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Train Localization by Mutual Correction of Acceleration and Interior Sound

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ABSTRACT
For efficiency of the track management, several on-board monitoring systems have been developed to check the track conditions operating in the commercial trains. These systems can detect the change of the track, as well as the location information by GPS. However it can't be utilized inside the tunnel or in mountainous areas. In this study, a method of train localization through the mutual correction of acceleration and interior sound is proposed and implemented with smart phones. First the acceleration in the travel direction is integrated to obtain the approximate train speed. Then the interior sound generated by passing the rail joint is utilized to calculate the train speed. Furthermore the background noise can be removed by sparse representation to extract the clear rail joint sound. Finally the travel distance is identified by the integration of the corrected speed to obtain the train location. A verification test has been carried out in the experiment train. The implement of the proposed method by a simple equipment such as smart phones can achieve a 5% identification accuracy. This approach is expected to provide a simple and accurate train localization tool for track management.

KEYWORDS: *Train localization, interior noise, acceleration, rail joint, signal processing.*

1. INTRODUCTION

For railway operators, the maintenance and management of the entire railway system is the duty. Among them, track management is an important business especially. The track receives iteratively external impact from running vehicles which results the distortion in the vertical and horizontal directions, i.e., rail irregularity. The slack regular maintenance on rail irregularity might lead to serious accidents such as huge vibration or even derailment. The periodic investigation of rail conditions is significant.

High precision inspection cars have been utilized for detected the defects in the rail in the world. The cost of the manufacture and operation of these cars, however, is very expensive, which prevents frequent usage in the daily maintenance. For efficiency of the track management, development of simple inspection techniques are desired.
Several on-board monitoring systems have been developed to check the track conditions operating in the commercial trains [1]. These systems can detect the change of the track by the analysis on the responses of trains measured by sensors, usually the acceleration responses in the axel box, bogie or the car. In the meantime, the exact location information of the detected change is also crucial for the sake of track maintenance, which is generally obtained by the GPS. However it can't be utilized inside the tunnel or in mountainous areas where GPS radio waves cannot reach. To solve this issue, tachometer generator or manual marker is utilized in Japan. A tachometer generator converts the instantaneous values of rotor speed of wheel into an electrical impulse signal to obtain the train velocity. It could accurately measures the train speed by compensating the error from idling, slip and so on, but the modification of the wheelset is necessary to install it. Therefore it is hard to be used in the commercial trains. The manual marker has been accepted in the railway industry even though the measurement accuracy highly depends on the experience of operators. It is obviously hard to be popularized to frequent daily usage. The development of a simple technique that can localize the train in such sections is necessary.

When the train passes the rail joint, the impact will generalize the impulse acceleration of the vibration, together with the distinct sound. In this study, a method of train localization through the mutual correction of acceleration and interior sound is proposed and implemented with smart phones. First the acceleration in the direction of travel is integrated to obtain the approximate train speed. In general, large bias and noise exist in this integrated speed. Then it can be corrected by the train speed estimated from the interior sound in this study. The interior sound generated by passing the rail joint is utilized to calculate the train speed with the known distance between the front and rear wheels. Furthermore the background noise can be removed by multi-resolution analysis or sparse representation to extract the clear rail joint sound. Finally the travel distance is identified by the integration of the corrected speed to obtain the train location. A verification test has been carried out in the test train.

2. BASIC IDEA AND FIELD MEASUREMENT

2.1. Basic idea

Rails are produced in fixed lengths and need to be joined end-to-end to make a continuous surface on which trains may run. The rail joint is a splice connecting the adjacent ends of rails, which exists in all the rail system. Since the location data of the rail joint should be mastered by the railway operator, it might be used as the mark to identify the train location. When the train passes the rail joint, an impact will result the impulse vibration, especially in the high frequency range, as well as the distinct sound. Previous research has shown the possibility to utilize the vertical acceleration recorded inside the car body to detect the corresponding train speed [2]. However, the accuracy level is still low, particularly in the accelerative and deaccelerative stage. Meanwhile high sampling frequency data are necessary since the impulse signals could be clearly identified only in the high frequency range. Those factors have prevented the application of this method in the simple measurement devices such as smart phone.

