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Smart Light Rail: integrated speed and position supervision system

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ABSTRACT
In Hong Kong, the Light Rail (LR) is a manual driving railway involving interface with road traffic. Speed supervision, turnout signal alert, platform duty reminder, fleet management and inter-vehicle distance monitoring have been regarded as effective ways to improve operational safety and customer satisfaction with the LR. Owing to the lack of a single solution for all the aforementioned functions, a novel and cost-effective integration of global positioning system (GPS) and radio frequency identification (RFID) technologies, named the integrated speed and position supervision system was designed, which aligns the zero-tolerant culture of the MTR for safety through assisting its well-trained train captains to further improve operational safety. This paper presents accurate speed and location tracking with accuracies of within 3 km/h and 2 m, respectively. It covers both hardware and software designs, and explores both theoretical and practical considerations. To further enable timely reminders, user-friendliness and high reliability, human factor analysis has been conducted and the system conformed to IEC61508 Safety Integrity Level 2, which corresponds to the probability of failure per hour of at most 10^{-6}. With this integrated solution, the customer-centric LR service for a 500,000 daily patronage can be enhanced and the MTR – one of the world's leading railways – can be evolved to be a smart railway.

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1. Introduction

The Light Rail (LR) system is one of the most important means of travelling in the northwestern New Territories of Hong Kong, with approximately 500,000 passenger-trips per day [1]. Its similarities to road vehicles, such as manual driving and following a series of road signs and traffic lights, as well as its interface with road traffic are the unique features and challenges of the LR system when compared with other heavy railways.

1.1. Background

Following an incident on the LR service in May 2013, speed supervision of vehicles is regarded as an effective way to provide more structured reminders to train captains of the importance of adhering precisely to safe driving practices [2]. Furthermore, there is an increase in the LR patronage as well as the LR traffic density owing to a more frequent train service and larger fleet size, which pose rising challenges to the LR operations. To further improve manual driving safety, operational efficiency and customer satisfaction, turnout signal alert, platform duty reminder, fleet management as well as inter-vehicle distance monitoring in the LR, all became the keen interests of the MTR. These triggered the birth of the integrated speed and position supervision (iSPS) system, offering the following five key functions grouped into three categories:

Localised data processing

(1) Speed supervision: to enhance smooth driving by train captains according to the over 500 changes in speed limits along the network.
(2) Turnout signal alert: to improve the awareness of train captains when passing through over 60 turnout signals (point indicators) for directing the vehicles to different directions of tracks.
(3) Platform duty reminder: to improve the delivery of platform duties at around 160 platforms for smooth passenger journeys.

Centralised data processing

(4) Fleet management: to real-time monitor at the backend around 140 vehicles running in the LR system consisting of 36 km of track and 11 routes.

Distributed data processing

(5) Inter-vehicle distance monitoring: to supervise train captains while driving behind another vehicle with consideration of the braking profile of the LR, especially in higher speed sections.

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1.2. Reviews of market solutions

1.2.1. Fixed speed camera

A fixed speed camera is a proven product for speed monitoring. However, this product only supports fixed point detection and discrete monitoring of speed. Besides, it is reactive and has limited feedback to the train captains. Speed can be made available but the status is momentary due to the incapability of continuous monitoring. As a result, this product is not cost-effective and may encounter difficulties in implementation due to the nature of the LR system and the space available in on-site environment.

1.2.2. Automatic train protection systems

Automatic train protection systems are available in many railway systems for applying automatic control under some scenarios such as over-speeding and passing a signal without authority.

An automatic warning system (AWS) [3] uses a pair of magnets mounted on the centre of the track consisting of a permanent magnet and an electromagnet. Sensors on the train detect the state of the magnets as the train passes over them. For a signal at proceed, the system sounds a bell and the driver needs not take further action. Otherwise, a horn sound will be generated to alert the driver to acknowledge this warning. The brake will be applied automatically if there is no acknowledgement received within a defined period.

A train protection and warning system (TPWS) [4] was developed to enhance AWS by applying the brake when a train fails to stop in front of a red signal or approaches a red signal at a speed higher than the allowed value. Pairs of loops are mounted on the track, which emit different pairs of simple sinusoidal frequencies when energised (i.e. the signal is in danger). For speed supervision part, over-speeding is determined via the loops separated by a pre-defined distance and the time difference between passing across these loops.

In summary, AWS is designed for mitigating passing a signal without authority but not for speed supervision, while TPWS is used for mitigating passing a signal without authority but not for continuous speed supervision. Most importantly, one prerequisite of applying automatic train protection systems is that the vehicles have to operate in a closed system where the interfaces with road traffic can be segregated permanently (e.g. no road junctions) or temporarily (e.g. by applying barriers). This condition is not fulfilled in the LR where interfacing with road traffic is inevitable.

1.2.3. Radio based technologies

Radio frequency identification (RFID) tags are typical devices for locating vehicles along the track and enabling track-to-train communication. The information can be picked up by the vehicles so that the vehicles can be aware of their positions. Zhang and Tentzeris [5] discussed the application of RFID technology in monitoring and regulating the high-speed railway system. Nimje et al. [6] proposed the use of RFID for train tracking, which aims at reducing train collisions and accidents. Jadhav et al. [7] proposed RFID for reducing accidents at the level crossings through detecting trains before and after the level crossing areas. Furthermore, RFID technology was applied in railway condition based monitoring [8]. RFID technology also has a wide range of applications in the LR system. An example was discussed in Lee and Tsang [9]. An RFID system was implemented in the LR system for vehicle identification, which can be applied to passenger information as well as to maintenance systems. However, RFID tracking is discrete since RFID tags are installed at fixed and discrete locations.

