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Fire and Explosion Hazards for Covered Tunnel Entries/Exits with Heavy Traffic and Long Waiting Time

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Abstract

Tunnel entries/exits with heavy traffic are usually queued up with vehicles for hours. There are proposals to cover those areas to give better views and be able to tackle the pollution from the vehicle queue. However, fire and explosions at those crowded covered tunnel entries/exits (CTE) are very hazardous because of so many vehicles with packed double-deck buses and trucks carrying high amount of combustible goods waiting for long time. The bus interchange stations are full of queuing passengers. The authority must review it thoroughly on such safety issues for occupants trapped inside for hours and fire behaviour. Fire and explosion from vehicles using clean fuel such as liquefied petroleum gas (LPG), hydrogen and lithium-ion battery and even flammable refrigerants with propane would have more challenges.

Further, smoke spread to adjacent buildings is demonstrated to be very hazardous in several big fires in Hong Kong including a ship fire in 2021 and big fires at a construction site and a warehouse in 2023 with hundreds of neighbours to evacuate. This paper alerts the Authority to fire hazards associated with CTE. In-depth fire hazard assessment and additional firefighting schemes for these special task forces are required.

1. Introduction

As addressed by the former Chief Executive of the Hong Kong Special Administrative Region (HKSAR), China, at the Annual Dinner of the Hong Kong Institution of Engineers 2018, green design would be targeted in future development [1]. Green construction projects will need support from the local engineers. This author gave a verbal response [2] while receiving the Gold Medal 2018, emphasizing that there are many fire hazards behind the greens of construction designs [3] which must be addressed properly through variable engineering approaches, not just pure fire science.

There are even green construction proposals for environmental protection by covering busy tunnel entries/exits in dense urban areas, with decorated with attractive finishes including light-emitting diodes in Asia-Oceania regions. New fire and explosion hazards will be encountered inside busy covered tunnel entries/exits (CTE) with heavy traffic in addition to the current ones at the areas adjacent to tunnels such as double-deck bus fires [4-6], electric car fires [7,8] and bus explosions as occurring in Sweden and Mainland. Waiting time for vehicles can be up to hours, much longer than normal tunnel traveling time of several minutes. Crowded CTE areas are difficult to evacuate and rescue.

Putting more people inside CTE as a building should be controlled by more stringent fire codes of the Buildings Department, although it is easier to go through the Highways Department because no big fire disasters were experienced in tunnels and bridges before in Hong Kong. However, there are big problems in firefighting and rescue in the covered spaces, giving more challenges to the first respondents.

Fires due to engine overheating, mechanical and electrical failure would be more common. Many air-conditioned double-deck buses with good thermal insulation envelopes burnt completely within 15 minutes once on fire, as observed twenty years ago [9]. Furthermore, taxis using natural gas and electric cars can also burn. Explosions of flammable clean refrigerants in air-conditioning systems have already been reported [10]. Fire might spread between vehicles to give larger fire size when the CTE is under heavy traffic congestion. Therefore, fire scenario in CTE is potentially hazardous and firefighting is challenging.

Protection against big fires with so many vehicles, occupants and high fire load as heavy goods vehicles (HGV) must be provided adequately in CTE, or not allowing them to go through. However, the detailed nature of fires in CTE is not clearly understood. Big problems would be encountered in firefighting and rescue in enclosed spaces like tunnels, risking lives of our brave first respondents. Special task forces must be well equipped and trained.

2. Additional Fire Hazards Upon Coverage

Upon covering the tunnel entry or exit, there will be more fire hazards to watch for so many vehicles waiting for hours under some traffic jam during rush hours. There will be new scenarios to bring big disasters:

Firstly, burning of HGVs would produce big fires with peak heat release rates of over 200 MW. Burning of HGVs would give a heat release rate over 100 MW [11,12]. Several HGVs burning together during traffic jam would give much more hazardous consequences. Serious fire

hazards inside tunnels or other enclosed areas due to burning HGV have been reported. Several vehicular bridges collapsed while HGVs were burning on them [13,14]. Fire codes for vehicular tunnels have already been updated in some places [11]. Passenger footbridges above highways with burning HGVs might lead to even bigger disasters.

The potential fire hazards of burning HGVs inside CTE can be very serious [12]. The fire resistance of a tunnel is normally studied under some standard temperature-time curves, not yet deduced from burning HGV with 100 MW in heat release rate. The consequence had not been updated in highway fire codes nor fire safety management practices of many places. There are more vehicles using clean fuel, liquefied petroleum gas (LPG), battery or hydrogen [15].