The coexisted sound signal can be also utilized to recognize the joint location. As shown in Fig. 2.1, the interior sound could be recorded by the microphone set inside the car, which can identify the moment t_1 and t_2 of passing the joint from the front and rear wheel. Since the distance r between the two wheels is known, the train speed in the passing moment could be speculated easily.

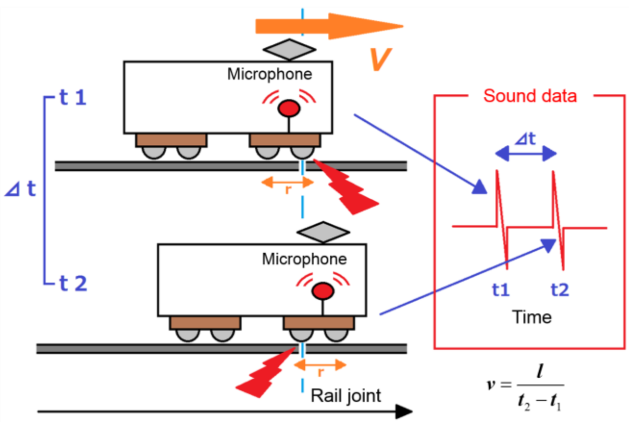


Figure 2.1 Basic idea to utilize interior sound for train localization

2.2. Field measurement

To verify the basic idea in 2.1, one field measurement was carried out in the Railway Technical Research Institute (RTRI) in Japan. The test train R291 (Fig.2.2a) running in the test line of RTRI was utilized. The car body was made by stainless steel and the length of each car is 19.67 m. The gauge is 1.067 m and the distance r between the two wheels in the same bogie is 2.1 m. The test line includes both strain line and curve line sections. The one-way distance between the start point and the end point is about 620~630 meters.

In this study, the implementation by the simple devices such as smartphones is considered as the priority. The iPod Touch, which functions the same with the smartphone except the communication function, was used in this study. It includes 3-axis acceleration sensor, 3-axis gyro and a built-in microphone. By the application named

(a) Test train R291 [3] (b) The sensor layout and the direction

Figure 2.2 The field measurement equipment

iDRIMS that was developed by the authors, the acceleration responses of three directions (the transverse direction *x*, the train traveling direction *y*, the vertical direction *z*), the angular velocity around each direction and the interior noise, a total of seven types of data was recorded. During the measurement, the iPod Touch was fixed to the floor by the anti-vibration pad, which lies on just upon the center of the front bogie to ensure it can record the sound from the two wheels in this bogie, shown in Fig. 2.2b. The sampling rate of measurement is 44,100 Hz for interior sound and 100 Hz with respect to the acceleration and angular velocity data. Furthermore, since iPod Touch could not receive the GPS signal inside the car, an additional GPS sensor was used to record the train speed as the real value for the following comparison. The sampling rate of the GPS sensor was 10 Hz. These two sensor system were synchronized by the recorded angular velocity data.

2.3. Measurement data

A total of 5 times of test run was performed by changing the maximum train speed. Two iPod Touch, called as iPod Touch A and B, were placed adjacently to verify the repeatability of the measurement. Alternatively the direction of the microphone is also investigated in each case, in order to clarify the appropriate measurement condition. The test cases are summarized in Table 2.1. In the following discussion, (4-A) is used to be denoted as iPod Touch A in the running case 4 and other cases can be can be described in the same manner.

Table 2.1 Summary of the test cases

Test case	Maximum Train speed (km/h)	Microphone direction
1	40	Downwards
2	40	Upwards
3	30	Upwards
4	30	Downwards
5	45	Downwards

As an example of the measurement result, Fig. 2.3 shows the acceleration data and interior sound data from case (4-A). For simplification, the amplitude of the sound is normalized to a unitless quantity. The sound results revel the impact impulse from the rail joint, suggesting the possibility as the sign of train localization. At the meantime large noisy signal also existed, which is expected to be eliminated for better identification. Further data processing will be discussed in the following sections by using case (4-A) as the example.

