engineering analysis to estimate the time to incapacitation for the general population [18] and is fatal to approximately 11% of the population of the exposed.

When assessing the impact of thermal exposure on the occupants, as with the asphyxiant gas FED, a thermal fractional effective dose FED-T=0.3 is considered an appropriate design value. For further details on the predicting the time to incapacitation from the exposure to heat from fires, the reader should consult the SFPE Handbook of Fire Protection Engineering [19]. Calculations of FED-T follow the procedure outlined in the ISO standard 13571:2012 - *Life-threatening components of fire — Guidelines for the estimation of time to compromised tenability in fires* [20].

1.3 Estimation of Required Safe Egress Time

Although experiments to measure time to evacuate a passenger railcar is beyond the scope of this study, a review of the literature gives indicative times for evacuation of similar commuter passenger railcars. The most relevant studies were conducted by the John A. Volpe National Transportation Systems Center (Volpe Center), in cooperation with the Massachusetts Bay Transportation Authority (MBTA)[21]. In this study, an MBTA commuter passenger railcar with 84 volunteer passengers was evacuated to a level platform which would be expected to give a similar evacuation time for the occupants to egress to an adjacent railcar. In this study, it took 1 min and 41 s to evacuate the train. This time should be considered optimistic because it does not account for:

- Time to become aware of the fire
- Decision time
- No allowance to gather other family members
- No time to gather personal belongings
- No other pretravel activity times
- No time to open an unfamiliar door
- No time to account for walking through the passage between railcars
- No congestion in the adjacent railcar for movement of the passengers egressing into the aisleway.
- Limitation in movement speed due to waning visibility in smokey conditions

If the passengers cannot evacuate to the adjacent railcar and instead, must exit to the right of way (ROW) the time required is much longer. In the Volpe Center study they also included the exit to the ROW using 15 volunteers in a train evacuation. When the results were scaled up to 84 passengers, it took 4 min and 14 s to evacuate the train, with no accounting for the pretravel activity time nor the time to stop the train.

2 Experimental Description

The passenger railcar used in this study was a single level intercity commuter railcar. Figure 1 is a photograph of the railcar interior space, showing the passenger seats and overhead storage area. The photo was taken at the endpoint of the railcar, from the fires area of origin (AoO). The railcar had 72 upholstered seats and one wheelchair parking space. There were 4 doors (2 on each side) that egressed to right-of-way (i.e. ground/track level) and 2 internal doors (1 at each end) for railcar-to-railcar movement. The overall dimensions of the railcar was 26.0 m (85’-4”) in length, 3.2 m (10’-6”) wide and 3.9 m (12’-8”) high. The finished floor level was 1.33 m (52.25”) above ground/track level. The floor plan for the railcar can be seen in Figure 2.

Figure 1 - Photograph of the railcar interior showing the seating configuration and overhead storage area.