Secondly, explosion from these fuels and clean refrigerants with propane [16] can lead to big fires in some cases to give very hazardous consequences. The prospect of controlling fires in the covered space can be a nightmare for firemen as the scenario is equivalent a fully occupied large carpark with the engines of vehicles. There have been very few in-depth studies on tunnel and large carpark safety under big fire and explosions. Even the detailed nature of the possible fire phenomena in underground or semi-enclosed spaces with big fires is not clearly understood. Nature of the key physical phenomena associated with a big fire in the large enclosed space must be better understood so as to determine appropriate fire safety systems.

Thirdly, using new clean fuel might create more problems. As reported in To et al. [17], short vehicular tunnels with heavy traffic in urban areas of densely populated cities of the Asia-Oceania Region, introduction of vehicles using clean fuel poses new concerns on the fire safety of existing road tunnels. Explosion hazards of an LPG taxi in a section of short vehicular tunnel were studied by using numerical software Flame Acceleration Simulator (FLACS). The scenario of LPG leaking into the concealed space beneath the tunnel floor level of CTE through vents at the road side is simulated. Results on predicted explosion pressure and temperature illustrate that appropriate protection measures should be provided. Existing fire safety codes should be revised by including an explosion scenario of LPG taxis.

Fourthly, tilted CTE would facilitate smoke spreading through openings. Buoyancy would give an acceleration component [18-24] along the slope to drive smoke up. However, there must be openings for ventilation provisions. First respondents can also enter the site through such openings for firefighting and rescue, if have additional equipment. Firemen must undergo more vigorous training on using such openings. This is certainly unfair to them to take much higher risks. Further, people trapped inside buses and cars are difficult to move out inside the enclosed areas with smoke, or even flames.

Some trucks are carrying illegal diesel [25]. These trucks would bring fire hazards while travelling through vehicular tunnels. A truck carrying about 500 liters of untreated diesel oil caught fire just outside a tunnel [15,26] in July 1999. The safety impact on a vehicular tunnel of a fire in an unprotected truck carrying illegal diesel should be watched. Further, an explosion once occurred in a container truck carrying motorcycles [27]. The shock waves generated from the explosion were so strong that glass and even some external finishes in nearby buildings were damaged. As reported in the news, the explosion even hurled hot shards of twisted metals up to the 38th floor of a building (nearly 120 m away) adjacent to the road. Fortunately, the explosion happened on an open highway, before the truck entered a tunnel.

In such covered space as CTE, a proper fire safety management scheme must be worked out. It is very important that adequate fire safety provisions be provided since there might be many crowded vehicles, particularly crowded buses and waiting queues passing through the tunnels. If necessary, all trucks of enclosed structure should be prohibited from using the vehicular tunnels during rush hours. Another possible solution is to inspect every truck of enclosed structure before it enters the tunnel. That was done years ago when the tunnels were first built, but the practice was abandoned later because of the heavy traffic conditions. An alternative solution is for the truck drivers to sign a statement guaranteeing that no dangerous goods were carried. Very heavy penalties would then be imposed on drivers caught doing so.

As experienced in the mini-storage fires [28], there are challenges whether the firefighting actions were appropriate [29,30]. Note that HGV might carry even higher fire load density than a ministorage! This is a very good lesson to learn in possible CTE fires. Further, the tunnel must be isolated from CTE in case of fire to avoid fire and smoke spread to it. This will be discussed in another paper.

There are other non-traditional accidental fire sources:

- Green energy sources such as hydrogen vehicles;
- Clean combustible refrigerants not controlled well;
- Electric vehicle (EV) batteries to give fire and even explosion, particularly the counterfeit batteries [31,32].

All these hazards would be of great threat to firefighters in evacuating people trapped under a roof and rescuing them. New special task forces must be set up with appropriate training, not just on compartment fire attack (CFA) in handling smaller scale fires. They must have additional personal protection equipment. Another important observation from recent big fires is on smoke spread to adjacent buildings, leading to mass evacuation. Those evacuations out

of buildings to open air were smooth. However, evacuation from CTE with huge covered roof areas is much more difficult.

3. Appropriate Firefighting at Crowded CTE

In the big fire in an old industrial building used as mini-warehouse [29], over 120 firefighters and 30 fire engines were deployed to fight against the blaze. Although no occupants were trapped in the fire site, firefighting teams were sent inside the site to take actions. Consequently and unfortunately, a fire officer and a sergeant were killed in the operation. Residents in adjacent buildings had to be evacuated to avoid exposure to smoke.

