NATIONAL TRANSPORTATION SAFETY BOARD
Investigative Hearing
Washington Metropolitan Area Transit Authority Metrorail train 302 that encountered heavy smoke in the tunnel between the L'Enfant Plaza Station and the Potomac River Bridge on January 12, 2015

GROUP	B
EXHIBIT	
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Agency / Organization

NTSB

Title

Radio-Communication Systems Factual Report

Docket ID: **DCA 15 FR 004**

NATIONAL TRANSPORTATION SAFETY BOARD
Vehicle Recorder Division
Washington, D.C. 20594

April 27, 2015

Radio-Communication Systems

Specialist's Factual Report
By Joseph A. Gregor

1. EVENT SUMMARY

Location: Washington, DC
Date: January 12, 2015
NTSB Number: DCA15FR004

On January 12, 2015, about 3:15 p.m., Eastern Standard Time, Washington Metropolitan Area Transit Authority (WMATA) Metrorail train 302 stopped after encountering an accumulation of heavy smoke while traveling southbound in a tunnel between the L'Enfant Plaza Station and the Potomac River Bridge. After stopping, the rear car of the train was about 386 feet from the south end of the L'Enfant Plaza Station platform. The train operator contacted the Operation Control Center (OCC) and announced that the train was stopped due to heavy smoke.

A following train (train 510), stopped at the L'Enfant Plaza Station at about 3:25 p.m., and was also affected by the heavy smoke. This train stopped about 100 feet short of the south end of the platform. Passengers of both trains, as well as passengers on the station platforms, were exposed to the heavy smoke. Train 510 was evacuated while it was stopped at the station platform. Some passengers aboard Train 302 began to self-evacuate as it remained in the tunnel. Emergency responders were dispatched to the scene and an evacuation of the train and station area ensued. As a result of the smoke, 86 passengers were transported to local medical facilities for treatment. There was one passenger fatality. Initial damages were estimated by WMATA at $120,000.00.

The parties to the investigation include the Washington Metropolitan Area Transit Authority, the Federal Transit Administration, the Tri-State Oversight Committee, the Amalgamated Transit Union 689, the International Fire Fighters Association 36, the District of Columbia Fire and EMS, the Metropolitan Police Department, and the Bureau of Alcohol, Tobacco, Firearms and Explosives.

2. GROUP

The following individuals served as members of the Communications group documenting specifics of the Washington Metropolitan Area Transit Authority (WMATA) and the Washington DC Public Safety (DCPS) Radio systems.

Chairman:	Joseph A. Gregor Electronic Engineer National Transportation Safety Board
Member:	Marshall Epler, PE, LEED AP Deputy Chief Engineer - COM and NET Systems Transit Infrastructure and Engineering Services Washington Metropolitan Area Transit Authority
Member:	Teddy Kavaleri Chief Information Officer DC Office of Unified Communications (OUC)

3. DETAILS OF INVESTIGATION

The National Transportation Safety Board (NTSB) Vehicle Recorder Division reviewed information describing the underground communication systems installed and maintained by WMATA, with funding from WMATA and the District of Columbia. These systems serve WMATA, the DC Fire and Emergency Management System (DC FEMS), and the Metropolitan Police Department (MPD). This review included information concerning the theory of operation, maintenance, and performance of these systems in the time leading up to and immediately subsequent to the accident.

3.1. Trunk Radio Systems

A trunk radio system is a networked voice communication system using radio frequency energy to carry voice information to and from any radio subscribed to the network. Modern trunk radio systems typically operate in the ultra-high frequency (UHF)[1] range.

A trunk radio system is generally employed to increase the number of discrete channels available to an operator – typically a large organization such as a local or State government – given a fundamental limit on the number of frequencies available in the RF spectrum. Use of a trunked radio system permits the sharing of a limited number of frequencies among a large number of individual users by assigning spectrum on-the-fly for the limited time period required to make an individual transmission. This permits maximum utilization of the available radio frequency (RF) spectrum, since most users are unlikely to be transmitting at the same instant.