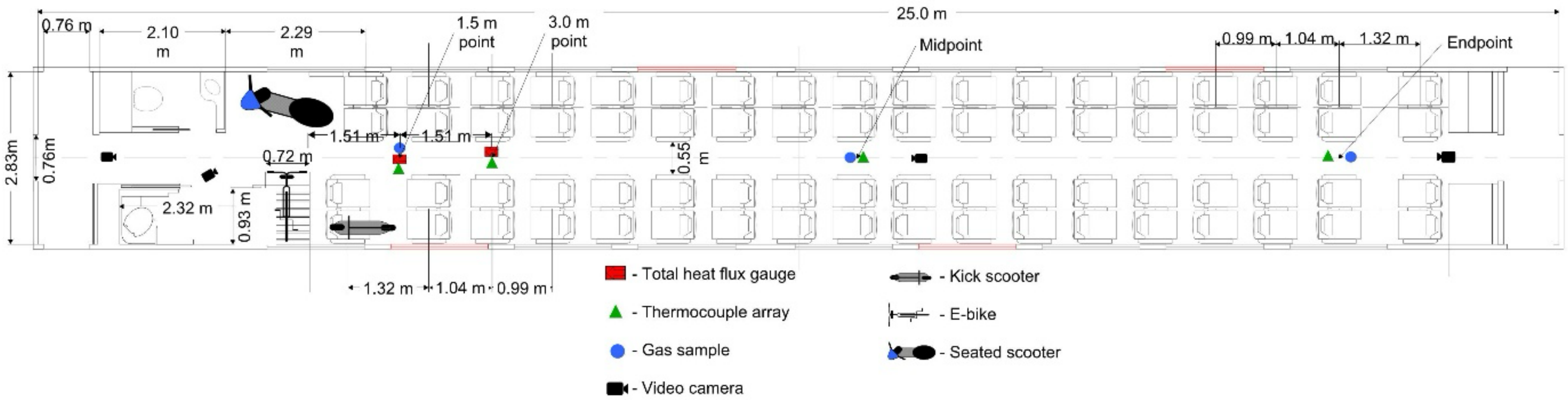

Figure 2 - Floorplan of passenger railcar showing instrumentation layout and locations of EMV used in these experiments.

Figure 3 - Photograph of the standing e-scooter (left), e-bicycle (center) and seated e-scooters (right), in situ just prior to starting ignition.

2.1 Electric Mobility Vehicle Locations

The vehicle position in each experiment were decided based on a review of places most likely to be used by passengers given the different vehicle sizes, locations available within the railcar, and general behavior of passengers to keep near to their possessions. Vehicle locations are shown in Figure 2 & Figure 3. The e-scooter with a fold down handlebar was placed in the overhead luggage area, though this vehicle could potentially also fit under the seats. The e-bike was hung by the rear wheel on a hook in a convertible luggage rack adjacent to the rest room. The front wheel was removed to enable the bike to fit the storage area. This hook can be seen on the right side of Figure 4. The seated scooter was parked in the wheelchair parking area at the end of the railcar. Seated e-scooters were placed in the only physical space where they would fit and leave open aisle space.

2.2 Instrumentation

The railcar was instrumented to measure gas temperatures, pressure, total heat fluxes, and gas species (O_2, CO_2, and CO) concentrations. Figure 2 shows the instrumentation layout used during these experiments. The instrumentation layout was the same for all experiments. Gas temperatures were measured with 1.25mm (0.05 in.) bare-bead, Chromel-Alumel (type K) thermocouples (TCs). Small-diameter TCs were used during these experiments to limit the impact of radiative heating and cooling. The total expanded uncertainty associated with the temperature measurements from these experiments was estimated to be ± 15%, as reported by researchers at NIST [22, 23].

Four total heat flux gauges were installed near the fire along the aisle at the 1.5 m (5 ft) and 3.0 m (10 ft) points, see Figure 2. Two gauges were installed at 0.91m (4 ft) and 1.51 m (5 ft) above the floor. The gauges were oriented horizontally in the plane of aisle. Total heat flux measurements were made with water-cooled Schmidt-Boelter gauges. Results from an international study on total heat flux gauge calibration and response demonstrated that the uncertainty of a Schmidt-Boelter gauge is typically ± 8% [24].

Six gas concentration sampling ports were installed at 3 different distances from the EMV down the aisle. The locations were near the EMV, the center, and the endpoint of the railcar. The sampling ports were installed at 0.91m (3 ft) and 1.51 m (5 ft) above the floor level to represent sitting and standing heights, shown in Figure 2. Gas samples were analyzed using oxygen (paramagnetic alternating pressure) analyzer and a combination carbon monoxide/carbon dioxide (non-dispersive infrared) analyzer. The gas sampling instruments used throughout the series of experiments have demonstrated a relative expanded uncertainty of ± 1% when compared to span gas volume fractions [25]. Given the non-uniformities and movement of the fire gas environment and the limited set of sampling points in these experiments, an estimated uncertainty of ± 12 % was applied [26].

All experiments were recorded with 4K resolution video cameras at 1.5 m (5 ft) and at floor level. Cameras were positioned at either end of the railcar and at the midpoint to enable qualitative assessment of visibility conditions during fire development. Cameras were also placed near each vehicle to monitor battery smoke release behavior closely during each experiment.

Figure 4 - Photograph of the standing e-scooter installed in the overhead rack with ceramic fiber blanket and cementitious fiber board installed on the ceiling and upper wall.