3. ANALYSIS METHOD FOR TRAIN SPEED

The overview of the proposed approach in this study is shown in Fig. 3.1. Theoretically it is possible to determine the train location by integrating twice the acceleration of traveling direction. However, this integration result usually cannot be directly used because of the large inclined integration error without any constrain from the boundary conditions. In this study, the transverse and vertical acceleration are processed by the threshold to determine the start time and the stop time of the train. By setting the train speed at both time to 0 constrainedly, the approximate estimated speed v_1 is obtained. Also, the estimated speed v_2 can be derived by the two wheels passing through the rail joint. Then the mutual correction of v_1 and v_2 results the estimated speed v_3, expected with less error. Finally, the location of the train, i.e. the running distance, can be determined by integrating the estimated speed v_3.

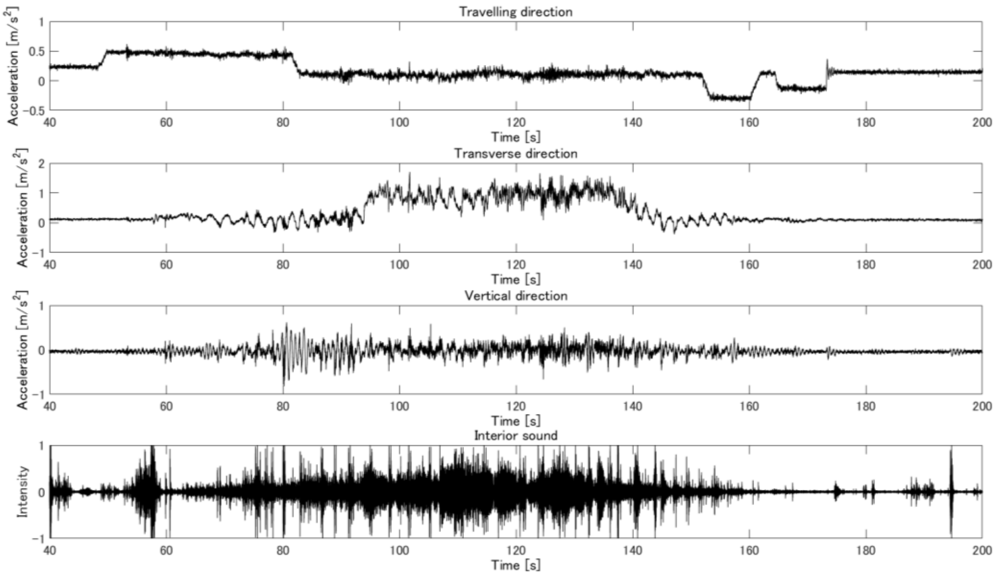


Figure 2.3 Measurement results from iPod Touch (4-A)

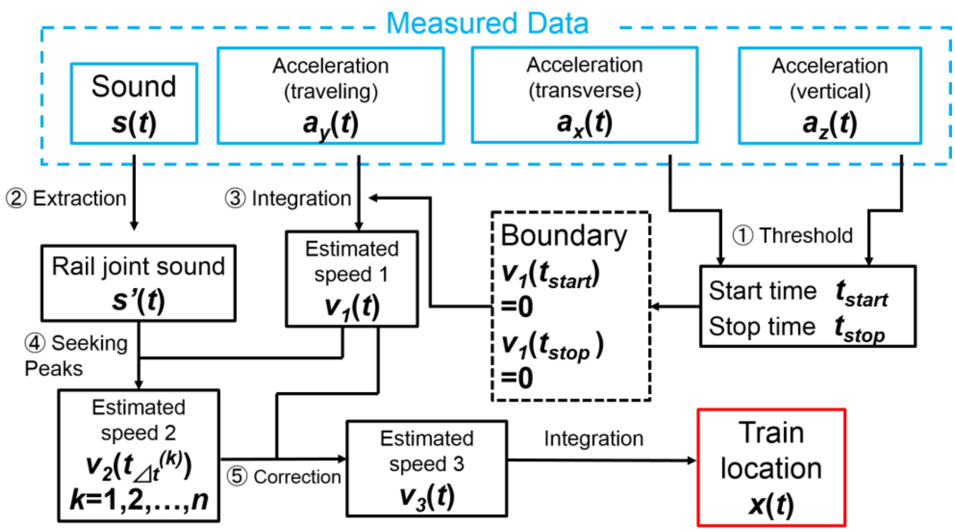


Figure 3.1 Overview of the proposed approach

3.1. Determination of start and stop time (approach ①)

Ishii *et al*. proposed a method to judge whether the train is moving by the vertical and transverse acceleration of the vehicle [1]. Based on this method, this study calculates the vibration index $\sigma^4(t)$, defined in Eq. 3.1, to determine the train status by start time and stop time of the train.