Many questions were raised in relation to the firefighting strategy, fire command and fire equipment. In particular, a question:

When to send firefighters to a crowded space with a big fire?

Another serious question affecting future firefighting actions was raised by experienced fire officers personally to the author in a Fire Forum held in Taiwan in 2016 [33] with the Society of Fire Protection Engineers, Asia-Oceania Chapters taking a leading role:

Under what conditions should firefighters be sent to a big fire site, particularly when there are so many occupants trapped inside the crowded space, in future?

The case of sending firefighters into the mini-warehouse fire above [29] could be a warning to the potential fire hazards and subsequent firefighting strategy in CTEs. Controlling fires in semi-enclosed spaces like CTE can be a nightmare for firemen as experienced in fighting against big fires in vehicular tunnels before. There are very few in-depth studies on tunnel safety under big fires and explosions involving crowded double-deck buses and HGVs. The above scenario must be considered extremely carefully before sending first respondents to the fire site inside any enclosed spaces with many vehicles queuing up.

There are many fire scenarios not yet encountered before, particularly when a roof is built above the CTE with heavy traffic.

The biggest challenge is sending the firefighters [29] to the fire site appropriately under concerns as raised above. A big fire might trap thousands of people travelling on double-deck buses queuing inside a crowded CTE with heavy traffic.

The nature of the key physical phenomena associated with a big fire in the large enclosed space inside CTE must be better understood so as to determine appropriate fire safety systems and firefighting strategy. Based on the case of mini-warehouse fire disaster, the operation of mechanical ventilation systems provided in the CTE, or positive pressure ventilation (PPV) by firefighters, once a fire occurs is a very important problem for research. In addition, whether fire protection coating to give 2-hour fire resistance period under a standard temperature-time curve is adequate to stand against big HGV fires [4,11,12] should be evaluated. Fire safety engineers can then design the appropriate fire safety provisions for the CTE.

A small tunnel fire occurred on 19 December 2022 [34]. As mentioned [35,36], portable smoke extraction fan was used by firefighters to take smoke out. Smoke was pushed out either by putting the PPV at outlet (e.g. windows) to suck the smoke out, or putting at the inlet (e.g. door). The PPV with water suppression or protections as water shielding is water turbine driven positive pressure ventilation blower. Applying water is something additional, and equipped at the Fire Department of New Taipei City Government. The long Suet Shan tunnel is under them [33] as visited in that conference.

Two types of PPV were used, one driven by water hose and one driven by battery. PPV was put at the entries to push fresh air into the fire compartment so that smoke will go out through outlets.

For the use of PPV inside tunnel, there is only one to two PPV in Reserved Heavy Pump. It is difficult to clear smoke in very long tunnels since the power of both types of PPVs have limit. CTE is much more hazardous because of big covered areas and high occupant loading. PPV might not be so effective as ventilation by natural means [36].

4. Green Rooftop

The roof of the CTE may be covered with plants to give a much more hazardous environment [37-75]. Safety is a deep concern as experienced several years ago at a local university [76-78]. Even too much rain might overload the green roof above a hall and the roof collapsed on 20 May 2016 [76]. Two staff members were mildly injured and one was shocked in the incident.

The government Buildings Department immediately started an investigation to assess the structural safety of the roof structure. The final report of the investigation [77] identified three overloading factors due to screeding of the roof structure: layering of the green cover, and localized ponding on the green cover. The university reported that the design, construction and maintenance of the (original) structural roof are unlikely to be the key contributing

factors. Anyway, the green roof may be an important factor contributing to the collapse of the roof. The senior management must be responsible.

Fire safety aspects of green rooftop have not been adequately assessed. Lack of maintenance and inadequate watering systems (due to arid weather) will cause drying of plants, creating substantial fire risk. Dry plants may be easily ignited and intensify fire spread [50]. The moisture content (MC) of a plant is one of the most critical factors affecting its ignitability. Plants under radiative heat flux at different MCs were studied before by cone calorimeter [50]. Ignition, heat release, and gaseous emissions were studied under radiative heat flux. When the plants were fresh and green, no ignition was observed for all three species. Some plant species started to ignite once MC was lower under higher heat flux of 50 kW m^{-2}. Thermal risk and smoke toxicity hazard also increased at lower MC. These findings demonstrate the importance of maintaining healthy live plants to ensure fire safety.