3 Results

The results from this study are presented as critical times in the fire timeline as shown in Table 1 and Table 2. Time zero starts when battery gas is first seen venting from the e-vehicle battery.

In Table 1, the second column from left gives the time of ignition of the battery gases that ranged from 2 s to 1 min and 30 s. The broad range in the times from onset of battery gas venting to ignition of the battery gases was typical for fires starting in LiB powered e-vehicles as there are many variables involved in thermal runaway, the ensuing thermal runaway propagation, and the ignition process.

Columns 3 and 4 give the approximate time that smoke first reached the midpoint and endpoint of the railcar based on video observations. This took 19 to 34 s post ignition, demonstrating how quickly the smoke can travel the entire length of the railcar. Before igniting, the initial smoke release not at high temperature and therefore lacked buoyancy to accelerate the smoke down the length of the railcar. Ignition and sustained flaming of the venting battery gases generated higher temperature smoke which dramatically accelerated smoke movement speed.

Columns 5 and 6 are estimates of the time when visibility was lost at the midpoint and endpoint of the railcar based on video observations from the cameras 1.5 m (5 ft) above the floor. They are a qualitative assessment and not a direct measurement. Loss of visibility is considered useful for comparison between tests and provides insight into the visibility conditions that would likely impact egressing occupants during a real fire incident. In all cases, visibility was lost first at the midpoint of the railcar, then the end. Visibility was lost end-to-end in the railcar in a time range post-ignition that spanned 1 min and 49 s (seated e-scooter 1) to 4 min and 6 s (seated e-scooter 2), with a median time of 3 min and 12 seconds. Loss of visibility can have significant psychological and physical effects on the occupants and can be expected to slow evacuation time.

Columns 7 through 9 give the estimated time to incapacitation, calculated from the gas species measurements at the AoO, midpoint and endpoint of the railcar, respectively.

The times presented in Table 1 are based on the time post ignition until FED=0.3. Gas measurements were made at both the 1.5 m and 0.9 m height above the floor which are both given in each of columns, separated by a slash (/). Tenability conditions were compromised by asphyxiant gases at the far end of the railcar in all experiments, though the area near the vehicle and the middle of the railcar remained tenable in the standing e-scooter experiment. Tenability in the entire railcar at a standing elevation was compromised most quickly in the first seated scooter experiment, with FED > 0.3 at 3 minutes and 37 seconds after gas ignition. The slowest time to compromise tenability occurred during the e-bike experiment, where the entire railcar became untenable within 7 minutes and 8 seconds. The median time until compromised tenability at a standing elevation was 4 minutes and 54 seconds.

Table 1 - Summary of significant times (seconds) including ignition, smoke movement, visibility, and to compromised asphyxiant tenability for all four experiments. Times start after thermal runaway was identified.

Vehicle	Ignition of battery gas	Smoke reaches midpoint of railcar	Smoke reaches endpoint of railcar	Visibility lost at midpoint of railcar	Visibility lost at endpoint of railcar	Asphyxiant tenability compromised at AoO (1.5m/0.9m)	Asphyxiant tenability compromised at midpoint (1.5m/0.9m)	Asphyxiant tenability compromised at endpoint (1.5m/0.9m)
Standing e-scooter	7	12	26	153	161	Not reached	Not reached	(279/403)
E-bike	2	10	28	110	231	557/520	445/546	428/586
Seated e-scooter 1	90	95	109	182	199	163/342	262/365	307/394
Seated e-scooter 2	27	38	61	204	273	337/*	327/383	343/402

*Sample line became plugged, making the data unreliable.