A typical trunk radio system is composed of several major elements:

- A pool of available / assigned *radio frequencies* for broadcasting voice transmissions,
- A pre-defined set of *talk-groups* used to designate the virtual channel on which a user will communicate,

[1] The UHF radio range extends from approximately 300 MHz to 3 GHz.

- A *system controller* that maps the selected talk-group to an available radio frequency,
- A *repeater* system composed of fixed-base radios designed to receive RF transmissions and re-broadcast an amplified version of the signal - to increase the effective range of the originating (typically portable) transmitter.

The operator of a trunk radio system is typically licensed to transmit on a certain number of discrete radio frequencies. Voice communications can be broadcast over these frequencies in either analog or digital form. Digitally encoded voice communication data may be broadcast either encrypted[2] or unencrypted. Typical signal bandwidths[3] are 12.5 kHz and 25 kHz. A typical radio transmission, be it analog or digital, will generally begin with a burst of digital metadata broadcast on a separate *control frequency*[4] that identifies the specific radio and the talk-group being addressed. It is this talk-group, and not the radio frequency being used, that designates the channel to which the radio is switched.

A typical trunk radio configuration involves a remote system controller. The system controller is an embedded computer system interfaced to a fixed-based radio that is tuned to the control frequency. Digital data within the header of any transmission made on this frequency is decoded by the system controller and used to direct the flow of any associated voice information.

In order for a radio to communicate on a trunk radio system it must first *log-in* to that system. The handshaking required to accomplish this may be automatic (data packets exchanged in the background when the radio is turned-on or enters the service area), or may require operator initiation (e.g. making a transmission), depending on the system configuration. Once a radio has logged into the trunk radio system, the user can communicate with any other radio that is logged in and switched to the same talk-group. The radio will revert to monitoring the control channel when not actively sending or receiving a voice message.

The process for a typical radio call is outlined as follows:

- A remote radio transmission begins with the user depressing the push-to-talk (PTT) switch on their radio. This triggers the broadcast of a channel request message on the control channel that includes the ID for the transmitting radio and the talk-group to which the radio is switched.

[2] Encryption refers to the digital encoding of a data stream in a manner that requires a specific key for recovery of the original data.
[3] The bandwidth of a signal defines the range of frequencies a single transmission can occupy. The centroid of this range is generally identified as the 'frequency' of the signal.
[4] A minority of trunk radio systems operate with a different paradigm that does not involve the use of a control channel. Such systems are beyond the scope of this report.

- The controller assigns an open frequency to the talk-group being requested and sends a channel grant message to all radios logged in and switched to that talk-group indicating that a transmission is incoming.
- Typically, the initiating radio will emit a confirmation sound to the user that the talk-group is active and a voice transmission can be made. The entire handshaking process typically takes less than one second.
- Once the voice transmission is complete, the user releases the PTT switch. This causes the initiating radio to broadcast an end-of-transmission message. The controller responds to this message by notifying all radios subscribed to that talk-group to resume monitoring the control channel, and releasing the communication frequency for use by another talk-group.

Each transmission made by any radio initiates the same chain of events anew; so that for any given talk-group, subsequent transmissions may be made on a different frequency, even if initiated moments later by the same radio. From the perspective of an individual user, the radio is transmitting to and receiving from the channel to which it has been switched. Only in this case, the channel does not specify a discrete frequency to which the radio has been tuned, but instead designates a talk-group with which the user desires to communicate.

A transmission may fail under certain conditions related to signal quality problems:

1) The radio is not visible to the trunk radio system at the time the operator depressed the PTT switch.
2) The radio was visible to the system, but the necessary handshaking required to assign the talk-group frequency and properly notify other radios subscribing to that talk-group could not successfully take place.
3) Handshaking was successful, but the signal level subsequently dropped below the threshold required for clear communication while the voice transmission was being made.

If condition 1) is operative, the initiating radio may warn the operator via a visual or auditory out-of-range message, depending on the system. If condition 2) is operative, the radio may warn the operator initiating the transmission with a system sound often described as a 'bonk'. If condition 3) is operative, the user of the initiating radio will generally receive no notification of a problem. Other users subscribed to the same talk-group may receive a broken or garbled version of the original voice communication.

