Safety Issues in Converting the Downtown Seattle Transit Tunnel

To Joint Bus/Light Rail Operations

Hamid Qaasim, Program Manager of System Safety & Quality Assurance, - Sound Transit

Abstract

Seattle's Link Light Rail system plans to use an existing Downtown Seattle Transit Tunnel (DSTT) as part of its Initial Segment, planned for operation in 2009. Adding light rail into this existing bus tunnel required joint operational planning to maximize passenger volume without service degradation. To avoid increasing bus volumes on the surface streets of downtown for as long as possible, the Sound Transit Board directed the Light Rail staff to complete the necessary design to convert the DSTT to a configuration in which both buses and the Link Light Rail can operate jointly. The 1.3-mile DSTT, which commenced operation in 1990, includes five side platform stations, three of which are fully enclosed subway stations. The buses that are currently using the tunnel are dual mode 60' articulated trolley buses, powered by 750vdc and diesel. The planned light rail vehicle will use 1500 vdc overhead catenary. This will be the first such joint operation of this type in North America. It is intended that conversion construction will start in 2007 and be complete in 2009. Several safety issues required proposed resolution before this decision could be implemented. These run the spectrum from operational control, tunnel traffic control, shared space for dissimilar power systems, fire suppression systems, and ventilation systems. This paper reviews these safety issues, proposed resolutions, and potential hazards.

Background

This paper provides a discussion of the safety issues involved with converting an existing trolley-bus transit tunnel in Seattle Washington to joint bus/rail use. Although the original design of the Downtown Seattle Transit Tunnel (DSTT) envisioned joint bus/rail use, it has operated as a trolley-bus tunnel since it's opening in 1990. Currently King County Metro and Sound Transit buses operate 24 bus routes with 70 buses an hour in one direction through the DSTT during the peak period. Sound Transit is currently in final design for the Link Light Rail System, which will add two-car light rail service at 6-minute headways through the DSTT during the peak period. The Link system will construct an initial 14-mile segment starting in the north end of the DSTT and continuing south through Seattle and into the City of Tukwila to approximately one mile north of the Seatac Airport, in the City of Seatac. This paper discusses the key safety issues that were examined as part of the decision to operate four joint bus/rail subway stations. Joint use is anticipated for only the initial years of the Link operation, until either Link service levels grow to a point that requires sole use of the tunnel or the light rail line extensions enable Link to replace express bus service through the tunnel. However, for risk assessment purposes, the useful life of the DSTT System is considered to be 40 years.

The Downtown Seattle Transit Tunnel (DSTT) is part of an existing transit system currently used by dual mode King County Metro and Sound Transit buses. These buses operate on diesel engines while on surface streets and electrical motors in the transit tunnel. The DSTT consists of five stations, with the stations at both the north and south portals as open-cut stations, where the buses switch power modes between diesel and electric. The three intermediate stations are all in the transit tunnel, where the buses operate on electrical trolley power. The existing tunnel alignment starts at the South portals at the north end of the International District Station. The alignment continues north in a twin bore tunnel to Pioneer Square Station. The next segment continues north to University Street Station. Following University Street Station, the alignment continues to Westlake Station. Finally, the alignment continues through the north portal to Convention Place Station. The total length of the DSTT alignment is approximately 6,868 feet.

Pioneer Square, University Street and Westlake Stations are underground stations with ventilation shafts at both ends. International District and Convention Place Stations are open cut stations. With the exception of Convention Place, the stations are approximately 380 feet long. The northernmost station at Convention Place has four side platforms, one long platform for northbound buses and three shorter ones for southbound buses. The other four stations have 2-380 foot long side platforms, one for northbound and one for southbound. Staging areas are provided for buses entering the DSTT at International District and Convention Place Stations. Buses enter these staging areas under diesel power and convert to 600–750 vdc overhead electrical trolley power before entering the tunnel sections. The staging areas at each end have a combination of traffic lanes that exit to local street service and express lane ramps that exit to the freeways for express bus service.