Alternatively, global positioning system (GPS) can be applied for positioning of vehicles. Bajaj et al. [10] presented a GPS fleet management solution and showed how this benefits the transportation industry in terms of productivity and efficiency. However, the trackside status (e.g. status of signals) cannot be passed to the vehicle. There is also a discussion on the application of GPS in the tracking of trackside workers and alerting these workers to any approaching trains [11]. Although there have been explorations of incorporating global navigation satellite systems (GNSS) into European railway signalling, the key challenges ahead are that further discussions among various parties such as manufacturers of signalling systems and equipment, and railway operators are required for using GNSS in safety-related applications [12]. GPS also has its application in railway maintenance. As proposed by Kumar et al. [13], GPS can be used to provide the location during rail crack detections and inspections to automate the reporting mechanism. Furthermore, Malathy et al. [14] extended this application by equipping live video streaming capability.

1.2.4. Manual driving monitoring systems

There are manual driving monitoring systems on the market, offering speed and safety warning via visual or audible signals to the drivers [15]. Moreover, some systems monitor the alertness of drivers through analysing the visual, audible or mechanical responses received from drivers [16]. In view of potential driver inattention due to distraction and fatigue, Dong et al. [17] presented a driver inattention monitoring system. However, all these systems are developed for road vehicles, not railways.

1.3. Novel integration of GPS and RFID in the LR system

Although GPS and RFID are mature technologies, the integration of GPS and RFID is also explored in different applications. There are no single products or standard solutions in the industry that can directly be applied to the LR for all the intended applications, namely speed supervision, turnout signal alert, platform duty reminder, fleet management and inter-vehicle distance monitoring. As such, the iSPS has been designed.

For example, Chakraborty and Biswas [18] proposed the integration of GPS and RFID for automatic door opening in buses. GPS was applied for providing the speed and location of the buses, while RFID was used for identifying the buses arrived at the stops. Similarly, Yelamarthi et al. [19] presented the implementation of robotics equipped with automatic navigation capabilities based on GPS and RFID for assisting visually impaired people.

As a result, customisation and innovative efforts are required to aggregate an array of technologies (i.e. GPS and RFID) such that the intended functionalities can be delivered to improve the LR safety and operating performance, and shape the LR to be a smart LR.

1.4. Pilot trials on the application of GPS and RFID in the LR

GPS and RFID are the cores of the iSPS. In order to verify the performance of these two technologies, two separate pilot trials using GPS and RFID technologies were conducted immediately following the incident in May 2013. Based on literature reviews, site surveys and measurements, the following two solutions were designed, developed and validated in the actual LR environment:

(1) GPS solution: to provide continuous speed supervision with position accuracy of within 3 m and fleet management for five selected vehicles along the whole LR system, including under podium areas without GPS coverage, e.g. terminus.

(2) RFID solution: to provide speed supervision with position accuracy of within 1.5 m and turnout management at the selected turnouts as well as platform management at the selected platforms for ten selected vehicles. Radiated powers of RFID equipment are 1 W. The distance between antenna of RFID reader and RFID tag was around 300 mm. At each location, no missing detection was allowed unless due to equipment failure.

The success of these pilot trials has provided a solid foundation for the design, algorithm and track profile of the fleet implementation of the iSPS. Although GPS supported continuous location tracking, the reception was limited at the under podium areas. In order to achieve high position accuracy, GPS was used for adjusting the primary position from an odometer at discrete reference points instead. On the other hand, RFID required equipment installation on tracks and thus might be limited due to the physical environment. These factors triggered the integration of GPS and RFID to provide a cost-effective solution. Detailed designs will also be covered in later sections.

1.5. Outline of this paper

The rest of this paper is organised as follows. In Section 2, the system architecture together with the hardware design and configuration are overviewed. Section 3 describes the system designs for speed supervision. In Section 4, the mechanism for turnout signal alert is proposed. In Section 5, platform duty reminder will be discussed. Section 6 presents the design for fleet management. Inter-vehicle distance monitoring will be proposed in Section 7. Finally, Section 8 summarises the work and discusses potential future possibilities.

2. System architecture and hardware configuration

In this section, the system architecture and the hardware configuration of the whole iSPS will be presented. The system comprises three parts, namely trainborne, trackside and backend.

2.1. Trainborne

On each vehicle, there is a set of equipment consisting of the following:

- Two units of controllers, each comprising processing, GPS and mobile capabilities and being connected to other trainborne devices as interfaces.
- Two units of RFID readers for detecting RFID tags installed along the track (antennae of RFID readers are installed to face downwards, i.e. perpendicular to rail surface).
- One unit of the panel for interaction with train captains.

The trainborne interfaces are listed as follows:

- Power supply: to power up the system.
- Odometer: to reflect the revolution of wheels by providing pulses.
- Door open status: to provide status on the door open operation.
- Coupled car status: to reflect the existence of a coupled car.
- Driver desk occupancy status: to inform the system whether the car is the driver car with the presence of a train captain.
- On-board information system: to provide information on the route and run numbers of the vehicle.