$$\sigma^4(t) = \sigma^2(a_x|_t^{t+1}) \times \sigma^2(a_z|_t^{t+1}) \tag{3.1}$$

Here $a_x|_t^{t+1}, a_z|_t^{t+1}$ denotes the transverse and vertical acceleration during the period t second to t+1 second respectively. $\sigma^2(\cdot)$ represents the variance of the data. Since the sampling rate of the iPod Touch is a 100 Hz, the vibration index of every second is calculated from 100 points of data. In this study, the threshold h is set as 1.4×10^{-7} m^4/s^8. When $\sigma^4(t) > h$ is satisfied more than continuous 60 seconds, the train is determined as moving status. At the same time, the start time t_{start} and the stop time t_{stop} could be identified accordingly.

3.2. Extract the interior sound by rail joint (approach ②)

The measured interior sound includes not only the rail joint sound, but also the background noise such as motor sound, aerodynamic sound and rolling noise. It is necessary to extract the rail joint sounds clearly by removing these background sound as much as possible. Some data processing algorithm has been proposed for the noise removal. In this study, the sparse representation method and multiresolution analysis method (MRA) are utilized. Due to the limited space, only the sparse representation method is discussed. But the results processed by the multi-resolution method will be also provided for comparison.

Sparse representations of signals have received a great deal of attentions in recent years. The problem solved by the sparse representation is to search for the most compact representation of a signal in terms of linear combination of atoms in an overcomplete dictionary. Recent developments in multi-scale and multi-orientation representation of signals, such as wavelet, ridgelet, curvelet and contourlet transforms are an important incentive for the research on the sparse representation [4]. Rail joint sound is a delta function-like waveform. Therefore, the ideal rail joint sound with the complete removal of the background noise would have a small number of non-zero elements. This kind of signal may be represented by a localized finite number of basis functions in the time domain. It indicates the possibility of the application of sparse representation for the rail joint sound signal.

In general, unless suitable basis functions are set, it is not possible to completely represent the observed signal as a linear combination of the basis functions. In contrast, an optimization problem of the residual vector $\mathbf{e} = \mathbf{y} - \mathbf{A}\mathbf{x}$ is considered to obtain the solution as Eq. 3.2.

$$\min_{\mathbf{x}} ||\mathbf{e}||_2 = ||\mathbf{y} - \mathbf{A}\mathbf{x}||_2 \quad s.t. \ ||\mathbf{x}||_0 \le p \tag{3.2}$$

Considering the background noise taken out only from a short period can be regarded as stationary signal with constant amplitude, only the rail joint sound is nonstationary signal. Under this condition, the nonstationary discrete wavelet transform and stationary discrete Fourier transform are chosen as the basis functions for the sparse representation of the rail joint sound and background noise, respectively. Denote $\mathbf{A}_w$ as discrete wavelet transformation matrix, $\mathbf{A}_F$ as discrete Fourier transform matrix, $\mathbf{y}$ as the measured interior sound signal interior noise, the following model is proposed.

$$\mathbf{y} = [\mathbf{A}_W \quad \mathbf{A}_F] \begin{bmatrix} \mathbf{x}_W \\ \mathbf{x}_F \end{bmatrix} + \mathbf{e} \tag{3.3}$$