The existing safety systems of the DSTT were designed in the 1980s in accordance with NFPA 130, Fixed Guideway Transit Systems. As such, they include Fire and

Emergency Management Panels, fire suppression systems, cross passages, emergency telephones, fire phones, emergency ventilation, SCADA, and other associated systems. Joint-use of these subway stations presents new potential hazards and requirements to bring the 11 year-old structure up to current codes based on major modifications to facilities and use. This meant that specific safety analysis were required for collision avoidance (traffic control), fire suppression, ventilation, and evacuation as key safety issues. This effort required close collaboration of the two transit agencies (King County Metro and Sound Transit), the Seattle Fire Department, and the Seattle Department of Construction and Land Use (DCLU). The Sound Transit Link project design team worked closely with King County Metro to understand the current operations of the DSTT, identify historical safety data for analysis, identify design solutions to potential safety hazards, and produce a preliminary hazard analysis acceptable to all parties.

Risk Assessment of Bus Fire in the DSTT

The following potential hazards are limited to a short list of key hazardous conditions, which are at the core of this discussion. At the top of the list are, bus fires in the DSTT, and bus collisions with another vehicle (bus or train) in the DSTT. These bus fire and collision hazards were quantified in terms of frequency of occurrence and severity, and a risk index was calculated to determine risk acceptability by Sound Transit in accordance with established risk acceptance matrix contained in the Link Light Rail System Safety Program Plan.

Worst-case safety hazards were evaluated first to ensure that we could mitigate any concerns. It became clear that since the trains were electrically powered and the buses would carry diesel fuel, the hazard potential from a diesel fire was considered the worst case. We used a combination of coach fire incident reports from the Seattle Fire Department along with King County Metro Safety & Operations reports of coach fires to develop predicted mean time between reported fire incidents in miles and hours.

Since this will be the first series of bus/rail joint-use subway stations in the U. S., an original preliminary hazard analysis was required to compute frequencies and probabilities of events. Under the auspices of the Link Fire/Life Safety Committee, a Preliminary Hazard Analysis was performed according to the FTA Hazard Analysis Guidelines for Transit Projects. This preliminary hazard analysis provided qualitative, and quantitative risk assessment of the frequency and probability of the potential incremental safety hazards presented by joint use.

This information was distributed for review and acceptance to the Authority Having Jurisdiction, for their concurrence on resolution of potential safety issues. To conduct this study, related statistics were reviewed from the FTA Section 15 Annual Report submitted by King County Metro, maintenance records of Metro, Metro safety department data, City of Seattle Fire Department incident data, and bus specifications for the Breda buses. Fleet statistics were evaluated for miles, operating hours, collisions, and fires. These statistics were evaluated based upon apportionment of the data from the total Metro fleet vs. the specific fleet of dual-mode buses used in the DSTT. Multiple probabilities were determined and compared for internal consistency. Using a potential electrical fire in a tunnel as a benchmark, the potential hazard risk assessments of the DSTT were compared for external consistency. Then, based upon existing Seattle tunnels, current Seattle codes, and current national standards for fire protection, risk reduction mitigation measures were proposed. Emergency ventilation scenarios were developed and Computational Fluid Dynamics (CFD) and SES computer simulation models were run to verify adequate air volume and appropriate temperature. Tunnel traffic control was evaluated for safety and design basis were developed to assure adequate spacing between buses and trains.

The Link Light Rail Fire/Life Safety Committee uses this common sense, plain language approach to hazard analysis and risk assessment in its work with the Authorities Having Jurisdiction, to gain their concurrence with the appropriateness of the more detailed, supporting technical analysis. Verification of conformance to design criteria and CCIL mitigations during design and construction will be performed as part of the Safety Certification process to ensure that we have full compliance with all applicable codes and system safety mitigation measures.

To determine the probability and frequency of a bus fire, statistical data on volume of bus operations in the period 1990-2000, along with projections for year 2010 was used to develop apportionment ratios to calculate the frequency of occurrence within the portion of the fleet dedicated to use in the tunnel. Data was collected on accidents, fire department responses to coaches, and operations reports. Statistics from FTA Section 15 reports were used to provide quality control validation of the data and subsequent calculations.