5. Smoke Hazard to Adjacent Residential Areas

Smoke generated by big fires in tunnels would affect air quality for a long time, say a duration of 1 or 2 days as experienced in big city fires. Three such big fires occurred within two weeks in 2021 on a ship, a yacht and a waste collection station [79-85]; two in 2023 [82,83,86-91]. All these illustrated that vast amount of smoke would affect citizens around the harbour area in Hong Kong. Mass evacuation was needed in one incident [82,83], but easier to handle under open space.

The big fire burning a small ship [81] affected over 0.2 million people living on the southwestern side of the harbour for a long time. That fire had small burning areas but huge volume of smoke emitted with unknown toxicity. Other fires emitting huge amount of smoke in dense urban area [83-85] have similar consequences. The toxicity potency is unknown because only gas species in limited number of monitoring stations were recorded by the government Environmental Protection Department.

A fire broke out at a construction site of a 48-storey tall building in downtown at midnight on 2 March 2023 as reported [82,83]. The blaze started on the roof of the site and was upgraded to No. 4 alarm about two hours later, then extinguished by the firefighters in the morning on 3 March 2023, burning for 9 hours. Many explosion noises were heard. The scaffolding around the building was engulfed in flame. Fire debris from the site were seen flying out. Huge amount of smoke spread to affect the adjacent areas and buildings. Among the five buildings affected, the rooftops of two caught fire. There were no casualties with only two injuries. It was reported by the Hong Kong Fire Services Department that the fire spread quickly and affected some

nearby buildings because of strong wind and dry weather. Large amount of combustible construction materials stored were burnt for 9 hours. The construction site was only equipped with temporary fire protection and firefighting systems. The height of the building and a large fire area of 60 m x 80 m also made firefighting difficult. The cause of the fire is still under investigation. Smoke spread to the downtown is the issue, though not so much as in the ship fire before [37].

A No. 3 alarm blaze broke out in a frozen warehouse [82,83] in downtown on 24 March 2023 afternoon. The fire area was 100 m x 80 m. Huge volume of black smoke was produced from the fire location and spread to nearby areas. About 3600 people reported strong smell of burning plastics were evacuated in the affected area. Some of them were transferred to temporary shelter areas. Two workers and two firemen were sent for hospitalization. The fire was under control and finally extinguished after 7 hours. Initial investigation revealed that the fire was caused by workers cutting materials inside the warehouse. This led to the failure of normal operation of fire pump, sprinkler system and the water drencher system. The sparks generated in the cutting process ignited combustible materials nearby and fire broke out.

Points to consider on all these fires emitting huge amount of smoke are:

- Difficult to put in fire service installations in sites. Should allocate more safety staff to watch.
- Fire safety management needed, but too high the cost in comparing with punishment amount, then who cares?
- A safety plan has to be worked out:
  - Maintenance plan, at least watching fire load density and dangerous goods.
  - Staff training plan, more safety guards?
  - Fire action plan, water provision by pumps as firefighting helicopter can only supply limited water in these two fires 2023.
  - Fire prevention plan, appears difficult in construction sites?

Anyway, budget is the problem. Firefighting appears to be good and the fire safety management should be improved. As in handling forest fire suggested by the former US President Trump [88-90], appropriate management is the key. Wind action on smoke spread can be studied by computational fluid dynamics (CFD) [92-111].

6. Responsibility of Top Management

There are serious safety problems as observed in many building fires [112]. Firstly, many active fire systems were not working. Secondly, high amount of plastics materials were burnt to give toxic smoke and a hazardous environment. It is difficult for old buildings to match up with new requirements as revealed in the investigation of the big Garlety Building fires 1996 [113]. Upgrading of old buildings to meet new fire safety requirements was slow [114]. There is no sufficient space to accommodate sprinklers, even the structural loading design of old buildings in Hong Kong has a high safety factor. As cost is always the main concern, penalty is a key point to consider. Government actions on having tighter occupational safety and health control and penalty were raised at the Legislative Council recently [115].

In upgrading hardware fire safety of old industrial buildings in Hong Kong [113], over 280,000 letters were issued to owners, as disclosed [114]. Adding sprinklers is not practical as demonstrated for over 20 years. Further, sprinkler might give adverse effects if put in inappropriate places. The sprinkler approach might not be an ideal option for most of the old buildings. It is urgent to implement modernized Fire Safety Management with promotion of safety culture, and raising penalty too.

