Measuring the Performance of Automated People Mover Systems

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Abstract

Measuring the performance and availability of Automated People Mover (APM) Systems is an important and necessary process that can be used to assess how well the system meets the Operations and Maintenance (O&M) service contract requirements and can be used to determine how well an APM System provides service to its passengers. This paper will discuss the many factors to be considered in order to assess the performance and availability of APM Systems.

Introduction

It is important and necessary to measure the performance and availability of APM Systems as part of the testing and commissioning of the various subsystems that comprise an APM System before it opens to passengers, and then continuously during passenger service. Issues to be considered when measuring System Availability include the importance, complex factors that affect the assessment of system performance and availability, complex methodologies and strategies required to properly assess system performance and availability, and how to interpret the final results. To measure the performance and availability of an APM System during testing and commissioning the APM System provider conducts a System Demonstration (or Trial Period) during which the APM System is operated as if it were carrying passengers. The availability results obtained during testing and commissioning are used as a verification of the design and installation of the completed APM System as well as an assessment of the O&M organization's ability to operate and maintain the various subsystems that comprise the APM System. During passenger service the availability results can be used to assess how well the APM System provides service to its passengers and how well the O&M provider meets the O&M service contract requirements.

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Performance measurements assess:

- Design of the APM System alignment
- Design and testing of the subsystems that operate, control and monitor the APM
- Construction quality
- Installation of hardware and software
- O&M organization including:
  - Structure
  - Staffing
  - Training
  - Operations procedures
  - Maintenance procedures
  - Policies
  - Strategies

APM System performance is usually measured as a ratio of service provided to the service required and reported as a percentage. This performance measurement can be generally characterized as 'System Availability' and quantifies the actual availability of the system relative to the availability specified in the O&M service contract. The main items to include in the overall APM System Availability calculation are the subsystems operated and maintained by the O&M organization. Items to include in performance measurements can vary from simply the adherence of APM trains to a specified schedule to more complex requirements such as including platforms, stations, platform doors, escalators, elevators, and fare gate service in the availability calculations.

There are many factors to be considered to properly assess the performance and availability of APM Systems such as:

- Importance
- Complex factors that affect the assessment of system performance and availability
- Complex methodologies
- Strategies required to properly assess system performance and availability
- How to interpret the final results

The Importance of Assessing System Performance

One of the first opportunities to measure performance is during the testing and commissioning period, or more specifically during a "System Demonstration" test period. A System Demonstration test period is a test performed by the APM System provider in conjunction with the O&M organization whereby the APM System is operated for a given time period as if it were carrying passengers. This test is used to:

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- Assess whether or not the installed system is ready for passenger service
- Demonstrate that all of the various subsystems that comprise an APM System are working reliably
- Demonstrate that the O&M organization has a sufficient number of trained personnel to operate and maintain these subsystems

A demonstrated high System Availability can be used as a measure of and requirement for successful completion of the System Demonstration test. Additionally, a high System Availability percentage at the end of the System Demonstration test shows that the installed or As-Built system is capable of providing the level-of-passenger service required or specified by the Owner.

System Availability measurements are used to continually assess how well an APM System complies with contract requirements and serves its passengers' needs. System Availability measurements are also used as an ongoing performance assessment of the O&M Organization including all of the O&M items listed in the introduction.

Modes of Transportation Service

There are at least three general categories of automated transportation service:

- Continuous Service
- Scheduled Service
- On-Demand Service

System Availability measurements can be different for each of these service modes. The measurement methodology for each type of service is therefore discussed separately in this paper.

Continuous Service - Continuous Service is when trains operate continuously throughout the system at regular intervals without stopping for extended periods of time and regardless of whether passengers are riding in or waiting for trains. Trains are separated by regular time intervals known as headways.

Scheduled Service - Scheduled Service is when trains operate on a given or predetermined schedule and stop once a route has been completed, or between route operations, regardless of whether passengers are riding in or waiting for trains. Once trains depart station platforms they travel along predetermined routes stopping at station platforms on their route to allow the transfer of passengers. When trains arrive at their final destination they remain parked until the next scheduled departure.

On-Demand Service - On-Demand Service is when trains operate on a route only if there is a service request by a passenger. This can be destination specific, in that trains only travel to requested stations, departing from stations where the

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travel requests were made, or along pre-determined routes stopping at all stations along the route. Once trips have been completed trains stop until another travel request is activated.

Factors Affecting System Performance

Some of the many factors that can directly or indirectly affect APM System availability are described in this section.