Radio systems operating at UHF frequencies rely primarily on line-of-sight[5] propagation. Most trunk radio systems employ a network of *repeaters* designed to extend the range

[5] In this context, line-of-sight indicates that the sending and receiving radios generally need to be within RF view of one another. Line-of-sight transmission can occur through low density materials that block light but do not effectively block RF energy – like glass, plywood, and drywall construction material, etc.

of individual radios; especially handhelds, that are generally restricted in range due to size, power, and antenna requirements. A typical above ground repeater system is composed of a co-located receiver and transmitter that are designed to receive transmissions, amplify the signal, and rebroadcast the boosted signal. Above ground repeater systems generally employ an omnidirectional[6] antenna mounted high atop a building or tower to offer optimal coverage over the nearby geographical area. Multiple repeaters with overlapping coverage area may be used to extend the overall coverage area.

Due to the large amount of high density material associated with any below ground structure, a below ground repeater system will generally be configured differently. In general, the use of multiple and distributed antenna systems will be required to obtain coverage in all desired spaces. Signals will be relayed between non-contiguous spaces using electrical or fiber optic cables, often passing through devices designed to boost the signal to compensate for propagation losses and external noise pickup.

Portable radios designed to operate on a trunk radio system may also support the capability to transmit and receive on a dedicated frequency or frequencies in the event of a repeater or control system failure. This is commonly referred to as talk-around mode. In this case individual radios may communicate via a repeater (if one is in view and operating) using the dedicated input and output frequencies of that repeater, or directly radio-to-radio using a single frequency (simplex). In any case, communication via talk-around is only possible between radios that are RF-visible either to a repeater system, or to one another, depending on the mode.

In a trunk radio system that operates both above ground and below ground, there must be an interface between the two regions. This is usually provided by fiber optic or RF conduits that carry the signal to and from a concentration facility that interfaces between each network. The signal path propagating from below ground to above ground is generally called the *uplink* and carries signals from subscriber units to the communication system core. The signal path propagating from above ground to below ground is generally called the *downlink* and carries signals from the system core to subscriber units.

3.2. Description of the WMATA Communication System

The WMATA communication system is based upon the 490 MHz Motorola SmartZone 3.0 trunk radio system. This system provides support for 397 talk groups by allocating 16 frequencies with 25 kHz spacing. Voice information can be distributed as a mix of digital and analog voice. Encryption is not employed. Digital voice employs C4FM

The ultimate range of the signal will depend on transmit power, receiver sensitivity, the local noise floor, and the composition and density of any intervening dielectric material. In some cases, signals can propagate around corners and for distances beyond the typical free-air distance due to multi-path and wave-guiding effects. However, such propagation is unreliable and these cases are beyond the scope of this report.

[6] An antenna that can send and receive signals with equal gain in all directions – typically covering a 360 degree view of the area over which the antenna is centered.

modulation[7] and TDMA multiplexing.[8] Ten repeater sites are used to provide above ground coverage over the geographical extent of the District of Columbia. The above ground communication system is tied to a below ground system that is described in detail in Section 3.2.1.

WMATA plans to transition to a new 700 MHz P-25[9] trunk radio system with a target date of 2021. This new system will support an Inter-RF Subsystem Interface (ISSI) link to regional partners including District of Columbia Public Safety (DCPS) users, to provide seamless handoff to radios crossing system boundaries. The new trunk radio system will also provide WMATA with enhanced monitoring and system health assessment capabilities.

3.2.1. Signal Flow Through the WMATA Below Ground Communication System

Radio signals broadcast in the underground are sent and received using a series of antennas located in the stations, entrance areas, and selected utility spaces. In addition, a distributed antenna system is used to provide RF communication capability in the rail tunnels. This distributed antenna system is composed of specially engineered coaxial cable designed to transmit and receive RF energy along its entire length while still propagating the majority of the signal longitudinally down the cable. This RF-leaky cable is strung down the length of the tunnel in individual segments. Each segment is coupled to the next in daisy-chain fashion via a bi-directional amplifier (BDA) designed to boost the signal and compensate for losses in each cable segment. The operating signal-to-noise ratio (SNR) of this system is quoted to be approximately 10 db.[10] A graphic depicting the basic elements of the combined WMATA / DCPS communication system is shown in figure 1.