The Preliminary Hazard Analysis was performed on the worst-case hazard of a diesel bus on fire in the tunnel. That analysis determined that our initial risk assessment on frequency and probability of occurrence for the worst credible mishap was IID. The mean-time-between-bus-fires (in years) in the DSTT during Joint Operations in 2010 was projected to be 15.53 years. In risk assessment terms, the frequency of "once every 15.53 years" for the entire DSTT is classified as "D-Remote, unlikely to occur, but can reasonably be expected to occur. Without mitigation, there is a potential for severe injury, major system damage, or prolonged service disruption. The consequences are similar to those of a minor electrical short that could produce an electrical fire. Operating hours were computed from the bus schedules and it was determined that there would be approximately 7,000 DSTT joint bus/rail operating hours per year. The probability of occurrence is in the range from once in 100,000 hours to once in 100,000,000 hours for an individual item and once in 5 years to once in 200 years for a fleet. By current FTA standards this risk assessment requires concurrence by the Authority Having Jurisdiction for the safety measures proposed as mitigation. A sensitivity analysis was performed to demonstrate that although the exact numerical calculations and the incident data may vary widely, the initial Hazard Risk Index generally remains in this same category. It must be emphasized here that although we have made a statistical projection of potential for a bus fire, there have been no reported bus fires in the 11 years of DSTT operation. The results of these hazard analyses are reported in the preliminary hazard analysis report and the mitigations were incorporated into the Critical and Catastrophic Items List (CCIL) for tracking of design and construction mitigation.

Fire incidents experienced from other sectors of the fleet provided empirical evidence of the presence of ignition sources and flammable material on the buses used in the DSTT fleet. Any fire with sufficient time to develop and if not suppressed immediately, has the potential to escalate into a catastrophic fire and potentially result in fatality. Using the worst credible case, PHA methodology, even a small electrical fire on a wiring harness, left unabated, could potentially escalate to a serious level. Such small electrical fires on buses are also noted to carry the same severity of risk, IID. We used this information to analyze the factors involved in a bus fire to ensure that we provided adequate controls that would minimize the possibility of such a fire. A complex series of events would need to occur between the instant of first ignition source in the presence of sufficient fuel load to escalate into a catastrophic bus fire event resulting in "disabled bus in the tunnel requiring evacuation in the tunnel". That series of events would necessarily include,

- A car borne ignition source with sufficient fuel to ignite
- Sufficient fuel to sustain the fire and not self extinguish
- Fire in an undetected location, fire not visible to the bus operator
- Fire is not suppressed/ extinguished by carborne automatic or manual fire suppression equipment
- The fire location, type and magnitude disables the bus motive power
- Type and magnitude of fire poses hazard to passengers
- The bus is disabled in the tunnel and requires evacuation.

Fire Suppression

Although road tunnels have fire suppression systems of sprinklers or foam, light and heavy rail transit tunnels typically do not. Because electric trains do not carry gasoline or diesel fuel, tunnel bores for these types of systems usually have standpipes, but no sprinklers. The existing bus tunnel has a deluge system, and for this joint use application the fire and building departments must consider the most severe case of a bus fire with diesel fuel. Therefore we were required to replace in kind or upgrade the existing tunnel deluge system.

The City of Seattle has two nearby transit tunnels, both of which have installed foam suppression according to the City of Seattle Fire Department to mitigate similar concerns, and be code compliant. We used the foam fire suppression as our high water mark for cost estimating to ensure that the scope and budget would meet the approval of the Authority Having Jurisdiction. The existing fleet of dual mode coaches will soon be ready for replacement, and plans are underway for a procurement contract for new coaches. Reviewing the state of the art for diesel coaches revealed that onboard fire suppression, and fire hardening is readily available on the types of dual power buses planned for the tunnel fleet replacement. As the procurement contracts are developed for replacement buses, those buses will be fire hardened and have on-board fire suppression systems in the engine compartments.