Design of the APM System

The basic design of the APM System can have a dramatic affect on its availability. APM Systems are typically designed to have 'normal' and alternate or 'failure' operating modes. The alternate modes are normally used to bypass or avoid guideway sections to perform planned or scheduled maintenance (usually during non-peak hours). During system problems or failures, the alternate modes are used to bypass or avoid failed or blocked guideway sections to maintain service in unaffected areas of the APM System or guideway. The higher the number of possible operational failure modes the more flexible the APM System, and greater flexibility can increase the overall availability of the APM System. However, it is important to note that increases in the number of subsystem components to provide increased operational flexibility make the APM System more complex, and without careful design and planning may in fact reduce availability due to an increase in failure rates.

The primary methodology used to increase the number of possible operating modes is adding crossovers, which provide the ability to bypass or 'run around' non-operating or failed guideway sections. While adding crossovers to an APM System increases the capital costs, the increased costs can be justified by the increased flexibility of the APM System. The addition of crossovers in an APM System, including how they are used in actual operation, requires careful consideration and planning since making the overall APM System more complex may reduce instead of increasing availability. Guideways could be added to increase the number of alternative operating modes, but the increase in real estate and corresponding costs can be greater than the costs of additional crossovers.

The primary drawback of using alternate operating modes to avoid failed or inoperable sections of an APM System is the time required to change system operations from the normal service mode to a suitable alternative mode. Typically when switching between service modes, all trains need to be stopped for safety reasons and located or positioned away from affected crossovers during transition periods (from normal to failure, and from failure to normal). To justify switching to an alternate mode, the time to correct a failure must be anticipated to be longer than the aggregate time to switch to and from failure modes.

One aspect of an APM Systems' availability is related to the time between trains (headways) and chances of correcting problems before they can affect multiple trains.

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The shorter the headways the shorter the response time needs to be in order to avoid impacting following trains, i.e. APM Systems operating with headways close the minimum achievable headway require lower 'Mean Time to Repair (MTTR)' times in order to achieve or maintain high availability. As MTTR becomes equal to the headway, the less available an APM System can become since the time to correct failures before they affect a following train becomes shorter. One way to offset the MTTR and headway relationship is to design the components that comprise an APM System to be more reliable, i.e. have a lower probability of failure. As average failures which affect two trains are less likely to occur due to increased reliability, the required System Availability is more likely achievable.

Design and Testing of the Subsystems

The reliability of the APM subsystems has a direct affect on the overall System Availability. For example, the failure of a data communications network that carries critical system data such as Automated Train Protection information will affect train operations in the region covered by the failure. The same is true for guideway switches, power rails, train guidance and other critical subsystems. Therefore, when designing each of these subsystems it is important to consider the following:

- Include as much redundancy as practical within each subsystem
- Utilize subsystem equipment and components that have high reliability
- Design subsystems to be repairable within a short time period (low MTTR)
- Perform a rigorous validation of all software

If the APM System has been designed with sufficient redundancy then single point failures may, depending on the failure and level-of-redundancy, result in no impact to service, reduced service, or cessation of service altogether. In this respect, it is appropriate to only assess reductions in System Operating Time for service not provided and provide credit for service provided.

Construction Quality

The quality of the installed hardware and software is a measure of how well the structural, electrical, electronic and electro-mechanical subsystems met the design and construction requirements. In general, an APM System constructed with good Quality Control enforcement, techniques, and methodologies will be less likely to experience construction-related failures or problems that would negatively impact the APM System availability.

Integration Testing of Hardware and Software

An important part of Quality Control enforcement is to conduct a thorough and rigorous comprehensive testing and commissioning program in both the initial construction phase and for any subsystems installed or replaced over the life of the APM System to ensure that each subsystem meets the design requirements and achieves the required availability.

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Operations and Maintenance Organization

The required response time of O&M personnel to subsystem failures is directly related to MTTR and System Availability. To keep the actual MTTR as low as possible, and depending on the complexity of the APM System, the policies and staffing of the O&M organization must be such that properly trained and equipped personnel are located at key locations throughout the APM System. Positioning O&M personnel at key or critical locations reduces the reaction time to subsystem failures; and if personnel are properly trained and equipped, the average repair time will be reduced, increasing the overall availability of the APM System. The selection of staff and training must insure that the O&M staff are sufficiently competent to troubleshoot and repair the various subsystems. The staff responding to system problems must be properly equipped or have access to the necessary equipment to quickly respond to the system's problems.

Therefore, when designing and implementing an O&M organization it is important to consider the overall organizational structure (including its hierarchy and the minimum qualifications for each position), staffing (number and competency), training program (initial and ongoing), operations procedures (how personnel should respond to operational problems), maintenance procedures (how personnel should maintain the subsystem equipment), corporate policies (hiring, firing, disciplinary), operational strategies (placement or location of personnel), inventories of spare and consumable parts, available tools and equipment, organization of the various maintenance areas, and organization of the central control or operations room, etc.