In Table 2, each column gives the estimated time to incapacitation due to thermal exposure at 1.5 m (5 ft) and 3 m (10 ft) from the vehicle, the midpoint and the endpoint of the railcar. Tenability conditions were compromised within 3 m (10 ft) of the vehicles by thermal exposure in all experiments except for the e-bike experiment, but thermal exposure did not impact tenability conditions beyond 3 m in any experiments for the 420 seconds measured. Tenability was compromised within 1.5 m (5 ft) of the standing e-scooter within 10 seconds of gas ignition, and within 3 m (10 ft) within 49 seconds. A large fireball that developed when the venting battery gas ignited, providing a significant heat flux to the instrumentation representing the first couple rows of passengers near to the vehicle. Similar thermal exposure likely occurred within 3 m (10 ft) of the seated e-scooters, as they also emitted large flames upon ignition, but those vehicles were located further from the heat flux gauges and thermocouples; The passenger seats shielded/protected the instruments from a line of sight view of much of the flames, so the apparent exposure was less as compared with the standing e-scooter which emitted flames overhead. Flames from the e-bike battery were effectively confined to the luggage rack area, so FED-T never exceeded 0.3. These results demonstrate that passengers and staff that are close to the EMV are at risk severe injury from the thermal radiation of the initial battery gas explosion.

Table 2 – Summary of times (seconds) to compromised thermal tenability for all four experiments.

Vehicle	**Thermal tenability compromised at 1.5 m**	**Thermal tenability compromised at 3.0 m**	**Thermal tenability compromised at midpoint**	**Thermal tenability compromised at endpoint**
Standing e-scooter	17	59	Not reached	Not reached
E-bike	Not reached	Not reached	Not reached	Not reached
Seated e-scooter 1	280	340	Not reached	Not reached
Seated e-scooter 2	200	340	Not reached	Not reached

3.1 Standing E-scooter

For the standing e-scooter experiment, the handlebar was able to be folded down making it possible for the scooter to be placed in the overhead rack at the front of the passenger railcar. Figure 5 shows the standing e-scooter in the overhead rack with the ceiling protection in place. Also visible in Figure 5 is the two heat flux gauge towers, first TC array, and the first gas sampling point. The first heat flux tower has been moved out of location during setup and was moved into place prior to starting the experiment.

During the experiment, multiple video cameras were installed inside the railcar as shown in Figure 2. Postprocessing the experimental videos reveals that the time delay from first visible battery gas to ignition was only 7 s. Figure 5 shows the sequence of 9 video images starting 1 s before ignition of the battery gas cloud. Time from the first visible release of battery gas is shown in the lower right corner of each image with ignition occurring at t=7s. The first image (t=6 s) shows the battery gas cloud just prior to ignition. The next 7 images show the flames extending along the ceiling, away from the e-scooter. The 7 s delay from first visible battery gas from the e-scooter to ignition, gives the occupants in the close proximity to the e-scooter almost no time to react to the hazard. Firefighters entered the railcar from the fire end to extinguish the fire, applying water on the fire, 253 s after battery gas was first ejected from the scooter.

Figure 5 – Video sequence from the standing e-scooter experiment, video sequence starts 1 s before ignition of the battery gas, images are shown at 1s intervals, t=0s is at ignition.

3.2 E-Bike

Figure 6 shows the sequence of 9 video images starting 1 s before ignition of the battery gas cloud. Postprocessing the experimental videos reveals that the time delay from first visible battery gas to ignition was only 1 s. Time from the first visible release of battery gas is shown in the lower right corner of each image. The next 8 images show the flames extending along the ceiling, away from the e-bike. The 1 s delay from first visible battery gas from the e-bike to ignition, gives the occupants in the close proximity to the e-bike no time to react to the hazard. The 1 s delay is not considered to be common and may have reduced the intensity of this fire. Firefighters entered the railcar from the fire end to extinguish the fire, applying water on the fire, 740 s after battery gas was first ejected from the e-bike.

Figure 6 – Video sequence from the e-bike experiment starting 1 s before ignition of the battery gases, images are shown at 1s intervals, t=0s is at ignition.

3.3 Seated E-Scooter 1

Figure 7 shows the sequence of 9 video images starting 1 s before ignition of the battery gas cloud. Postprocessing the experimental videos reveals that the time delay from first visible battery gas to ignition was 90 s. Time from the first visible release of battery gas is shown in the lower right corner of each image. The first image is 1 s before ignition and shows the battery gas cloud around the seated e-scooter and more battery gas collected on the floor. The next 8 images show the fireball and flame receding back to the seated e-scooter forming an established flame around the seat of the scooter. The 90s delay from first visible battery gas to the e-scooter ignition, would give the occupants in the immediate area of the e-scooter time to react to the hazard and evacuate the immediate area of the seated e-scooter. However, the time delay is unpredictable, previous research has shown that this delay can range from 5 s to over 90 s for identical seated e-scooters [27]. Firefighters entered from the fire end of the railcar to extinguish the fire, applying water, 1535 s after battery gas was first discharge from seated e-scooter 1.