The interface between the above-ground and below-ground components of the WMATA communication system occurs at one of two data concentration sites. The *prime site* – designated CTF in this report – is located in suburban Maryland. The *backup prime site* – designated JGB in this report – is located in the District of Columbia. The central processor responsible for controlling the WMATA trunk radio system resides at CTF,[11] which also serves as the primary voice communication data concentrator. All voice information from the above ground segment is combined at CTF and converted from electrical signals to optical signals that are downlinked via fiber optic lines to an equipment room – designated B01 in this report – located at a central location in the

[7] Constant Envelope 4-Level Frequency Modulation. The modulation scheme refers to the method by which the RF carrier signal transmitted by a radio is modified to carry information.
[8] Time Division Multiple Access. The multiplexing scheme refers to the method used to transmit multiple information streams on a single frequency or band of frequencies.
[9] The Association of Public-Safety Communications Officials (APCO) has created a set of voluntary standards for digital public safety radio that include specifications for a Common Air Interface (CAI) including an encoding format for digital voice and a standard for trunk radio operation.
[10] The decibel (dB) is a unit of measure representing a relative signal strength and is commonly used when representing signals that exhibit a high dynamic range. Decibel values are commonly quoted on a logarithmic scale – where +3dB represents a 40% increase in relative amplitude, and +10 dB represents an approximate tripling of the relative amplitude.
[11] The JGB site retains all the functionality of the CTF site, and acts as a redundant system in case there are problems with the infrastructure at CTF.

District of Columbia. In turn, all electronic voice information from the below ground system are combined in this same equipment room, converted to optical signals, and uplinked via fiber optic lines to the CTF. In this way, a radio located anywhere in the WMATA operating footprint has the ability to send and receive a voice signal to / from any other radio that is logged into the system.

The interface between the above-ground system and below-ground system is serviced by 26 fiber optic transceivers[12] - referred to as *head ends*. Each head end services one of the 26 segments of the WMATA underground communication system. Most segments share a common boundary passing through a Metro station. In the downlink direction, the optical signal representing above ground voice communications is converted into an RF signal that is transmitted in the underground spaces and train tunnels being serviced by that head end. To service the tunnel spaces, each RF signal is split (de-multiplexed) into four identical signals that are propagated down each tunnel.[13] In the uplink direction, RF signals received by antennas in these same regions are combined (multiplexed) by the head end into an optical signal that is sent to the CTF.

[12] A transceiver is a device that combines the capabilities of a transmitter and a receiver in one integrated unit. Any device capable of two-way communication is properly referred to as a transceiver. In this report, the terms ‘radio’ (normally used to refer to portable and fixed position voice communication devices) and transceiver may be considered synonymous.

[13] Typically, the BDA would couple signals in both directions (e.g. upstream and downstream) of the two train tunnels being serviced (e.g. eastbound train and westbound train) by the station.