Fire hardened vehicle passenger compartment, engine compartment fire suppression system, fire hardened diesel fuel tank are some of the primary risk mitigation measures included in the bus procurement. The tunnel fire suppression system will react at the early stages of a diesel fire and suppress it before a fire hardened bus could become fully involved in the fire. The main objectives of the fire suppression system is to lower the temperature of the fire-hardened vehicle shell by engulfing it in a sheet of water. Consideration was given to selection of extinguishing agents to minimizing slipping hazards and visibility hazards in the tunnel for evacuating passengers.

The existing tunnel fire suppression system consists of a deluge system with automatic and manual deluge valves activated by a linear heat detector strip. The deluge system is divided into 150-foot long zones. The fire department and building department required an upgrade to current codes for the tunnel conversion. They indicated that they wanted a foam fire suppression system similar to the ones in the two nearby road tunnels. Foam fire suppression along both sides of each tunnel bore was evaluated as the most expensive option, and single line sprinklers along the top center of the tunnel were evaluated as the least expensive. Upon further design review, it determined that a dual header sprinkler system would be installed in each bore. This plan results in four parallel headers with fitted sprinkler heads. Value engineering was performed on this design concept and it was determined that, by installing a specialty type of directional sprinkler head, the water could be directed from an angle onto the near side of a bus and over the top to the far side, thereby reducing the number of headers and sprinkler heads in half. Current plans are for a single header with twin, directional sprinkler heads. The single header, twin head sprinkler system can be installed for several million dollars less than the foam suppression system, since the savings over a dual header system alone are approximately 3 million dollars.

Traffic Control

The safety hazards arising from bus/ rail merge or conflict points along the alignment between WLS and CPS have been consolidated to address the worst-case scenario, which was from the northern terminus at convention Place Station (CPS). The potential energy of a fully loaded light rail train is significantly higher that of a bus, and since the buses have fuel tanks near the rear; it was imperative that safety practices be developed to protect against collision. Specific safety rules were developed for input into the computer simulation program that was used to model the bus/rail movements and headways in the tunnel. The Link System Safety Department analyzed the operating plans, bus schedules, and existing safety features of the tunnel to determine recommendations that would minimize the potential for a collision. These recommendations were directed at controlling separation between buses and trains, and controlling traffic movements within the tunnel. With a current throughput of over one bus per minute in one direction at peak, adding the light rail alone would require a delicate balance of passenger distribution. Adding restrictions for separation of buses and trains required many intense conversations between operations, systems engineering, planning, and system safety to determine the best balance. Once this balance was determined, the resultant safety rules were used as input into the computer program that ran the simulation model of bus and train movements. Development of these rules was a firm commitment by all of the organizations to Safety First. These safety rules were developed to guide the basis of design;

- A Link train may not enter a tunnel section until the bus or train ahead has exited that section.
- A platoon of buses will not be dispatched into a tunnel section until the train ahead has exited that section.
- A Link train may not enter a station until the train or bus ahead has exited the station.
- A platoon of buses may not enter a station occupied by a train. However, with special authorization from OCC, a bus may enter a station with disabled train at the platform, and use the bypass lane.
- The maximum number of buses in a platoon allowed in a section at one time is 5, consistent with the number of buses used in the tunnel emergency ventilation capacity simulation conducted separately.

Track circuits will be used to detect and identify the location of light rail vehicles. This is the most reliable and failsafe method of train detection. Bus detection would be via an on-board radio tag to a wayside receiver that can only detect the onboard tag when located at the specified check-in and / or checkout location. The receiver would forward to the vital check-in / checkout logic both the bus serial number and the route number for use in the logic. To assure the bus radio tag is functioning, the system would display the bus number prior to the first bus control signal for each direction. A bus operator would need to report any failure to see his/her number before proceeding.