Measuring System Performance

The measurement or assessment of an APM System's performance must be:

- Quantifiable and quantitative
- Objective and unambiguous to avoid or minimize multiple interpretations

In relation to expressing the availability of an APM System, System Availability can be expressed as a ratio as follows:

$$A_{system} = \frac{\text{Actual System Operating Time}}{\text{Scheduled System Operating Time}} \qquad \text{Eq. 1}$$

Or alternatively expressed as:

$$A_{system} = \frac{\text{Actual Service Provided}}{\text{Scheduled Service}} \qquad \text{Eq. 1a}$$

System Availability can be used to quantify how well an APM System operates relative to contractual obligations, i.e. actual trains in service with the required

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capacity servicing the required platforms, and escalators and elevators in operation versus the required operating schedule.

System Availability is calculated for each calendar day and can be expressed as A_{day} and calculated as:

$$A_{day} = \frac{\text{Actual System Operating Hours For The Day}}{\text{Scheduled System Operating Hours For The Day}} \qquad \text{Eq. 2}$$

The daily System Availabilities are then used to calculate a monthly average System Availability

A_{month} as:

$$A_{month} = \frac{\sum_{i=1}^{N} A_{day\,i}}{N} \qquad \text{Eq. 3}$$

Or alternatively:

$$A_{month} = \frac{A_{day1} + A_{day2} + \dots + A_{dayN}}{N} \qquad \text{Eq. 3a}$$

System Availability for the month, A_{month}, is the value most commonly reported and used to determine how well the APM System operated relative to contractual obligations.

To assess the 'Actual System Operating Time' it is necessary to consider the various subsystems that comprise an APM System. The major subsystems from a passenger service perspective are the trains, guideway, stations, escalators, elevators, and fare card system (if utilized). These subsystems directly affect passenger service and therefore should be included in the measurement of overall APM System Availability. Therefore it may be necessary to collect and use data from each of these subsystems in order to assess the availability of the overall APM System.

Subsystems that are normally part of an APM System, but do not directly affect passenger service are the video monitoring (Closed Circuit Television or CCTV), audio communications such as public address and telephone, and Passenger Information Displays such as dynamic signs, and data communications. Minor or local failures of these subsystems will not directly negatively impact or reduce the service to passengers since it is possible to continue to provide effective passenger service with one or more of these subsystems failed or operating with diminished capacity. The APM System Owner or O&M organization may decide to cease train operations if any one of these subsystems fails completely since information to passengers, the ability to continue to operate trains, or the security of passengers may be compromised to an unacceptable level.

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Items to be included in System Availability are:

- ***Mode Availability*** - A measure of the actual performance of the APM System (in regards to operating the system according to the scheduled mode type) as compared to the scheduled mode, i.e. Normal versus an Alternative or Failure mode. Mode Availability can be calculated as:

$$A_M = \frac{\text{actual time the system was operated in the scheduled operating mode}}{\text{scheduled time for the operating mode}} \quad \text{Eq. 4}$$

- ***Fleet Availability*** - A measure of the actual number of vehicles in service versus the scheduled number of vehicles to be in service. Fleet Availability can be calculated as:

$$A_F = \frac{\text{actual number of vehicle hours in service}}{\text{scheduled number of vehicle hours in service}} \quad \text{Eq. 5}$$

- ***Platform Availability*** - A measure of the ability of passengers to transfer between trains and station platforms, and can be calculated as:

$$A_{PL} = \frac{\text{actual number of platform hours in service}}{\text{scheduled number of platform hours in service}} \quad \text{Eq. 6}$$

- ***Platform Doors in Service Availability*** - A measure of passenger transfer capacity, or flow rate between the trains and the station platforms, and can be calculated as:

$$A_{PD} = \frac{\text{actual number of platform door hours in service}}{\text{scheduled number of platform door hours in service}} \quad \text{Eq. 7}$$

- ***Response Time Availability*** - Primarily applicable to On-Demand service, a measure of the time between the activation of a travel or trip request and the time the train or vehicle actually departs with a passenger. On-time trip departures are departures that occur when the train or vehicle departed within a maximum allowable time period. Overall Response Time Availability can be calculated as:

$$A_{RT} = \frac{\text{number of on-time trip departures}}{\text{total number of trip departures requested}} \quad \text{Eq. 8}$$

- ***Trip Time Availability*** - Primarily applicable to On-Demand service, a measure of the actual trip time versus the maximum allowable trip time. On-time trips are when the train or vehicle successfully completed a trip within the maximum allowable trip time. Overall Trip Time Availability can be calculated as:

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$$A_{TT} = \frac{\text{number of on-time trips}}{\text{total number of trips requested}} \quad \text{Eq. 9}$$

- ***Late Departures Availability*** - Primarily applicable to Scheduled service, a measure of actual train departure time versus scheduled train departure time. Overall Late Departures Availability can be calculated as:

$$A_{LD} = \frac{\text{actual number of on-time departures}}{\text{scheduled number of departures}} \quad \text{Eq. 10}$$

- ***Late Arrivals Availability*** - Primarily applicable to Scheduled and On-Demand service, a measure of actual train arrival time versus scheduled train arrival time. Overall Late Arrivals Availability can be calculated as:

$$A_{LA} = \frac{\text{actual number of on-time arrivals}}{\text{scheduled number of arrivals}} \quad \text{Eq. 11}$$

  Note that trains that departed late should be included in the number of on-time arrivals and not be considered as late arrivals if they arrive no later than the scheduled arrival time plus the late departure time since this would result in a double penalty.

- ***Misrouting Availability*** - Primarily applicable to Scheduled and On-Demand service, a measure of the number of train or vehicle trips that did not arrive at their intended or scheduled destination versus the total number or train or vehicle trips and can be calculated as follows:

$$A_{MR} = \frac{\text{actual number of trips routed correctly}}{\text{total number of trips requested}} \quad \text{Eq. 12}$$

- ***Elevators Availability*** - A measure of the number of elevators in service versus the scheduled number of elevators and can be calculated as:

$$A_{EL} = \frac{\text{actual number of elevator operating hours}}{\text{scheduled number of elevator operating hours}} \quad \text{Eq. 13}$$

- ***Escalators Availability*** - A measure of the number of escalators in service versus the scheduled number of escalators and can be calculated as:

$$A_{ES} = \frac{\text{actual number of escalator operating hours}}{\text{scheduled number of escalator operating hours}} \quad \text{Eq. 14}$$

- ***Fare Gates Availability*** - A measure of the number of fare gates in service versus the scheduled number of fare gates and can be calculated as:

$$A_{FG} = \frac{\text{actual number of fare gate operating hours}}{\text{scheduled number of fare gate operating hours}} \quad \text{Eq. 15}$$

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- ***Ticket Vending Machines Availability*** - A measure of the number of ticket vending machines in service versus the scheduled number of ticket vending machines and can be calculated as:

$$A_{FM} = \frac{\text{actual number of fare machine operating hours}}{\text{scheduled number of fare machine operating hours}} \quad \text{Eq. 16}$$

Calculating System Availability

The typical period to measure A_{system} is one day, or A_{day} as shown in Equation 2. For an APM System, it is typical to provide different levels-of-service throughout the day since there are different levels-of-demand for service throughout the day. In this manner, an operating day would be separated into time periods of different levels-of-service and A_{system} for the day becomes the summation of the operating time periods for the day. The operating periods for a typical day can be summed up as:

$$\mathbf{TP_{day}} = \sum_{i=1}^{i=N} \mathbf{TP_i} \quad \text{Eq. 17}$$

Or alternatively:

$$\mathbf{TP_{day} = TP_1 + TP_2 + \ldots + TP_i} \quad \text{Eq. 17a}$$

Where:

- TP_{day} = Scheduled total operating time period for one day.
- TP_i = Length of each individual scheduled operating time period.

Each scheduled time or service period (TP_i) is multiplied by the availability of the subsystems provided during the period ($A_{subsystemS}$) to reflect the actual service provided by the APM System as follows:

$$\mathbf{TP_{iactual}} = \mathbf{TP_{ischeduled}} * \prod_{S=1}^{S=N} \mathbf{A_{subsystemS}} \quad \text{Eq. 18}$$

Or alternatively:

$$\mathbf{TP_{iactual} = TP_{ischeduled} * A_{subsystem1} * A_{subsystem2} * \ldots * A_{subsystemS}} \quad \text{Eq. 18a}$$

Where:

- $$\mathbf{A_{subsystemS}} = \frac{\text{actual hours operated by subsystem S}}{\text{scheduled hours for subsystem S}} \quad \text{Eq. 19}$$

The total actual operating time for the day, $TP_{dayactual}$, is calculated as follows:

$$\mathbf{TP_{dayactual}} = \sum_{i=1}^{i=N} \mathbf{TP_{iactual}} \quad \text{Eq. 20}$$

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Or alternatively:

$$\mathbf{TP_{dayactual} = TP_{1actual} + TP_{2actual} + \ldots + TP_{iactual}} \qquad \text{Eq. 20a}$$

Where:

- $TP_{dayactual}$ = Actual total operating time period for one day.
- $TP_{iactual}$ = Length of each individual actual operating time period.