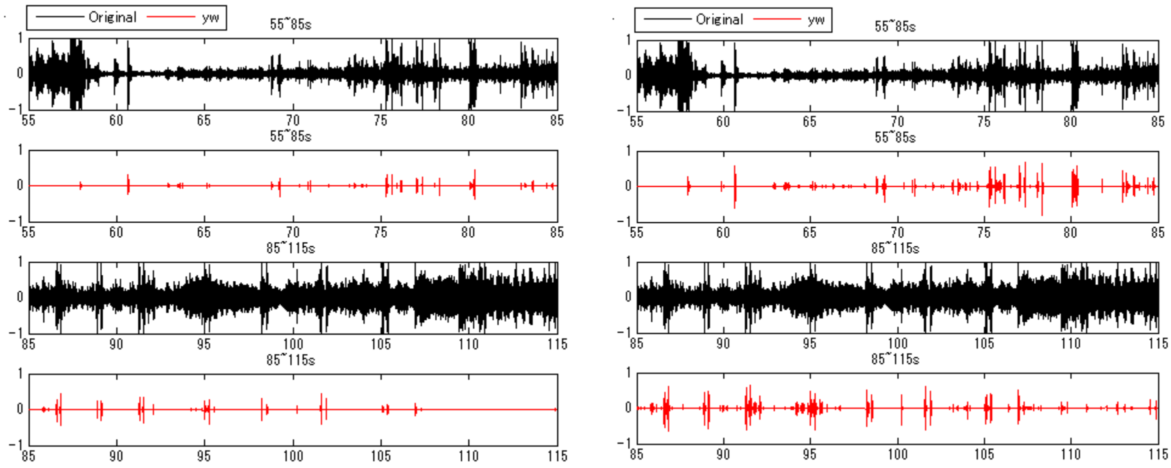
Here, $\mathbf{A}=[\mathbf{A}_W \quad \mathbf{A}_F]$, $\mathbf{x}=[\mathbf{x}_w^T \quad \mathbf{x}_F^T]^T$ is regarded under the model of Eq.3.3. By solving this optimization problem, sparse wavelet basis $\mathbf{x}_w$ and sparse Fourier basis $\mathbf{x}_F$ could be obtained. In this case, $\mathbf{x}_w$ and $\mathbf{x}_F$ become sensitive to the nonstationary component and the stationary component in the interior sound, respectively. Hence, two types of signals $\mathbf{y}_w = \mathbf{A}_w\mathbf{x}_w$ and $\mathbf{y}_F = \mathbf{A}_F\mathbf{x}_F$ which approximately express the two types of sparse basis, can approximately represent the rail joint sound and the background noise. The two kinds of the signal are able to be separated. In this study, the below optimization problem is defined for practical.

$$\min_{\mathbf{x}} ||\mathbf{e}||_2 + \tau||\mathbf{x}||_1 = ||\mathbf{y} - \mathbf{A}\mathbf{x}||_2 + \tau||\mathbf{x}||_1 \tag{3.4}$$

Here, τ is a constant to define the trade-off relationship between the residuals $\boldsymbol{e}$ and sparsity, corresponding to the constant p in Eq. 3.2. The larger τ is, the more important for sparsity. Accordingly the solution obtained from the Eq. 3.4 becomes sparser. In this study, the code GPSR (Gradient Projection for Sparse Reconstruction) was utilized in MATLAB [5]. It solves the minimization problem by discrete cosine transform (DCT) for $\mathbf{A}_F$ and discrete wavelet transform (DWT) of Daubeches7 for $\mathbf{A}_w$. Each time frame includes 2^{17} date, i.e., about 3 seconds' data. Since the magnitude of the background noise might change with time, the value of τ varies in every time frame as Eq. 3.5.

$$\tau = \frac{\max|\mathbf{A}^T\mathbf{y}_i|}{c} \tag{3.5}$$

Here, i is the numbering of the time frame, and c is a constant. The value of c is chosen as 2 and 4 in the following discussion. Fig. 3.2 shows the extracted results after data processing for both cases.



(a) *c*=2 (b) *c*=4

Figure 3.2 The extracted result by the sparse representation

Comparing the case of *c*=2 with the cases of *c*=4, the peaks are fewer. When *c* is 2, although the peaks are clearly visible, the pair of rail joint sounds from the front and rear wheel may loss one signal (such as around 90 seconds in Fig. 3.2). On the other hand, whereas relative more peaks are identified, it may extract the nonstationary noise other than the rail joint sounds when *c* is 4.

3.3. Derivation of the estimated speed 1 (approach ③)

The measured acceleration in travel direction is integrated by the trapezoidal rule to obtain the train speed. By modifying the boundary conditions $v(t_{start}) = 0$ and $v(t_{stop}) = 0$ obtain in 3.1, the integration error of the long drift could be eliminated. The result of estimated speed v_1 are shown in Fig. 3.3.