Figure 7 – Video sequence for the first seated e-scooter experiment starting 1 s before ignition of the battery runaway gases were visible, images are shown at 1 s intervals, t=90 s at ignition.

3.4 Seated E-Scooter 2

Figure 8 shows the sequence of 9 video images starting 1 s before ignition of the battery gas cloud. Postprocessing the experimental videos reveals that the time delay from first visible battery gas to ignition was 27 s. For this experiment, the ignition of the battery gas was triggered by an electric match. Time from the first visible release of battery gas is shown in the lower right corner of each image. The first image is 1 s before ignition and shows the battery gas cloud around the seated e-scooter. The next 8 images show the fire growth on the seated e-scooter centered over the battery compartment below the seat. Firefighters entered the railcar from the fire end to extinguish the fire, applying water on the fire, 576 s after battery gas was first discharged from the seated e-scooter.

Figure 8 –Video sequence for the seated e-scooter 2 experiment, starting 1 s before ignition of the flammable thermal runaway gases, images are shown at 1s intervals, t=27 s at ignition.

4 Limitations

One passenger railcar was available to conduct the experiments. It was therefore necessary to limit fire spread from the e-vehicles to the interior linings, wall, floor and ceiling linings because the test site, test staff and passenger railcar were available for only four days. Fire spread was limited by placing noncombustible cementitious board over the wall and ceiling surfaces immediately adjacent to the EMV, so that multiple experiments could be conducted using the same instrumentation layout. This can be seen around the scooter in Figure 4. Additionally, fires were suppressed by fire service personnel when the fire size threatened flame extension to the surface finishes of the passenger railcar beyond the noncombustible board, and after gathering enough data to inform tenability analyses. The resulting fires should be considered less severe than the fire that would have continued to spread with the linings unprotected.

5 Conclusions

Fires started by thermal runaway in the battery pack of electric micromobility vehicles that may be carried aboard railcars by passengers can rapidly develop smoke conditions that impede egress and cause incapacitation of passengers by thermal and asphyxiant gas exposures.

Occupants within 3 m (10 ft) of an EMV fire could be incapacitated by thermal exposure from the emitted fireball and fire plume within 20 to 60 seconds based on Thermal Fractional Effective Dose (T-FED) calculations. Occupants are unlikely to detect and respond to an EMV battery thermal runaway until battery gas is seen discharging from the battery. The time between a visible release of battery gas until the ignition of the gas cloud was typically short and there were no other reliable warning signs observed.

Fires initiated by inducing propagating thermal runaway in the different EMV battery packs created untenable conditions at a standing height inside the railcar in a span of 3 minutes and 37 seconds to 7 minutes and 8 seconds after flaming ignition based on asphyxiant gas FED calculations. The median time until compromised tenability was 4 minutes and 54 seconds. The limitations of these experiments suggest ASET may be less than the minimum of 3 minutes and 37 seconds determined from the seated e-scooter experiment. These experiments did not include measurement of required safe egress time (RSET). However previous research demonstrates that RSET should be expected to be no less than 1 minute and 41 seconds under ideal conditions (both railcar exits at level platform) and no less than 4 minutes, and 14 seconds under less-than-ideal conditions (both railcar exits to right of way).

Numerous factors will increase the amount of time required for safe egress. Once the gas cloud ignited, smoke from the EMV fire rapidly spread to the opposite end of the railcar, within approximately 20 to 30 seconds. Visibility was lost end-to-end in the railcar between 1 minute and 48 seconds and 4 minutes and 6 seconds from fire ignition (median 3 minutes and 12 seconds). Other factors include time to become aware of the fire, decision time, gathering family members and personal belonging, other pretravel activities, the need to open an unfamiliar door, movement speed impact by walking through the passage between railcars, congestion in the adjacent railcar(s), and time needed for the train to stop once alerted to the EMV fire. One particularly severe egress handicap could be passenger and staff inability/unwillingness to move past a burning EMV. The most severe condition likely a burning EMV positioned in the last railcar at the single exit available to the adjacent car during train movement.