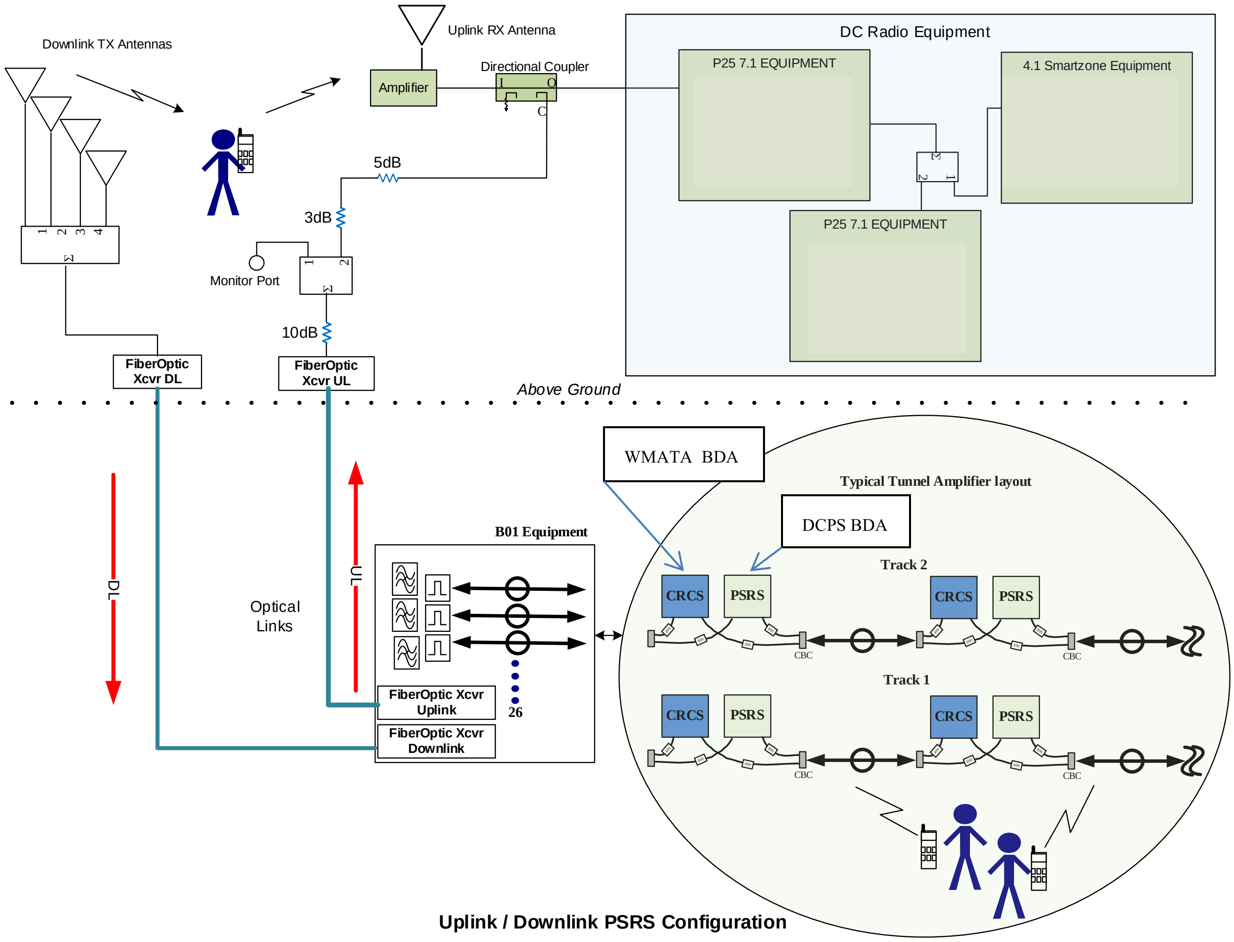

Figure 1. Uplink / Downlink configuration for the WMATA / DCPS communication system

3.3. Description of the District of Columbia Public Safety Communication System

The DCPS communication system was originally based upon a dual frequency 460 MHz / 800 MHz Motorola 4.1 trunk radio system installed around 2003. This system provided support for hundreds of talk groups by allocating up to 31 frequencies with 25 kHz spacing supporting digital voice between radios and encryption if desired. The system supports C4FM,[14] CQPSK,[15] and WIDE[16] modulation schemes using FDMA multiplexing. Ten above ground repeater sites are used to provide above ground coverage over the geographical extent of Washington, DC. The above ground communication system is tied to a below ground system covering the underground spaces in the WMATA rail system that is described in detail in Section 3.3.1.

[14] Continuous 4-Level Frequency Modulation.
[15] Compatible Quadrature Phase Shift Keying.
[16] Wideband simulcast. Simulcast refers to a communication strategy whereby multiple sites broadcast simultaneously on the same frequency to enhance coverage and resistance to signal distortion. Simulcast systems rely on extremely precise time synchronization to prevent destructive co-channel interference.