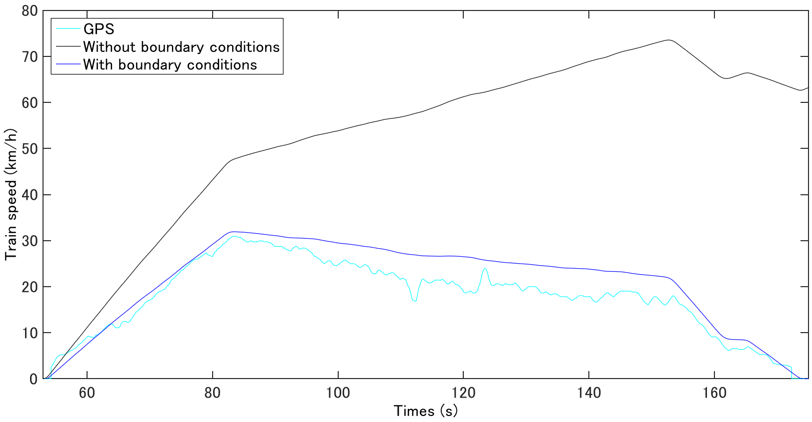


Figure 3.3 Train speed estimated by integration of the acceleration

3.4. Derivation of the estimated speed 2 (approach ④)

The rail joint sound extracted in 3.2 and the estimated speed v_1 obtain in 3.3 are used to estimate train speed v_2 by the quotient of the wheel distance and the time difference. The key of this approach to detect the correct pair of the rail joint sound. Two techniques are proposed in this study to reduce the error detection during the pairing. The first one is to set the threshold of the peak for rail joint sound. All the sound lower than this threshold should be discarded. The rail joint sound depends on the train speed varying with time. The threshold is defined as Eq. 3.6 by trial and error. In other words, the threshold is chosen as the 20% of the maximum value of the absolute value of the initial peak in the interval of 10 seconds. The second technique is to limit the search range Δt in time interval by using the approximate train speed v_1 by Eq. 3.7. In this study, ε is chosen 25% to ensure all the possible peaks aren't missing.

$$h(t) = 0.2 \times \max | s'(t - 5 < t < t + 5) | \tag{3.6}$$

$$\text{Minimum} \quad \Delta t_{min} = \frac{r}{(1+\varepsilon)v_1(t_1)} \qquad \text{Maximum} \quad \Delta t_{max} = \frac{r}{(1-\varepsilon)v_1(t_1)} \tag{3.7}$$

3.5. Derivation of the estimated speed 3 (approach ⑤)

In order to obtain the continuous train location by integrating the estimated speed, it is desirable that the final estimated speed is also continuous data. Therefore the estimated speed v_1 which is continuous data could be corrected by the discontinuous estimated speed v_2. Three correction parameters β_1, β_2, and β_3 are used in the first-degree polynomial function in Eq. 3.8 to determine the corrected speed $v_3\left(t \mid v_1(t) \mid \beta_1, \beta_2, \beta_3\right)$. For simplicity, the start time t_{start} is treated as t=0. For any v_2 at $t = t_{\Delta t}^{(k)} (k = 1,2,\cdots,n)$, the correction parametersβ_1, β_2, and β_3 could be obtained by solving the optimization problem in Eq. 3.9.

$$v_3(t \mid v_1(t) \mid \beta_1, \beta_2, \beta_3) = \int_0^t \{(\beta_1 t + \beta_2)\dot{v_1}(t) + \beta_3 t - \gamma\}\,\mathrm{d}t$$

$$\gamma = \frac{1}{t_{stop} - t_{start}} \int_0^{t_{stop}-t_{start}} \{(\beta_1 t + \beta_2)\dot{v_1}(t) + \beta_3 t\}\,\mathrm{d}t \tag{3.8}$$

$$(\hat{\beta}_1, \hat{\beta}_2, \hat{\beta}_3) = \arg\min_{(\beta_1,\beta_2,\beta_3)} \sum_{k=1}^{n} \left(v_2(t_{\Delta t}^{(k)}) - v(\, t_{\Delta t}^{(k)} \mid v_1(t) \mid \beta_1, \beta_2, \beta_3)\right)^2 \tag{3.9}$$

3.6. Result of the estimated train speed

The final results of the estimated train speed are shown in Fig. 3.4. After the mutual correction with v_1 and v_2, the corrected speed v_3 has revealed high accuracy level compared with real value (GPS speed).