There is resilience on the trainborne design with two controllers and two RFID readers. The panel monitors

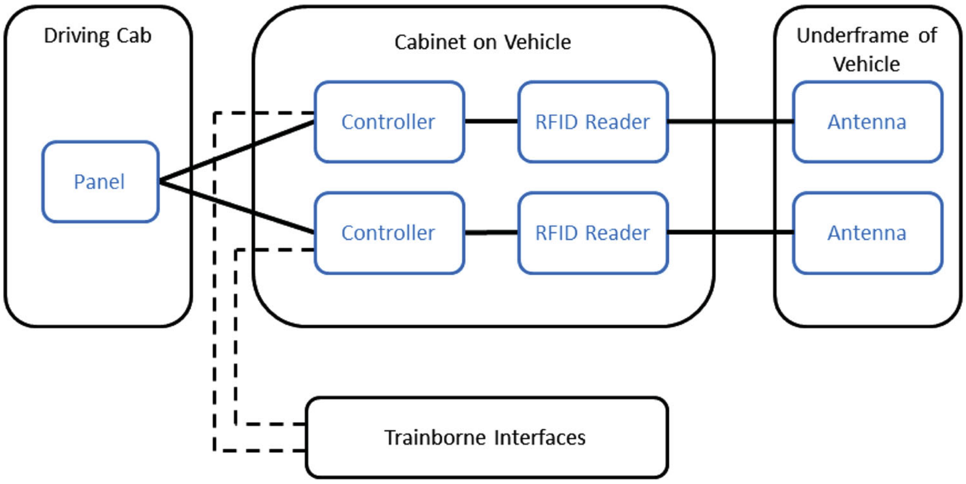

Figure 1. Trainborne architecture of the iSPS.

the statuses of the controllers and RFID readers and determines which controller's output will be reflected on the panel. Figure 1 summarises the trainborne architecture.

2.2. Trackside

There are two types of location installed with RFID tags. At each location, two RFID tags are provided as resilience design.

(1) Platform: RFID tags are installed at the arrival end of a platform as reference points for location tracking.
(2) Turnout: RFID tags connect to the point indicators for the signal statuses and are installed at locations corresponding to the last points to brake due to the presence of authorised signals ahead.

The design at turnout is further elaborated in Figure 2. An authorised signal is defined as the presence of a proceed aspect for only one turnout direction together with the absence of a stop aspect. Failsafe design is implemented in the way that no authorised signal will be reflected by RFID in the event of equipment faults.

The RFID equipment operates under the frequency band between 920 MHz and 925 MHz, which complies with the performance specification under OFCA 1049. RFID tags are installed to face upwards (i.e. perpendicular to the rail surface). Radiated powers of RFID equipment are 0.3 W. The distance between the antenna of the RFID reader and the RFID tag is around 300 mm. In order to support the position accuracy of RFID detection of within 1 m (i.e. 2 m detection zone) under all speeds up to 80 km/h which is the design speed of the LR, an on-site measurement was conducted to fine-tune the position accuracy, while design calculations were conducted to ensure the RFID detection rate was frequent enough to detect at least once within the 2 m detection zone under a speed of 80 km/h. In other words, the minimum RFID detection rate is calculated as follows:

$$\frac{80 \div 3.6\,(\mathrm{ms}^{-2})}{2\,(\mathrm{m})} = 11.1\ \mathrm{Hz}. \qquad (1)$$

Moreover, to assure the reliability of the trainborne and trackside equipment, the iSPS conforms to the requirements as stipulated in IEC61508 Safety Integrity Level 2 in order to achieve the probability of failure per hour of at most 10^{-6}.

2.3. Backend

Backend comprises the central server and a number of monitoring workstations interconnected using network

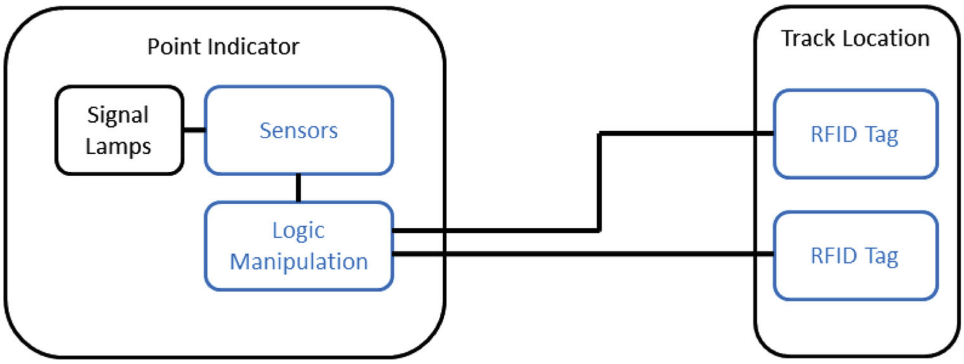

Figure 2. Design at turnout.

switches. The central server is also equipped with internet access capability, enabling vehicles to report data to it. All these wide area network connections ride on the long term evolution (LTE) backbone [20] due to the high throughput, low latency and mobility-supported features. In order to strengthen the network security provision, firewalls are deployed before internet access by backend and as the virtual private network (VPN) server for the connections with vehicles. Moreover, the central server acts as a bridge between trainborne equipment and external interfaces on the internet, for example the time server, assisted-GPS (A-GPS) server and endpoint protection signature server.

3. Speed supervision

This function comprises three parts, namely speed calculation, location tracking and alert generation.