It is imperative that both train and bus movements be regulated by an integrated signal system. Each vehicle will be able to maintain safe separation in accordance with the operating rules. A potential for human factor errors, bus malfunction, excessive queuing, congestion, and the high frequency of conflicting moves at crossing/merging and staging areas at IDS and CPS/ Pine Street Tunnel increase the risk of buses fouling the Link tracks when the train is approaching. While the train operates on cab signal at reduced speed in the approach to merge points at IDS and CPS/ Pine Street Tunnel, the primary reliance is that buses approaching merge and crossing points will obey the grade crossing flasher. The integrated signal system will provide warnings to buses and trains that a conflicting movement is ahead. The buses will receive a red signal that a train is in the merge zone ahead and the trains will receive a horizontal amber bar to warn that a bus is fouling the tracks ahead in the merge zone.

Ventilation

Emergency operations generally result from a malfunction of a vehicle (train or tunnel bus). The most serious is a vehicle fire with mechanical problems, thus disabling the vehicle in the tunnel and requiring passenger evacuation. For such conditions the tunnel emergency ventilation system must be able to maintain at least one evacuation path from the vehicle, clear of smoke and hot gases, blowing the hot smoke in the desired direction and enhancing passenger safety. It is assumed that smoke leakage to the adjacent tunnel through tunnel cross passages will be avoided to the extent possible. The design of a tunnel and station ventilation system needs to take into account the potential for a major fire to occur at any location in the tunnel or stations where the train or tunnel bus has access. Each subway station has four 200,000 cfm emergency ventilation fans and an additional 100,000 cfm of capacity from station exhaust fans.

The type of vehicle used in the system determines the largest fire that can occur. A maximum Heat Release Rate (HRR) of 45 million Btu/hr has been estimated for the SoundTransit system trains according to the Design Criteria. A maximum HRR of 60 million Btu/hr was estimated for the buses. This estimated HRR was reduced from 85 million Btu/hr, derived from PIARC (Permanent International Association of Road Congresses) data based upon the fire hardening of the existing bus fleet and the presence of an onboard pre-engineered dry chemical fire suppression system. The original ventilation design also used a HRR of 60 million Btu/hr based on the vehicle combustible load and 75 gallons of diesel fuel. The current analysis is therefore consistent with that used for the original ventilation system design. The hybrid bus operates on electric power inside the tunnel and on diesel power outside the tunnel.

The emergency ventilation analysis was focused on determining fan capacities and operational modes to meet the current edition of NFPA 130. The following minimum design criteria was used for the emergency ventilation simulations:

- "Worst case" scenario was defined for each tunnel ventilation zone
- Only one fire incident at a time was assumed
- Meet critical velocity for a bus fire with a HRR of 60 MBtu/hr.
- Points of safety or egress are available on either end of a disabled train in the tunnel
- Smoke leakage to adjacent tunnels should be avoided to the extent possible
- For a train or bus fire in a cut-and-cover station, evacuation will be through the station entrances
- Air temperature in the evacuation path shall not exceed 140°F
- Emergency fans should withstand an air temperature of 482°F for one hour
- When the entire fan capacity is required for one tunnel only, the dampers to the other tunnel will be closed.

Tunnel emergency scenarios consisted of modeling one stopped tunnel bus on fire in the steepest tunnel section between fans, ventilating against buoyancy (downhill) in order to determine the fan sizes required to meet the largest duties (the worst case scenario). Per the operational scenarios, four buses were stopped behind the bus on fire. The minimum distance assumed between stopped buses was about five feet. Station emergency scenarios consisted of modeling one stopped bus on fire in the center of the station, with four buses waiting in the tunnel to enter the station (two buses in each direction). The ventilation will be "All-exhaust", "Push-pull", or "Pull only" mode depending upon the geometry and flow patterns.

All ventilation fans were modeled first at the existing capacity as described above. Where existing fans did not meet the critical velocity criteria, new, higher capacity, fully reversible fans and/or new reversible jet fans were considered, as appropriate. In some fire scenarios, partial closing of a station entrance was modeled as a possible alternative to meet the critical velocity criteria. In line with the current practice, emergencies were assumed to occur one at a time, in one tunnel, and in one direction only (no simultaneous fires). The predicted airflows were shown in KCFM at constant density (outdoors ambient temperature) to permit checking of the flow balance. The actual airflows are higher where predicted higher temperatures are shown. These details are in the DSTT ventilation report.