The System Availability for the day, A_{day}, as calculated in Equation 2 would be modified to include the summation of the individual time periods as follows:

$$A_{day} = \frac{TP_{dayactual}}{TP_{dayscheduled}} \qquad \text{Eq. 2m}$$

Where:

- $TP_{dayscheduled}$ = Scheduled total operating time period for one day.

Continuous Service

For APM Systems operating in Continuous Service mode, Mode Availability (A_M) is a measure of whether or not the APM System is providing the required service to all station platforms scheduled to be served during the time period measured. A_M is calculated for each time period as shown in Equation 4.

The Availability equation for the individual time periods, TP_i, Equation 18, would be modified to include mode Availability as follows:

$$TP_{iactual} = TP_{ischeduled} * A_M * \prod_{S=1}^{S=N} A_{subsystemS} \qquad \text{Eq. 21-CS}$$

Or alternatively:

$$\mathbf{TP_{iactual} = TP_{ischeduled} * A_{mode} * A_{subsystem1} * A_{subsystem2} * \ldots * A_{subsystemS}} \qquad \text{Eq. 21a-CS}$$

Where:

- Mode Availability, A_{mode} , as defined in Eq. 4
- Subsystem Availability, $A_{subsystemS}$, as defined in Eq. 19

If the APM System experiences a failure such that the scheduled service cannot be provided, it is important to provide incentives to the O&M Organization to provide alternate service during the failure period. One method to accomplish this is to multiply the total time the APM System is operated in the alternate mode by a Service Reduction Factor (SRF). This provides credit for the alternate service provided in lieu of the scheduled service, and therefore encourages the O&M Organization to provide as much service to passengers as possible when experiencing a failure.

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When an alternate mode of service is provided, the calculation of A_M should to be modified to include the alternate service provided during the failure period. Equation 4 is then modified as follows to include the alternate service time:

$$A_M = \frac{\left[\begin{matrix}\text{actual time the system was operated in} \\ \text{the scheduled operating mode}\end{matrix}\right] + \left[\begin{matrix}\text{actual time the system was operated in} \\ \text{the alternate operating mode}\end{matrix}\right] * SRF}{\text{scheduled time for the operating mode}}$$

Eq. 4m-CS

Several methods of defining the appropriate SRF to use when alternate service is provided are possible. One approach that can be used for most situations is to base SRF on the ratio of the capacity provided versus the capacity scheduled during the time alternate service was provided as follows:

$$SRF = \frac{\text{actual capacity provided}}{\text{scheduled capacity}}$$

Eq. 22

It is important to note that the actual capacity provided during a failure mode is only useful if the alternative mode operated provides service to all stations scheduled to be served or is otherwise acceptable to the APM System Owner. If the alternative service provided during a failure period is not useful to passengers, SRF should not be calculated using Equation 22, but rather be either zero or a value lower than that calculated by Equation 22. Since the number of possible alternative modes-of-service is limited, the APM System Owner should define the desired alternate operating modes and SRF values for each, similar to the following:

Table 1: Sample SRF Values to Use When the APM System is Operated in an Alternate Mode

Actual Mode / Schedule Mode	Mode 1	Mode 2	Mode 3	Mode 4
Mode 1	SRF = 1	SRF = 0.75	SRF = 0.5	SRF = 0.1*
Mode 2	SRF = 1	SRF = 1	SRF = 0.75	SRF = 0.25*
Mode 3	SRF = 1	SRF = 1	SRF = 1	SRF = 0.75
Mode 4	SRF = 1	SRF = 1	SRF = 1	SRF = 1

In Table 1, the * denotes conditions where the SRF given in the table is less than the SRF calculated using Equation 22. For these situations, the alternate mode operated did not provide the minimum level-of-service acceptable to the APM System Owner; for example not all stations served.

Scheduled Service

For APM Systems operating in Scheduled Service mode, there are at least two types of Availabilities for passenger service that can be included in the Availability calculations; Late Departures Availability and Late Arrivals Availability. These are a

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measure of how well the train System operated according to a predetermined schedule.

The Availability equation for the individual time periods, Eq. 18, would be modified to include Late Departures Availability and Late Arrivals Availability as follows:

$$TP_{iactual} = TP_{ischeduled} * A_{LDi} * A_{LAi} * \prod_{s=1}^{N} A_{subsystemS} \quad \text{Eq. 23-SS}$$

Or alternatively:

$$TP_{iactual} = TP_{ischeduled} * A_{LDi} * A_{LAi} * A_{subsystem1} * A_{subsystem2} * \ldots * A_{subsystemS} \quad \text{Eq. 23a-SS}$$

Where:

- Late Departures Availability, A_{LDi} , as defined by Eq. 10
- Late Arrivals Availability, A_{LAi} ,as defined by Eq. 11
- Subsystem Availability, $A_{subsystemS}$,as defined in Eq. 19

Trains that departed late should be included in the number of on-time arrivals and not be considered as late arrivals if they arrive no later than the scheduled arrival time plus the late departure time since this would result in a double penalty. For example, if a train departed late by one minute, it should not be counted as a Late Arrival if it arrived within one minute of its scheduled arrival time.