Prior to 2013, the District was using a Motorola 4.1 system utilizing 16 frequencies on the 800 MHz band and 15 frequencies on the 460 Hz band with 25 KHz spacing to support approximately 250 talk groups across 20 agencies (police, fire, and EMS). The control system[17] for the 4.1 system is located at the Public Safety Communications Center (PSCC) in northwest Washington.[18]

The DC Office of Unified Communications (OUC) is currently transitioning to a new dual-frequency 700 MHz / 800 MHz Motorola P-25 7.11 trunk radio system. During this transition, the DCPS communication system utilizes both systems operated in a dual-hybrid mode with a Motorola SmartX Site Converter providing the interface between each system. The SmartX Site Converter is located at the PSCC.

The Motorola P-25 7.11 system is capable of utilizing 16 frequencies on the 800 MHz band and 10 frequencies on the 700 MHz band. The system supports C4FM, CQPSK, and WIDE modulation schemes. Operations on the 800 MHz band support FDMA[19] multiplexing with 12.5 KHz spacing. Operations on the 700 MHz band support FDMA and TDMA multiplexing and operation with 12.5 KHz or 6.25 KHz frequencies spacing. The control system for the P-25 7.11 system is located at the OUC facility in southeast Washington.

In early 2013, the District migrated all MPD users to a new P25 7.11 system utilizing ten 700 MHz frequencies and four 800 MHz frequencies. DC FEMS users continued using the Motorola 4.1 system with twelve 800 MHz frequencies. In December 2014, DC FEMS users were migrated to the P25 system with an additional seven 800 MHz frequencies. DC FEMS users were restricted to using 800 MHz frequencies for interoperability, since the WMATA below ground system is only capable of transmitting on UHF and 800 MHz frequencies. While DCPS below ground radio communications are carried exclusively on the 800 MHz band, any 800 MHz DCPS radio operating below ground can communicate with any other radio operating in the DCPS communication system regardless of type.

In 2013, the existing UHF interface between the WMATA communication system and the MPD communication system was moved over as part of the P-25 upgrade to support continued interoperability between WMATA and MPD. This permitted two MPD 800 MHz talk groups to be manually patched to the WMATA communication system. MPD also has a citywide talkgroup (CW1) that is available for MPD users communication capability inside metro tunnels and platforms. Fire and Emergency

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[17] The control and interface functions are performed at a Master site that controls interconnection between the different components of the radio system including dispatch sub-system, access to recording system, audio/RF communication between 800 MHz and UHF systems, reporting and statistics servers, provisioning system, and a Prime Site that handles the audio traffic and interconnects the RF sub-systems for the 10 Remote RF Base station sites. All DC FEMS and MPD trunked talk group communications are recorded and the data is stored for 3 years at the OUC.
[18] The PSCC is a centralized communications center managed by the Office of Unified Communications for the purpose of providing police, fire, and EMS call-taking and dispatching.
[19] Frequency Division Multiple Access refers to a channel access method whereby users share RF bandwidth by dynamically allocating unique frequency bands to each user.

Management System (FEMS) radios do not have a process in place to be directly patched on WMATA talkgroups.

3.3.1. Signal Flow Through the District of Columbia Public Safety Communication System

The DCPS below ground communication system operates on the 800 MHz band. Radio signals broadcast in the underground are sent and received using an independent series of transceivers located in the stations and entrance areas. However, the same antenna system used for the WMATA below ground system is shared by the DCPS system to provide RF communication capability in both stations and rail tunnels. In the rail tunnels, the same distributed antenna system composed of RF-leaky coaxial cable is utilized. However, due to the difference in RF frequency and associated signal losses between the two systems, the BDAs used to boost the signal for the DCPS communication system are separate and independent units spaced closer together than the WMATA BDAs.

The interface between the above-ground and below-ground components of the DCPS communication system is made in a downtown location – designated OJS in this report – that is located near the WMATA backup prime site. Voice signals received from the above ground system are combined with voice signals received from the below ground system through a directional coupler before entering the DC Equipment Room at OJS. The equipment in this room interfaces with both the 4.1 and P-25 7.11 trunk radio systems, each of which have their own separate control processor located offsite. Data flow between the two systems is managed via the Motorola SmartX Site Converter located at the OUC.