We ran the model with the existing fans and that scenario did not meet all of the current requirements. From these scenarios, it was determined that in some cases, the existing ventilation would require some modification to meet the worst-case scenarios, based on current codes and standards. Resetting the blade angles and upgrading of blades to make the fans fully reversible was considered. The next step in the process was to determine if all new fans installed in the existing openings would meet the requirements. For this scenario, the emergency ventilation simulations meet all requirements with all new fans of higher capacity. Preliminary cost estimates were performed on proposed systems, and independent value engineering was performed to evaluate costs and options.

It was estimated that full replacement would require more than $10 million in additional expenditures. Considering the magnitude of this cost, we explored various combinations of upgrades and retrofits to determine the most cost effective approach to satisfying the current ventilation requirements. The current plan is for adjustments to the emergency fans to increase airflow and reversibility in conjunction with using the station exhaust fans as booster fans. Additional controls would be installed to add to the increased operational efficiency. Operational tests and measurements were performed on the existing fans in their current state to correlate actual performance of the mature system with the planned design performance. This information was used as part of the basis of design for the retrofit.

Generally the fans at one end of the station exhaust smoke, with intake air being drafted down into the station at the other end. Because airflow drafted down into the station areas is sometimes weak, the Computational Fluid Dynamics analysis was required to ensure that smoke does not migrate past the fan into the station. These results are reported in the ventilation reports. The preferred ventilation method for fires in the existing DSTT stations was determined by Computational Fluid Dynamics (CFD) analysis. This was necessary because the critical velocity criterion does not apply in large open areas and SES cannot model details of the complex three-dimensional flow in stations. SES runs were made to establish the flow pattern and to provide boundary conditions. Then the CFD was used to determine the details of the flow patterns, the heat and smoke distribution. The heat and smoke concentrate in the center of the station and spread to the mezzanines above the flow of incoming make-up air. The smoke spreads to the stairs and beyond on the platform level as well, preventing access to the mezzanine stairs. Push-pull operations modes in stations are normally implemented to ventilate toward the end nearest the fire, clearing the largest possible portion of the station. The worst case, then, is a fire near the center of the station being ventilated towards one end. Various fan combinations were tried for each station, and in all cases, the station exhaust fans were operated and the station supply fans turned off. Ventilation scenarios were developed and computer simulations were run to verify that the proposed system would safely meet the requirements.

Conclusion

The focus of this paper is to alert the reader to the amount of effort and time required to move forward with a decision an these types of system safety issues. The time to prepare the preliminary hazard analyses, ventilation simulations, bus movement simulations, and traffic analyses is small compared to the time required to assemble sufficient data, gain consensus, and explain the results of the technical work. This design development process occurred over the period of a year. It takes considerable discussion, collaboration among technical disciplines, and detailed engineering analyses to translate some of these safety and operational concepts into reality. As with many areas, the importance is not in the exact numerical resultants, but moreover, the importance is on the iterative process that moves the project team forward to a technical solution. Even the areas of code interpretation require some iteration to get to a resolution that will be acceptable to all parties. These safety issues weren't easily identifiable, and the solutions required considerable planning and discussion prior to implementation. Converting the existing Downtown Seattle Transit Tunnel to joint use required an integrated approach to collaborative design development. Overall this conversion required a substantial commitment to ensuring that the patrons of the transit system would be protected. This paper illustrates that the FTA mandated, value engineering played a key role in achieving best value for the dollar. Engineering of a transit system is by nature, an iterative, collaborative process that, as shown here, can result in a safe, state-of-the-art system.

References

Federal Transit Administration, "Evacuation and Rescue of Elderly and Disabled Passengers from Paratransit Vans and Buses", U. S. Department of Transportation, 1984.

Federal Transit Administration, "Fire Safety of Passenger Trains", U. S. Department of Transportation, 1993.

Federal Transit Administration, "Hazard Analysis Guidelines for Transit Projects", U. S. Department of Transportation, 2000.