3.1. Speed calculation

The real-time speed of the light rail vehicle (LRV) at time t, denoted by $v(t)$, is given as follows:

$$\frac{[c(t) - c(t-\Delta t)] \times (\pi D_{\text{system}}/N)}{\Delta t}, \tag{2}$$

where $c(t)$ denotes the accumulated odometer pulse counts at time t, Δt denotes the time interval for calculating the speed, N refers to the number of odometer pulses generated per wheel revolution, and D_{system} is the wheel diameter used in the system. The explanation is as follows:

$$\begin{aligned} v(t) &= \frac{d}{dt}x(t) = \lim_{\Delta t \to 0} \frac{x(t) - x(t-\Delta t)}{\Delta t} \\ &\approx \frac{[c(t) - c(t-\Delta t)] \times (\pi D_{\text{system}}/N)}{\Delta t}, \end{aligned} \tag{3}$$

where $x(t)$ denotes the accumulated distance travelled at time t.

Under the design and specification of the LR, the distance calculated from the odometer pulse counts should be a stepwise function of time, thus Δt will be chosen to balance between the accuracy and the processing performance.

3.2. Location tracking

Because of the railway nature, the location tracking algorithm proposed for the iSPS is largely different to that documented by Kim and Kim [21] which used GPS for the primary positioning, supplemented by RFID, inertial navigation system and dead reckoning. Primary location tracking is based on the distance travelled, calculated from odometer pulse counts, where $d_{\text{odometer}}(t)$ is the distance travelled at time t and is given by $d_{\text{odometer}}(t) = c(t) \times (\pi D_{\text{system}}/N)$. The actual distance travelled at time t, denoted by $d_{\text{actual}}(t)$, is given by $d_{\text{actual}}(t) = d_{\text{odometer}}(t) + d_{\text{error}}(t)$, where $d_{\text{error}}(t)$ denotes the error which is defined by (simplified by removing other negligible errors) $d_{\text{error}}(t) = d_{\text{wheel}}(t) + d_{\text{slip/slide}}(t) + d_{\text{compensation}}(t)$. The error at time t due to the difference between actual wheel diameter, denoted by D_{actual}, and the wheel diameter used in the system, denoted by D_{system}, is expressed as $d_{\text{wheel}}(t) = c(t) \times (\pi(D_{\text{actual}} - D_{\text{system}})/N)$. This error is due to two main reasons, namely normal wear and tear during movement of the vehicle and wheel reprofiling during maintenance. The error at time t due to wheel slip/slide is given by $d_{\text{slip/slide}}(t)$, while $d_{\text{compensation}}(t)$ denotes the error in the compensated position compared with the actual position due to GPS and RFID tolerance at reference points, which will be bounded by δ.

There are two types of reference points, namely RFID reference points and GPS reference points. The RFID reference points are those locations installed with RFID tags at platforms and turnouts as mentioned in Section 2.2, while the GPS reference points are designated stopping positions at platforms which are chosen based on the following “R^2 Principles”:

(1) Reliable: the accuracy of GPS measurement at a selected reference point should be within 20 m root mean square (RMS) [22]. The GPS distance (in m) is calculated using the following formula [23]:

$$12742000 \sin^{-1} \times \left(\sqrt{\begin{array}{c} \sin^2\left(\frac{lat_1 - lat_2}{2}\right) \\ + \cos(lat_1)\cos(lat_2)\sin^2\left(\frac{lon_1 - lon_2}{2}\right) \end{array}} \right), \tag{4}$$

and the bearing from (lat_1, lon_1) to (lat_2, lon_2) is expressed as [24]:

$$\tan^{-1}\left(\frac{\sin(lon_2 - lon_1)\cos(lat_2)}{\begin{array}{c}\cos(lat_1)\sin(lat_2) - \sin(lat_1) \\ \cos(lat_2)\cos(lon_2 - lon_1)\end{array}} \right), \tag{5}$$

which will be mapped from the domain −180° to +180° to the domain 0° to +360°.

(2) Robust: a pre-defined region and reference point will be selected such that (i) the pre-defined region contains over 50% of GPS measurement when the vehicle is at the reference point, and (ii) the error probability for GPS measurement to fall within the pre-defined region while the vehicle is outside the platform should be below 10%, assuming the distributions of the GPS measurement are identical. An example of distribution is shown in Figure 3.

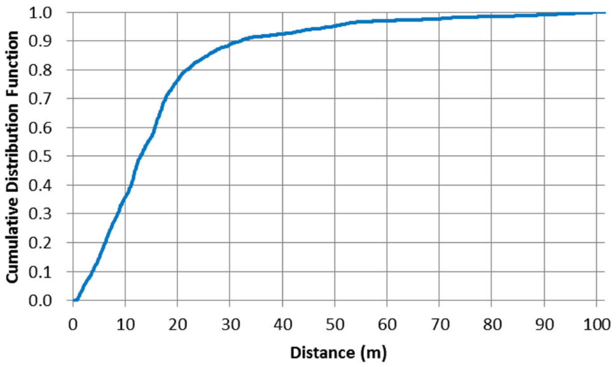

Figure 3. Cumulative distribution functions for the distance of GPS measurements at a reference point.

The relationship between the pre-defined region and error probability is expressed in Proposition 1.