On-Demand Service

For APM Systems operating in On-Demand Service mode, there are at least three types of Availabilities for passenger service that can be included in the Availability calculations; Response Time Availability, Trip Time Availability, and Misroutings Availability. These are a measure of how well the train or transportation system operated in response to trip or travel requests by passengers.

The Availability equation for the individual time periods, Equation 18, would be modified to include mode availability as follows:

$$TP_{iactual} = TP_{ischeduled} * A_{RTi} * A_{TTi} * A_{MRi} * \prod_{s=1}^{N} A_{subsystemS} \quad \text{Eq. 24-ODS}$$

Or alternatively:

$$TP_{iactual} = TP_{ischeduled} * A_{RTi} * A_{TTi} * A_{MRi} * A_{subsystem1} * A_{subsystem2} * \ldots * A_{subsystemS} \quad \text{Eq. 24a-ODS}$$

Where:

- Response Time Availability, A_{RTi} ,as defined in Eq. 8
- Trip Time Availability, A_{TTi} ,as defined in Eq. 9

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- Misroutings Availability, A_{MRi} ,as defined in Eq. 12
- Subsystem Availability, $A_{subsystemS}$,as defined in Eq. 19

Calculating TP_{day}

The appropriate equations (CS, SS, or ODS) used in the final determination of TP_{day} is dependent on the type of service provided by the APM System. Therefore, when Equation 2m is used to calculate TP_{day}, the individual values for TP_i used in the numerator depends on the type of service provided by the APM System.

Since the overall Availability for a day is calculated for discrete operating periods, the start and end of each period must be clearly defined. The operating periods can be delineated in two ways:

- Changes in scheduled service.
- Down time periods.

Changes in scheduled service represent changes in how the system or subsystem is operated and are easily quantifiable. For example, the operating mode, the number of trains, platform doors, elevators, etc. in service.

Down time periods are time periods when normal service is disrupted. For example a scheduled operating period might be broken into three shorter periods: normal service, alternative service, normal service as follows:

$$\mathbf{TP_{1actual} = TP_{1N1} + (TP_{1a} * SRF) + TP_{1N2}} \qquad \text{Eq. 25}$$

Where:

- $TP_{1actual}$ = The total adjusted time operated for the scheduled period
- TP_{1N1} = The total time of normal service before switching to alternative service
- TP_{1a} = The total time of alternative or no service as applicable
- SRF = Service Reduction Factor as defined in Eq. 22
- TP_{1N2} = The total time of normal service after switching from alternative service

Note that the term 'TP_{1a} * SRF' is primarily applicable to APM Systems operating in Continuous service.

The primary problems that occur when attempting to determine down time periods is the events that trigger or signal the end of normal service, the start of alternate or no service, the end of alternate or no service, and the start of either normal service or a different type of alternate service. For example, an 'Emergency Brakes Applied' alarm from a train with date/time information might be considered as the start of a train failure, but may not considered as an interruption of normal service until a 'Train Stopped' indication with date/time information is received from a following train.

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APM System Owners and APM System O&M Companies have vested - often differing - interests in establishing the start and end times for periods of alternative or no service. It is vital that what constitutes 'normal' and 'abnormal' service is as clearly defined and measurable as possible. For example, normal service for an APM System can be specified as a given number of trains operating in a predefined route at defined headways, and with all train and station platform doors opening and closing as required. This example can be extended to any of the subsystems such as elevators, escalators, fare gates, or any other service to be provided by the APM System.

Using the above definition for normal service, one way to define the start of abnormal service could be the date/time a train stopped due to a failure, such as a failure onboard the train or a wayside failure or event. The end of abnormal service could be when all trains are moving normally again; the stopped lead train and any trains queued behind it.