The interface between the above-ground system and below-ground system is serviced by 26 fiber optic transceivers independent from those servicing the WMATA system. Each head end services one of the 26 segments corresponding to the WMATA underground communication system. Most segments share a common boundary passing through a Metro station. In the downlink direction, the optical signal representing above ground voice communications is converted and split (de-multiplexed) into multiple electronic signals that are transmitted in the underground spaces and train tunnels being serviced by that head end. In the uplink direction, RF signals received by antennas in these same regions are combined (multiplexed) by the head end into an optical signal that is sent to the DC Equipment Room at OJS for processing and routing.

3.4. Maintenance of the Below Ground Communication System

WMATA maintains all of the communication infrastructure for both the WMATA below ground system and (through an MOU) the DCPS below ground system. Based on best practices, the maintenance strategy for any complex system can follow one of four broad models:

1. Corrective maintenance or Run-to-failure – involving the detection of an anomaly or failure and repair or replacement of the malfunctioning component.
2. Preventative maintenance – involving the replacement or refurbishment of components at pre-defined intervals determined by the criticality of the component and experience concerning its wear and aging characteristics.
3. Predictive maintenance – involving the replacement or refurbishment of components based on monitored condition and performance measures.
4. Reliability-centered maintenance or Continuous improvement – involving the analysis of possible failure modes based on past experience and system design or modification intended to proactively mitigate these failures.

The maintenance strategy selected for any component or subsystem will depend on several factors including:

- Cost – The repair and replacement cost of a system will influence the maintenance strategy selected. In general, the run-to-failure strategy incurs lower costs than the preventative strategy; and the preventative strategy is lower in cost than the predictive strategy. The most expensive strategy is continuous improvement, which is usually limited to large scale and highly critical systems involving vast resources and extreme failure costs.
- Likelihood-of-failure – The reliability of a system will influence the maintenance strategy selected. Systems with components that are inexpensive to replace and exhibit a wide range in time-to-failure are candidates for the run-to-failure strategy. Systems deemed highly reliable and with components that exhibit a well-defined useful life may be efficiently maintained using the preventative maintenance model. Systems that degrade gracefully over time are candidates for predictive maintenance.
- Consequence or Impact – The consequence of failure will be a major driver for the resources allocated toward the maintenance of any system. A low consequence system, like a station platform annunciator, may be a good candidate for lower cost maintenance strategies like run-to-failure. A high consequence system, like a train signal system, justifies a greater allocation of maintenance resources.

In practice, a system evaluation following the basic principles of risk management – taking into account cost, likelihood-of-failure, and potential consequence – is used to determine an appropriate maintenance strategy. Of particular interest are systems that exhibit a probability of failure that diverges from the potential consequence of failure. At one end of this spectrum would be systems and components that exhibit a high incidence of relatively low consequence failures. At the opposite end of this spectrum would be components that exhibit an extremely low incidence of potentially high consequence failures. Hybrid maintenance strategies may be crafted to address cases anywhere along this spectrum, resulting in a multi-pronged maintenance approach.

Prior to the January 12, 2015 accident, the approach instituted by WMATA for maintaining both the WMATA and the DCPS below ground communication system corresponded most closely to the corrective or run-to-failure maintenance model. Communication system malfunctions were identified as users operating day-to-day reported problems through a *trouble-ticket* process. This triggered a maintenance action designed to validate, diagnose, and correct the reported problem.

This approach was supplemented by qualitative testing performed by the DC OUC that included rotating spot checks made by personnel using hand-held radios moving through selected underground spaces and verifying positive communication capability. Checks were conducted approximately every 1 to 2 months at 4 to 5 locations and included station platforms, trains, and tunnels.[20] Any problems found were reported to the WMATA point of contact by e-mail and phone call.

[20] Tunnel testing was accomplished using portable radios operating in trains while transiting the tunnels.