Proposition 1: Given that the radius of the pre-defined region is R and the track distance between the reference point and the platform end is D, the error probability is upper bounded by:

$$\frac{\tan^{-1}\left(R/\sqrt{(D-R)(D+R)}\right)}{\pi}(p_{D+R}-p_{D-R}), \quad (6)$$

where p_{D+R} and p_{D-R} are the probabilities for a GPS measurement to be contained within $D+R$ and $D-R$, respectively.

Proof: The error probability will be the probability that the GPS measurement falls into the pre-defined region, which is upper bounded by the differences in the probabilities for a GPS measurement to fall within $D+R$ and $D-R$ from GPS coordinates beyond platform areas over the minimum sector that can cover the pre-defined region. The result follows from the cumulative distribution functions of GPS distances and the bearings and the results of coordinating geometry for circles [25]. In particular, the distribution of the bearings is close to uniform distribution from 0° to +360° (Figure 4). Figure 5 further illustrates the idea of the proof via geometric illustration of Proposition 1.

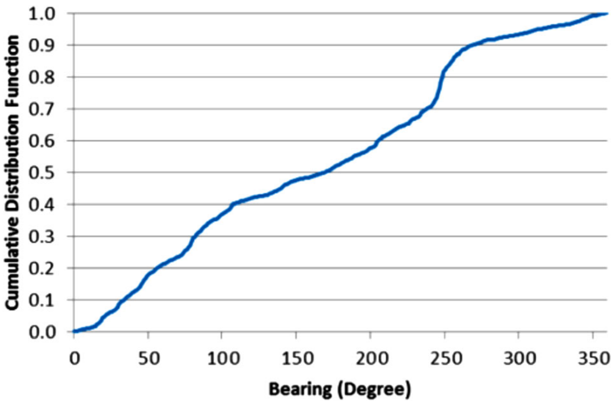

Figure 4. Cumulative distribution functions for bearing of GPS measurements at a reference point.

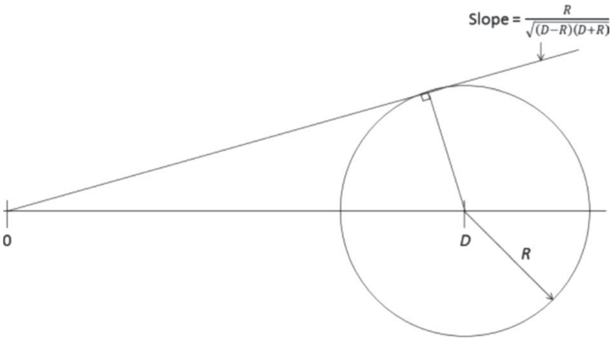

Figure 5. Illustration of the proof of Proposition 1.

Table 1. Notation involved in the calibration of wheel diameter.

D_i:	Distance between reference points i and i-1
d_i:	Distance in stopping positions between reference points i and i-1
c_i:	Increment in pulse count between reference points i and i-1
$\tilde{D}^{(i)}$:	Wheel diameter based on the data between reference points i and 0
δ_i:	Deviation between the distance from reference points 0 and i and the distance in stopping positions from reference points 0 and i
δ:	Tolerance in stopping position with respect to actual position

There are three types of data involved in the calibration of wheel diameter, namely pulse count, actual stopping position, and actual distance between the reference points. In the calibration mechanism, three consecutive reference points are used for the calculation – reference points 0, 1 and 2. Table 1 shows the notations that are applied in the calculation. Therefore, the wheel diameters can be calculated as $\tilde{D}^{(1)} = (N/\pi)(D_1/c_1)$ and $\tilde{D}^{(2)} = (N/\pi)((D_1+D_2)/(c_1+c_2))$. Assume that there is no wheel slip/slide between the reference points, due to the RFID and GPS tolerance, $\tilde{D}^{(1)}$ and $\tilde{D}^{(2)}$ may not be identical. The difference in circumferences is given as follows:

$$\begin{aligned}|\pi\tilde{D}^{(1)} - \pi\tilde{D}^{(2)}| &= N\left|\frac{D_1}{c_1} - \frac{D_1+D_2}{c_1+c_2}\right| \\ &= N\left|-\frac{1}{c_1}\delta_1 + \frac{1}{c_1+c_2}\delta_2\right|.\end{aligned}$$

Lemma 1: The feasible region for δ_1 and δ_2 is expressed as $\delta_1-\delta_2-2\delta \le 0$, $-\delta_1+\delta_2-2\delta \le 0$, $\delta_1-2\delta \le 0$, $-\delta_1-2\delta \le 0$, $\delta_2-2\delta \le 0$ and $-\delta_2-2\delta \le 0$.

Proof: Based on the distance between reference points i and i-1, $-2\delta \le \delta_1 \le 2\delta$ and $-2\delta \le \delta_2 \le 2\delta$ are obtained. For $-2\delta \le \delta_2 \le 0$, $\delta_2 \le \delta_1 \le 2\delta+\delta_2$ are obtained. For $0 \le \delta_2 \le 2\delta$, $\delta_2-2\delta \le \delta_1 \le \delta_2$ are obtained. By symmetry, $\delta_1 \le \delta_2 \le 2\delta+\delta_1$ for $-2\delta \le \delta_1 \le 0$, and $\delta_1-2\delta \le \delta_2 \le \delta_1$ for $0 \le \delta_1 \le 2\delta$ are obtained. Finally, the result follows by combining them as:

$$\begin{aligned}&\{(\delta_1,\delta_2)| -2\delta \le \delta_1 \le 2\delta, -2\delta \le \delta_2 \le 0, \\ &\quad \delta_2 \le \delta_1 \le 2\delta+\delta_2\} \\ &\cup \{(\delta_1,\delta_2)| -2\delta \le \delta_1 \le 2\delta,\ 0 \le \delta_2 \le 2\delta, \\ &\quad \delta_2-2\delta \le \delta_1 \le \delta_2\}\end{aligned}$$

$$\begin{aligned}&\cup \{(\delta_1,\delta_2)| -2\delta \le \delta_1 \le 0, -2\delta \le \delta_2 \le 2\delta,\\ &\quad \delta_1 \le \delta_2 \le 2\delta+\delta_1\}\\ &\cup \{(\delta_1,\delta_2)| -2\delta \le \delta_1 \le 0, 0 \le \delta_1 \le 2\delta,\\ &\quad \delta_1 - 2\delta \le \delta_2 \le \delta_1\}.\end{aligned}$$

Proposition 2: The maximum value of $|\pi\tilde{D}^{(1)} - \pi\tilde{D}^{(2)}|$ is $((2\delta\pi D_{\max})/(d_{\min} - 2\delta))$, where $d_{\min}$ is the minimum distance between two reference points.

Proof: The objective is re-written to maximise the following:

$$\left|\pi\tilde{D}^{(1)} - \pi\tilde{D}^{(2)}\right| = \begin{cases} N\left(-\dfrac{1}{c_1}\delta_1 + \dfrac{1}{c_1+c_2}\delta_2\right), \\ \quad \text{for } (c_1+c_2)\delta_1 - c_1\delta_2 \le 0 \\ N\left(\dfrac{1}{c_1}\delta_1 - \dfrac{1}{c_1+c_2}\delta_2\right), \\ \quad \text{for } -(c_1+c_2)\delta_1 + c_1\delta_2 \le 0 \end{cases}, \tag{7}$$

and is the maximum of optimal values of the sub-problems. Sub-problem 1 is the maximisation of $N(-(1/c_1)\delta_1 + (1/(c_1+c_2))\delta_2)$ with the constraints stated in Lemma 1 together with $(c_1+c_2)\delta_1 - c_1\delta_2 \le 0$. While Sub-problem 2 is the maximisation of $N((1/c_1)\delta_1 - (1/(c_1+c_2))\delta_2)$ with constraints stated in Lemma 1 together with $-(c_1+c_2)\delta_1 + c_1\delta_2 \le 0$. Each sub-problem is a linear programming problem and is hence a convex programming problem. The optimal solutions of both sub-problems satisfy the Karush–Kuhn–Tucker (KKT) conditions [26], which both give a maximum value of $(2N/c_1)\delta$. As a result:

$$\left|\pi\tilde{D}^{(1)} - \pi\tilde{D}^{(2)}\right| \le \frac{2N}{c_1}\delta \le \frac{2N\delta}{(N(d_{\min} - 2\delta)/\pi D_{\max})} = \frac{2\delta\pi D_{\max}}{d_{\min} - 2\delta}.$$

If the difference in circumference is within $((2\delta\pi D_{\max})/(d_{\min} - 2\delta))$, the value of $\tilde{D}^{(2)}$ is trusted to be consistent and will be adopted as D_{system}. At the same time, the position will be adjusted to the position of reference point 2 to compensate $d_{\text{error}}(t)$.

3.3. Alert generation

Over-speed alert is a primary alert generated to train captains, and over-speeding is defined as $v(t) > V_{\text{limit}}$, where V_{limit} is the speed limit. Apart from over-speed alert, a pre-alert can be supported due to the continuous location tracking. Pre-alert aims at reminding train captains to apply the brake in order to avoid over-speeding when entering the next speed limit zone, even though there is no over-speeding currently. The calculation of pre-alert is based on the next speed limit zone with a different speed limit from the current one. Based on the current speed, minimum acceleration (i.e. maximum deceleration) for the vehicle, the distance to the next speed limit zone (with speed limit $V_{\text{next limit}}$) and the response time of train captain denoted by $v(t)$, $a_{\min}$, $d_{\text{remaining}}(t)$, and T_{R}, respectively, the pre-alert will be generated when $v(t) > V_{\text{next limit}}$ and $d_{\text{remaining}}(t) \le D_{\text{minimum}}(v(t), a_{\min}, T_{\text{R}}, V_{\text{next limit}})$, where D_{minimum} is the minimum deceleration distance required, assuming the current speed is maintained during response time and minimum acceleration is applied during braking and is given by the following:

Table 2. Numerical examples on minimum deceleration distance.

		$V_{\text{next limit}}$ **(km/h)**							
D_{minimum} (m)		0	10	20	30	40	50	60	70
$v(t)$**(km/h)**	**10**	3							
	20	12	9						
	30	27	24	15					
	40	47	45	36	21				
	50	74	71	62	47	27			
	60	107	104	95	80	59	33		
	70	145	142	134	119	98	71	39	
	80	190	187	178	163	142	116	83	45

$$D_{\text{minimum}} = T_{\text{R}}v(t) + \frac{V_{\text{next limit}}^2 - (v(t))^2}{2a_{\min}}. \tag{8}$$

If the conditions for generating both alerts are satisfied, over-speed alert will have the highest priority for overriding pre-alert.