Sample Availability Calculation

Sample Availability data for an operating day without any downtime events are provided in Table 2 below. For this example, the APM System is scheduled to provide Continuous Service with four-vehicle trains and six platform stops (single side) per round trip. The daily operating schedule for this example is four six-hour time periods as follows:

- **TP_1-3 trains**
- **TP_2-6 trains**
- **TP_3-9 trains**
- **TP_4-3 trains**

The Availability criteria considered for this example are: Mode (A_M), Fleet (A_F), and Platform Doors (A_{PD}). A_M is calculated for each six-hour time period using Equation 4m:

$$A_M = \frac{\begin{bmatrix}\text{actual time the system was operated in} \\ \text{the scheduled operating mode}\end{bmatrix} + \begin{bmatrix}\text{actual time the system was operated in} \\ \text{the alternate operating mode}\end{bmatrix} * SRF}{6 \text{ hours}}$$

Eq. 4m-1

A_F is calculated for each six-hour time period using Equation 5:

$$A_{F1} = \frac{(3*4*6) \text{ hours}}{72 \text{ hours}} = 1.0$$ (3 4-vehicle trains) Eq. 5-1

$$A_{F2} = \frac{(6*4*6) \text{ hours}}{144 \text{ hours}} = 1.0$$ (6 4-vehicle trains) Eq. 5-2

$$A_{F3} = \frac{(9*4*6) \text{ hours}}{216 \text{ hours}} = 1.0$$ (9 4-vehicle trains) Eq. 5-3

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$$A_{F4} = \frac{(3*4*6)\ \text{hours}}{72\ \text{hours}} = 1.0 \qquad \text{(3 4-vehicle trains)} \qquad \text{Eq. 5-4}$$

A_{PD} is calculated for each time period using Equation 5:

$$A_{PD} = \frac{(6*8*6)}{288\ \text{hours}} = 1.0 \qquad \text{(6 platforms, 8 doors each)} \qquad \text{Eq. 7-1}$$

Table 2: Sample Availability Data without Downtime Event

Time Period	Scheduled System Hours	Mode Availability (A_M)	Scheduled Vehicle Hours	Actual Vehicle Hours	Fleet Availability (A_F)	Scheduled Platform Doors Hours	Actual Platform Doors Hours	Platform Doors Availability (A_{PD})	Time Period Actual (TPactual)
TP_1	6	1.0	72	72	1.0	288	288	1.0	6
TP_2	6	1.0	144	144	1.0	288	288	1.0	6
TP_3	6	1.0	216	216	1.0	288	288	1.0	6
TP_4	6	1.0	72	72	1.0	288	288	1.0	6
Total	24								24
A_{day}	100%								

Sample Availability data for an operating day with one downtime event involving a reduction in trains is provided in Table 3 below. In this example, one four-vehicle train is removed from service for one hour during time period TP_2.

Table 3: Sample Availability Data with One Downtime Event

Time Period	Scheduled System Hours	Mode Availability (A_M)	Scheduled Vehicle Hours	Actual Vehicle Hours	Fleet Availability (A_F)	Scheduled Platform Doors Hours	Actual Platform Doors Hours	Platform Doors Availability (A_{PD})	Time Period Actual (TPactual)
TP_1	6	1.0	72	72	1.0	288	288	1.0	6
TP_{2-1}	3	1.0	72	72	1.0	288	288	1.0	3
TP_{2-2}	1	1.0	24	20	0.833	288	288	1.0	0.833
TP_{2-3}	2	1.0	48	48	1.0	288	288	1.0	2
TP_3	6	1.0	216	216	1.0	288	288	1.0	6
TP_4	6	1.0	72	72	1.0	288	288	1.0	6
Total	24								23.833
A_{day}	99.30%								

The Fleet Availability in Table 3 was calculated as follows:

$$A_{F2-2} = \frac{20\ \text{hours}}{24\ \text{hours}} = 0.833 \qquad \text{Eq. 5-4}$$

The Daily Availability in Table 3 was calculated as follows:

$$A_{day} = \frac{(6+3+0.833+2+6+6)\ \text{hours}}{24\ \text{hours}} = 0.993 \qquad \text{Eq. 2m-1}$$

Excluding Minor Service Interruptions

Since it is impractical to expect an APM System to always operate without any minor or short duration failures, it is appropriate to not reduce calculated Availability for

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minor or short-duration failure events. Failure events considered as minor or short-duration events should not be considered as a reduction in System Availability if they cause minimal disruption to passenger service. These short duration failure events can be classified as 'Excludable Events' since they will be excluded from the System Availability calculation. The APM System Owner needs to define events that can be considered as causing minimal impact on passenger service. One method to define or set a limit on what is considered minor or short duration failure events is to consider the time between trains or headways. Trains stopped due to failures that are restarted before impacting the service of following trains can be considered as short duration failure events.

While excluding penalties for minor or short-duration failure events can be beneficial in that doing so encourages the O&M Organization to minimize the duration of service interruptions, it is important to establish a daily, weekly, or monthly limit on the maximum number of allowable minor or short-duration failure events. If the APM System experiences short duration failure events exceeding the maximum allowed, the APM System Owner may assess penalties proportional to the number of events. Setting limits on the maximum number of acceptable short-duration events encourages the O&M Organization to properly maintain the APM System equipment and subsystems and provide continuing competency training to all O&M personnel.