The top management is supposed to be responsible for safety. The penalty associated with general safety and Occupational Safety and Health Ordinance in Hong Kong was very low before. For instance, penalty for the tower crane accident in 2007 was only HK$36,000 (US$4,500) [115,116]. Consequently, it is very difficult to convince the top management to invest in safety. This led to serious criticisms and in response the Safety & Health Circular No. 10/2009 Alert on Safe Handling of Tower-Crane Lifting Operations was issued by the government in July 2009 [117,118]. The situation changed a little bit [119-121], though the fine was still low only at HK$10 million maximum.

It is very difficult to convince senior management to spend resources to implement safety under this culture. Increasing penalty might alert more responsible on safety. The safety culture seems to be changing recently. The recent incidents of tower crane collapse [122,123] and the falling down of a huge light-emitting diodes (LED) screen in a concert in 2022 [124] are more serious cases, and the latter is even a criminal case. Further, two medical doctors were charged in 2022 against criminal offense on a case in 2017 [125]. Safety aspects should be watched more carefully by responsible persons and top management of the organizations. Demand on recruiting more safety experts with practical experience is expected to be higher.

At the moment, safety management cost is very expensive and much higher than punishment of a few thousand dollars. The proposal of introducing safety culture in handling public safety [31,126-130] on top of safety technology and safety management should be considered. Tighter monitoring and punishment might be needed if there is any violation of safety codes [131-139].

The senior management preparing to cover the tunnel entry and exit must be responsible for shouldering the possible consequences [128] as listed above on fire and explosion.

Further, covering the CTE with green is hazardous. Overloading the green roof by moisture as in a local collapse [76] several years ago is a good lesson to learn. The senior top management must be responsible as in the stage case [124] to avoid having such incidents again. Apart from other hazards concerning public safety leading to big disasters, protection against accidental big fire and explosion is a big problem to handle. Similar to other green architectural features, there are potential fire hazards on those sustainable designs as experienced before for over 20 years [28-30,124]. Note that there had been arson fire [141], terrorist attack fire, natural disaster fire and explosion from clean fuel such as LPG taxi [142] and even clean refrigerants with propane [16]. In-depth fire hazard assessment of the proposed claimed sustainable design must be carried out. The senior management must be responsible.

Another example of unsatisfactory control on fire safety management is the big fire broke out in a hospital in Beijing on 18 April 2023 [143]. Firefighters put out the fire in about an hour after arrival and evacuated about 70 patients. However, 29 were killed in the fire, most of them being elderlies with limited mobility. Twelve management staff including the director of the hospital have been detained by police. This might be a good approach for the HKSAR to follow as proposed [128]. Top management should shoulder responsibility as in Mainland.

Taking the recent big construction site fire on 2 March 2023 as an example, such fire and impact to adjacent areas under strong wind can be avoided, if adequate budget was spent on recruiting guards on safety management. Big boss might recruit tens of security guards surrounding them while outside. Why not spend some more resources on recruiting guards to watch better in construction sites without adequate fire safety provisions? Collapse of the green roof of a university multi-purpose hall without further tracing on the responsibility is a question. Covering the top by green [76-78] is another concern. There might be challenges [144-147]. The top management must be responsible for all hazards as in Mainland.

Nobody will care about safety issues if there is only low penalty such as in the tower crane incident 2007 with a fine of only HK$ 36,000. In other words, costing of consequence should be higher. The maximum fine of HK$10 million is still low?

7. Conclusions

There are many fire hazards behind the greens of all the proposed designs, and must be addressed properly. Points to watch are new fire and explosion sources; huge amount of people trapped in CTE; smoke affecting others; difficulties in firefighting and rescue. Otherwise, serious fire hazards would happen. The firefighting scheme has to be enhanced on handling CTE fires and rescue. Special task forces have to be set up with appropriate fire commands to avoid sacrificing staff.

Responsibility of top management must be the key part in safety culture. Lesson learnt from green roof collapse at a university should be a warning signal, alerting top management to safety responsibility. Implementing safety culture schemes as in Mainland in laying higher responsibility to top management might work. They must be more responsible by themselves and to shoulder responsibility as in the incident in Beijing, not getting some appropriate persons to handle intelligently with the Authority.

As a conclusion, the authority handling fire safety must review such proposals vigorously. Additionally, firefighting schemes under hazardous fire environment have to be drafted to handle cases with huge number of people trapped under a big roof. Fire command is a key issue, and special task forces have to be set up in addressing questions raised above. Fire safety management must be implemented under top management responsibilities. Disasters from the ministorage fires must be avoided. This is only the first publication of an extensive study on fire hazards of green buildings. More articles will be published.

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