3.4. Actual LR environment

In the following, the actual environment is considered in the LR and some numerical examples are illustrated. The parameters used are $a_{\min} = -1.3\,\text{ms}^{-2}$, $T_{\text{R}} = 2$ seconds, $N = 110$ and $D_{\max} = 720$ mm. Table 2 shows some examples of the minimum deceleration distance under pre-alert.

4. Turnout signal alert

This section introduces the principles of turnout signal alert. Owing to the differences in operations and designs at non-terminus turnouts and terminus turnouts, the locations of providing the alerts are customised accordingly.

4.1. Non-terminus

A vehicle shall not pass a turnout with a speed exceeding 15 km/h and a point request loop is installed 18 m before the point indicator for the train captains to request the correct direction to proceed. In order to be able to stop in time before the point indicator in case there is no authorised signal, the reminder at the last point to brake has to be delivered at the following distance before the point indicator:

$$\begin{aligned}&\text{RFID Accuracy} + \text{Reaction Distance},\\&\quad + \text{Braking Distance},\end{aligned} \tag{9}$$

$$= 1\,\text{m} + \left(\frac{15}{3.6} \times 2\right)\text{m} + \frac{(15/3.6)^2}{2 \times 1.3}\text{m} = 16\,\text{m}. \tag{10}$$

In other words, the last point to brake will be at 2 m after the point request loop.

4.2. *Terminus*

A vehicle has to stop at the point request loop to wait for the availability of the intended platform to berth at terminus. As such, the location for providing the alert will be the same as the point request loop. A temporary speed limit of 0 km/h will also be imposed to remind the driver to stop in front of the point request loop. Once the vehicle stops, this temporary speed limit will be removed. At the same time, if the vehicle moves again without authorised signal, the turnout signal alert will be generated.

5. Platform duty reminder

Based on the location tracking function provided, a vehicle can be accurately located along the LR. With the interface on driver desk occupancy status, it can be determined whether that system is located in the car with the presence of a train captain. The system will only deliver a platform duty reminder for the car with a train captain. Moreover, with the interface on coupled car status, the vehicle length can be determined to ensure the system knows when the whole vehicle berths within the platform. Furthermore, platform duty reminder aims to facilitate the delivery of platform duties, thus through the interface with an on-board information system, the system can determine whether the vehicle is running a passenger service. Finally, when the whole passenger-service vehicle berths within the platform, reminders on the delivery of platform duties will be generated until the door open is detected.

6. Fleet management

The workstations at the backend display the latest information received from the vehicles. Based on the received information in the data harvesting process, the workstations convert and encapsulate the information for user monitoring. The positions of the vehicles are shown on the map, while the remaining details consist of speed, descriptive names for the locations, alert statuses and equipment healthiness.

The workstations also support report generation, which retrieves the stored data and exports based on the user requirements, such as vehicle number, date and time, route and run numbers, speed, position and wheel diameter.

Moreover, the workstations allow the updating of track speed profiles and remote downloading to the vehicles via the LTE network. Upon completion of downloading the changes, the updated track speed profiles will be activated for the operations accordingly. To ensure the track speed profiles are up-to-date, the vehicles will update the currently used version to the central server as cross-checking.

7. Inter-vehicle distance monitoring

The previously mentioned functions of speed supervision, turnout signal alert and platform duty reminder all rely on local data and are processing within a vehicle. However, the fleet management function of the system actually collects real-time data, including vehicle identity, speed, position, route and so on, of the entire LR. With this holistic picture of the LR, backend can inform a vehicle of the speed and position of the vehicle in front of it through data analysis. Based on this information, a vehicle can determine whether there is enough separation with the vehicle in the front.

Proposition 3: Given the speed of the vehicle in the front (v_0), the speed of the vehicle (v_1), the acceleration of the vehicle in the front (a_0), the acceleration of vehicle (a_1) and the response time of the train captain (T_R), the minimum separation with the vehicle in the front is given as follows:

$$\max\left\{0, v_1 T_R - \frac{v_1^2}{2a_1} + \frac{v_0^2}{2a_0}\right\}. \tag{11}$$

From safety's perspective, it is assumed that $a_0 \le a_1$.

Proof: Denote the separation with the vehicle in the front by S, the situation is modelled as the following optimisation problem which minimises S with the following constraints:

$$\begin{aligned}&S + v_0 t + \frac{1}{2}a_0 t^2 \ge v_1 T_R + v_1(t - T_R)\\&\quad + \frac{1}{2}a_1(t - T_R)^2, \text{ for } T_R < t \le T_R - \frac{v_1}{a_1},\end{aligned} \tag{12}$$

$$S + v_0 t + \frac{1}{2}a_0 t^2 \ge v_1 t, \text{ for } 0 \le t \le T_R, \tag{13}$$

$$0 \le t \le -v_0/a_0, \tag{14}$$

$$S \ge 0. \tag{15}$$

Case 1: $T_R - v_1/a_1 < -v_0/a_0$ (i.e. The vehicle stops before the vehicle in the front does.)

- If $0 \le t \le T_R$, $S \ge \max\{0, v_1 T_R - v_0 T_R - \frac{1}{2}a_0 T_R{}^2\} = 0 \overset{\text{def}}{=} S_{1a}$.