Exclusion of Extra Service Not Requested by APM System Owner

Typically, extra service that was not requested by the Owner outside or in addition to normal service is excluded from any consideration in the System Availability calculation. If a disruption in service occurs, then running extra trains at a later time cannot be used to offset or decrease reductions in Availability caused by the service disruption. The reason for this rationale is that providing extra service after a down time event does not compensate for passengers inconvenienced during the actual down time event.

Exclusion of APM System Failures Outside the Control of the O&M Organization

APM Systems interact with, depend on, and are influenced by systems, subsystems, and forces not controlled, operated, or maintained by the O&M Organization. When an external event interrupts the operation of an APM System, these interruptions must be documented and excluded from System Availability calculations, and the APM System Owner notified of the event. Examples include:

- Passenger induced delays (passengers hold platform or vehicle doors open past the departure time, acts of violence, medical emergencies, etc.)
- Extreme weather conditions such as flooding, excessive snow buildup, or excessive wind
- Loss of power from the electric utility
- Fire caused by equipment not operated or maintained by the O&M Organization

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APM System Performance Measurements

Measuring an APM System's performance must be as quantitative as practical. APM System performance measurements that are qualitative or subjective lead to debate and multiple interpretations. This inevitably leads to disagreements between the APM System Owner and the O&M Organization. Accordingly, the measurement and evaluation criteria must be as unambiguous as practical.

Using the System Availability Results

The System Availability calculation results can be used as an assessment of how well the APM System is being operated and maintained and as a means to encourage the O&M Organization to provide passenger service that is acceptable to the APM System Owner. Monthly payments to the O&M Organization can be increased for excellent performance and reduced for substandard or poor performance. These adjustments may be incentives used by the APM System Owner to encourage the O&M Organization to provide good service and improvements where needed.

If the System Availability results are used as a basis for payment incentives or adjustments to the O&M Organization's monthly invoices, it is important to establish a payment percentage scale that establishes performance benchmarks versus invoice payment percent. This payment scale defines System Availability percentages and a payment adjustment factor that is used to either reduce or increase the monthly invoice amounts. The payment scale or payment factor (PF) can be either linear or non-linear. For a linear scale, the correlation between System Availability percentage and PF is linearly proportionate, meaning each percent reduction in System Availability equals a proportional percent reduction in monthly payment:

$\mathbf{A_{month}}$	**PF**
100%	100%
99%	99%
Etc	Etc

One method to include positive incentives is to adjust the payment scale to set the 100% PF equal to a value less than 100%, and if the actual Availability exceeds this value then the payment factor becomes greater than one in direct relation to A_{month}. For example:

$\mathbf{A_{month}}$	**PF**
100%	100.5%
99.5%	100%
99%	99.5%
Etc	Etc

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Another method to include positive incentives is to add an additional fixed value payment amount whenever A_{month} exceeds a set value. For example, whenever A_{month} >= 99.5%, a $5,000 bonus would be added to the monthly invoice. One drawback of payment incentives is that it can become difficult for the Owner to establish an annual budget.

If the PF follows a non-linear scale, monthly payments can be reduced quickly and if A_{month} is less than a set minimum value, PF = 0. For example:

A_{month}	PF
>99%	100%
>98% A_{month} <=99%	95%
>97% A_{month} <=98%	90%
Etc	Etc
<90%	0%

The primary rationale for using a non-liner scale for PF is based on how down time events are perceived by passengers. For some APM Systems, minor service interruptions are often perceived as major problems, and therefore the APM System Owner desires the means to strongly encourage the O&M Organization to operate and maintain the APM System to avoid these interruptions.

Summary

For multiple reasons, it is important to continually measure and assess the performance of APM Systems. This paper presented various topics to consider when measuring or assessing APM System performance, how to calculate System Availability and using the results.

O&M Organizations can review the historical availability of the various subsystems for trends to determine if additional action is required such as replacement, redesign, major overhauls, etc.

To insure the accuracy of System Availability calculations, both the APM System Owner and O&M Organization should utilize personnel experienced in measuring and assessing the Availability of APM Systems. Experienced personnel are necessary to insure that the appropriate factors and criteria are considered including a review of the root data or information used to calculate A_{month}. This is important whether or not the APM System Owner provides the O&M services.

As a final note, an important issue for any APM System is passenger perception. If the APM System was carefully planned, designed, installed, tested, and operated and maintained effectively, the resulting service will meet the needs of the passengers, and passengers will likely perceive the APM System as providing good or even excellent service regardless of whether or not it meets all contractual obligations.

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