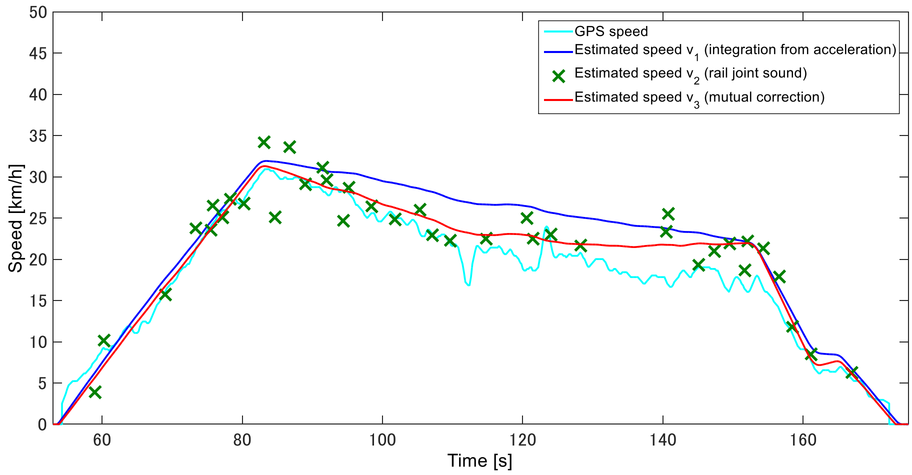


Figure 3.4 Train speed estimated by integration of the acceleration

4. RESULTS OF TRAIN LOCALIZATION

Speed estimation results (v_1 and v_3) and GPS speed are integrated by the trapezoidal rule to obtained displacement data, which indicates the location identification results. For each case, MRA denotes the rail joint sound extracted by multiresolution analysis, SR2 by sparse representation (c=2) and SR4 by sparse representation (c=4). The location identified from GPS speed is regarded as real value. The error ratio is calculated by Eq. 4.1. Table 4.1 summarizes the error ratio of each extraction method for all 20 measured cases (approximately 620 m). The extraction technique by sparse representation is slightly better than MRA, especially for SR2. The error of train localization is about 0.5 to 15%, with about 5% on average. In Fig. 4.1, the average error ratios of localization results by v_1 and v_3 are compared in box-and-whisker plot (20 cases). The train localization by mutual correction of acceleration and interior sound is found to be much more accurate than using the acceleration only. The error is about 5% on average, in the order of 1-10%.

$$\bar{\varepsilon} = \frac{1}{t_{stop} - t_{start}} \int_{t_{start}}^{t_{stop}} \frac{|X_3(t) - X_{\mathrm{GPS}}(t)|}{X_{\mathrm{GPS}}(t)} \mathrm{d}t \tag{4.1}$$

Table 4.1 Summary of error ratio for the train localization

Extraction method	MRA	SR2	SR4
Maximum	1.55%	0.64%	0.62%
Minimum	14.02%	13.15%	10.55%
Average	6.62%	5.85%	5.79%
Median	6.96%	6.19%	6.24%

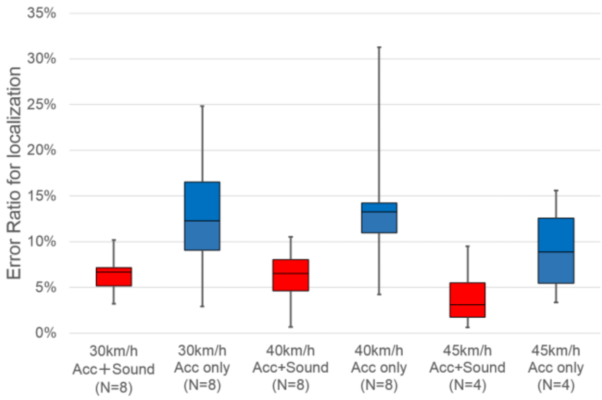


Figure 4.1 Train localization error ratio (SR4)

5. CONCLUDING REMARKS

The method for train localization by mutual correction of acceleration and interior sound is proposed. The identification error of the method is about 5 ± 5%, which is sufficiently applicable in the situations where GPS localization cannot be utilized. This approach is expected to provide a simple and accurate train localization tool for track management. Furthermore the accuracy improvement is expected when inter-station distance is known. It is also necessary to verify the feasibility of the proposed method in the tunnel section because of the change in sound environment.

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