- If $T_R < t \le T_R - v_1/a_1$, $S \ge \max\{0, v_1 T_R - v_0 T_R - \frac{1}{2} a_0 {T_R}^2\} = 0 \overset{\text{def}}{=} S_{1b}$.
- Therefore, $S \ge \max\{S_{1a}, S_{1b}\} = 0$.

Case 2: $T_R - v_1/a_1 \ge -v_0/a_0 > T_R$ (i.e. The vehicle in the front stops no later than the vehicle does and after the train captain of the vehicle applies the brake.)

- If $0 \le t \le T_R$, $S \ge \max\left\{0, v_1 T_R - v_0 T_R - \frac{1}{2} a_0 {T_R}^2\right\} \overset{\text{def}}{=} S_{2a}$.
- If $T_R < t \le -v_0/a_0$,

$$S \ge \max\left\{0, \frac{1}{2} a_1 {T_R}^2 + \frac{v_0}{a_0}(v_0 - v_1 + a_1 T_R) - \frac{1}{2}(a_0 - a_1)\left(\frac{v_0}{a_0}\right)^2\right\} = 0 \overset{\text{def}}{=} S_{2b}.$$

- If $-v_0/a_0 < t \le T_R - v_1/a_1$, $S \ge \max\left\{0, v_1 T_R - \frac{v_1^2}{2a_1} + \frac{v_0^2}{2a_0}\right\} \overset{\text{def}}{=} S_{2c}$.

- Therefore, $S \ge \max\{S_{2a}, S_{2b}, S_{2c}\} = S_{2c}$.

Case 3: $T_R \ge -v_0/a_0$ (i.e. The vehicle in the front stops no later than the train captain of the vehicle applies the brake.)

- If $0 \le t \le T_R$, $S \ge \max\left\{0, v_1 T_R + \frac{v_0^2}{2a_0}\right\} \overset{\text{def}}{=} S_{3a}$.
- If $T_R < t \le T_R - v_1/a_1$, $S \ge \max\left\{0, v_1 T_R - \frac{v_1^2}{2a_1} + \frac{v_0^2}{2a_0}\right\} \overset{\text{def}}{=} S_{3b}$.

- Therefore, $S \ge \max\{S_{3a}, S_{3b}\} = S_{3b}$.

From Case 1, the result further implies that $v_1 T_R - (v_1^2/2a_1) + (v_0^2/2a_0) \le 0$. By combining Case 1, Case 2 and Case 3, the overall solution is given as follows:

$$S \ge \max\left\{0, v_1 T_R - \frac{v_1^2}{2a_1} + \frac{v_0^2}{2a_0}\right\}.$$

Therefore, the minimum distance is the braking distance of the vehicle minus that of the former vehicle or zero, whichever is larger. Table 3 illustrates some examples of the minimum separation distance in the LR.

Table 3. Numerical examples on minimum separation.

Minimum separation distance (m)		v_0(km/h)								
		0	10	20	30	40	50	60	70	80
v_1 **(km/h)**	**10**	9	7	3	0	0	0	0	0	0
	20	23	22	17	10	0	0	0	0	0
	30	43	42	38	31	21	8	0	0	0
	40	70	68	64	57	47	34	18	0	0
	50	102	101	96	89	79	66	51	32	11
	60	140	139	135	127	117	104	89	70	49
	70	184	183	179	171	161	149	133	114	93
	80	234	233	229	222	212	199	183	165	143

8. Conclusion and future work

Speed supervision, turnout signal alert, platform duty reminder, fleet management and inter-vehicle distance monitoring have been regarded as effective ways to improve operational safety and customer satisfaction in the LR, which faces challenges such as manual driving, interface with road traffic and increasing traffic density. There is no single solution for all the aforementioned functions. In this paper, an innovative integration of GPS and RFID technologies is designed and implemented. Vehicle locations can be identified accurately and continuously to enable speed supervision by timely reminders to train captains of (potential) over-speeding. RFID reflects the status of the point indicators to the vehicles for the delivery of reminders on any stop signal ahead. Moreover, the proposed solution reminds train captains to carry out platform duties when the vehicles berth inside the platforms. All the data are harvested and returned to the backend for fleet management via the LTE backbone. With all these data being analysed at the backend, inter-vehicle distance monitoring on the separation with the vehicle ahead can be provided. These align with the zero-tolerant culture of the MTR for safety by assisting its well-trained train captains to further improve operational safety. Human factor analysis has been conducted to ensure operational effectiveness while the system was designed with high reliability by conforming to IEC61508 Safety Integrity Level 2, corresponding to the probability of failure per hour of at most 10^{-6}.

As a next step, the application of the Internet of Things (IoT) [4] as well as big data analysis will be explored to improve the manual driving behaviour of drivers based on the data collected. Moreover, bring your own device (BYOD) can be visualised with the provision of mobile apps on functions riding on the big data stored by the system, such as for passenger viewing of train schedules. The arrival information can be deduced through the collection of a vast amount of data. In summary, the future opportunities help enhance the customer-centric train service for a 500,000 daily patronage of the LR and shape the LR to be a smart LR.

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Mr Sum Chan joined the MTR in 1995 and is now a subject matter expert in the design of passenger information systems in the MTR. He has over 10 years' experience in design and implementation of various electronic and computer control systems for rail passenger communication such as passenger information display systems and public address systems. He received his M.Sc. degree in Information Technology from The Hong Kong University of Science and Technology. Currently he leads a small team studying and developing several new systems that adopt cutting-edge technologies for enhancing customer experience in the MTR.

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