In addition to observed challenges to occupant tenability, it was observed that the fire-retardant materials of the passenger railcar cannot prevent melting and ignition from EMV fires, based on video and postfire observations. The rapidly developing and intense fires from LiB vehicles fires heated the plastic ceiling surface finish panels well ahead of the flames, beyond the noncombustible board used around the EMVs. This caused plastic ceiling panels to melt and drop, and it caused the ignition of plastic wall materials. Although the seats and surface linings are treated with fire retardants, they will still burn given thermal exposure from a large enough fire source. The e-vehicles used in these experiments are large enough fire sources to overcome the fire-retardant treatment and spread the fire over the interior finish in the railcar. This was the most obvious in the second seated e-scooter test where the fire was allowed more time to spread with the railcar. LiB cells undergoing thermal runaway expelled embers and hot/molten metal that attacked upholstered seating. These hot expulsions may overwhelm fire retardant material protections and present increased risk of fire spread.

6 Considerations for Improved Passenger Safety

Analyses of these experiments have enabled the development of considerations to improve passenger safety through updates to railcar construction, electric micromobility vehicle policy, passenger railroad staff training, and public safety education.

6.1 Modifications to Passenger Railcar Configuration

1. Consider isolating EMVs into a separate compartments from the passengers or separate railcars. Careful consideration should be given to any fire separation and overpressure venting of this space. Such areas would require specific design advice on the required fire resistance and pressure relief for explosion venting (for example, the venting enclosure for batteries built into the Boeing 787 Dreamliner [28]).
2. In areas where EMV are stored for transport, consider lining these areas with noncombustible materials to reduce fire growth.

6.2 EMV Policy

1. Do not put any EMV in the last railcar due to:
    a. Reduced exit capacity to adjacent railcars resulting in longer escape times,
    b. Potential for inability for passengers to egress past the vehicle/fire,
    c. Potential for inability for staff to pass vehicle/fire to assist passengers.
2. Do not allow any EMV to be placed under the seats. Having an intense LiB driven fire under the seats will hasten involvement of seat foam and fabric and contribute to the fire.
3. Consider requiring storage areas (e.g., in luggage racks, in overhead bin) that place devices away from people to prevent rapid thermal injuries in the event of a sudden thermal runaway and fireball.
4. Consider implementing restrictions on maximum EMV battery size to limit potential fire severity.
5. Provide instructive announcements during evacuation including messaging discouraging collection of personal items, etc.
6. Carefully consider policy regarding extinguishment of e-micromobility device fires. It is unlikely that portable extinguishing equipment can extinguish an e-micromobility battery pack fire. It is probable that fire extension to passenger railcar materials can be prevented for smaller personal electronic devices. More information can be found on battery extinguishment here: https://training.fsri.org/course/111/the-science-of-fire-and-explosion-hazards-from-lithium-ion-batteries.
7. Consider a program for inspection and pre-registration of e-vehicles that have been tested by a NRTL to UL 2849 and UL 2271.

6.3 Passenger Railroad Staff Training

1. Provide updated training to passenger railroad staff highlighting:
    a. Rapidity of fire development,
    b. Severity of potential smoke exposures,
    c. Dependency of passenger exposure on egress time,
    d. Potential means of reducing passenger time (e.g., discouraging collection of personal items, consideration of the mobility impaired, etc.)
2. Provide training to staff to assist with recognizing whether devices have been tested by a nationally recognized testing laboratory (NRTL) to UL 2849 and UL 2271.
3. Review guidance for emergency stops with respect to the urgency of reducing passenger evacuation time from the passenger railcar of origin.
4. Evacuation should be started immediately upon signs of thermal runway of an EMV.

6.4 Public Safety Education

Improve passenger awareness of li-ion battery fire hazards, and personal means of reducing those hazards, by providing printed materials from or digitally directing them to educational materials from li-ion battery fire public safety education campaigns such as ULRI's Take C.H.A.R.G.E. (www.batteryfiresafety.org)

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