A Mathematical Model for Detection of Railway Track Cracks Based on the Track Signalling System

Kamel H. Rahoma, Samaa A. Mohammad and Nagwa S. Abdel Hameed
Electrical Engineering Departent, Faculty of Engineering,Minia Unversity, Minia, Egypt
kamel_rahouma@yahoo.com, samaa_ahmed.pg@eng.s-mu.edu.eg, nagwa_minia@yahoo.com

Abstract

Egypt railway is the second constructed railway in the world after the establishment of British railway. It is also one of the largest railway networks around the world with passenger volume of 1.4 million passengers per day. In this paper, we are considering the major problems which lead to accidents that include trains with faulty speeds, manual control of the railway gliders and cracks on the railway tracks. The paper handles detection of cracks in railway tracks. If these deficiencies aren't early detected and controlled, it might lead to a number of derailments result heavy loss of both of life and property. The paper depends on studying each railway track as series impedance and ballast shunt admittance. This happens based on the transmission line theory. The derivate ABCD parameters are computed using the two port network principles. The track circuit blocks of the signaling system of railway is used to input voltage for the track circuit model because it is already distributed along the railway tracks. For a certain number of tracks, a repeated two port network section is used to compute the ABCD parameters of the network. If the tracks exist, the total ABCD parameters of the track are multiple of the single track circuit ABCD parameters. In case of having these values changed, it means that there is a cut on the tracks. MATLAB is used for modeling the track as a transmission line. Input – output voltage and current characteristics are studied by using SIMULINK software to simulate the equivalent circuit of railway track and the results of input – output voltage and current characteristics the existence of crack can be detected. Then the paper represents the crack distance and the required barking distance to stop the train. From the results the paper provides an electrical model to make early detection of crack from large distance that reach 1722 meters that guarantee the availability to stop the train with respect to the barking distance which equal to 766 meters for 120 km/hr train.

Keywords: *Egyptian Railway, Railway Crack Detection, Transmission Line Theory, Two Port Network, Series Rail Impedance, Shunt Ballast Admittance, Electrical Modeling.*

1. Introduction

Egyptian railway is the second constructed railway in the world. It is used to transfer both of passengers and goods on wheeled vehicles running on rails which are known as railway tracks[1]. It started to be established on July 12, 1851 and started to be operated on 1854[2]. As a result of the long life of the work of the Egyptian railways in addition to some general problems such as the small capital allocated for repair and development and also some technical deficiencies such as its dependence on the human control in the management and movement; all these reasons led to some of the massive incidents that end the lives of thousands among minor and serious injuries casualties or fatalities as well as significant loss of property over the last twenty years. In the report issued by the Central Agency for Public Mobilization and Statistics in 2018; it is reported that the number of train accidents in Egypt in the last 14 years, specifically; the time period from 2003 to 2017 reaches 16174 accidents. It is the worth mentioning that 2017 is the year that witnessed 1657 accidents left 61 injured and 29 deads according to the data reported by the agency[3]. According to the reported opinions of the railway's workers reported that the Egyptian railway faces some serious problems which cause the most harmful effects on passengers and public property like; expiry or end life of tractors, shortage of spare parts, poor maintenance in workshops, worn out semaphores and signals, security and tracking devices fail, broken roads, worn out wagons and failure to apply safety requirements[4].

Upon that information the Egyptian railway problems can be classified into three main categories as following:

(1) Operating problems

It is the problems related to the operated railway like:

a. Types of trains available and their suitability for the geographical nature of the railways
b. The railway signal system concerned with monitoring railways, freeing them or filling them with trains
c. Railway stations spread along the line and its ability to accommodate the size of passengers and their service

(2) Maintenance, inspection and periodic follow-up problems

It is the problems related to the follow up for the railway construction itself to guarantee that passengers and properties are safe out of danger from any unexpected railway problems like:

a. Regular maintenance of tractors and ensuring their safety and willingness to travel
b. Monitor the performance of trains and not load them at a passenger rate above their possibility or the possibility of rails
c. Monitor the speeds of trains along the railway to avoid collision of trains or collision of trains in the terminal building itself, as happened in the Misr station accident in 2019
d. Periodic examination of the bars and making sure that they are free from any fractures or cracks that could lead to serious accidents

(3) Financial problems

This type of problem is related to the capital allocated to the railways, as it affects the viability and possibility of any kind of problems related to the aforementioned railways, as the previous two points. This is because if the capital allocated to the railways is not sufficient to perform periodic inspection and maintenance and periodic renewal of the various sectors (trains, tractors, tracks, signaling instruments ...etc.) that make up the railways, this of course makes the railways vulnerable to the occurrence of problems that result in serious accidents that lead to loss of life and property.

From this classification it can be concluded that the second classification, which is the problems related to the periodic follow-up of the railways, is the most influential and occurring in the Egyptian railways. Based on this, the problem of detecting cracks and fractures in the railway tracks was chosen as the research point in the paper, and this is based on several reasons as following:

a. The railway tracks are the backbone of the movement of tractors and trains on the tracks, and if a certain problem occurs, this means stopping the whole railway from working.
b. The system used in Egypt to monitor the bars depends to a large extent on the signal men in the various points (lanes and stations) who check the bars in a semi-primitive manner with simple tools and this does not give accurate results when it comes to a crack in the nerve of the penis that cannot be seen with the naked eye

c. The danger of cracks in the rails lies in the fact that this is not only related to the safety of the train that passes through it, but rather it is related to the performance of railways in general. This is because when rails are loaded with more than their regular load (tractors, load weight of goods or passengers) continuously for a long time, it makes rails worn out, which makes it very easy for them to be cracked and then broken. In this case we need to evaluate the railway performance

d. When a crack occurs in the bars, it leads with time to a break in the bars and when the train passes over it and it is loaded with a load of up to tens of tons in addition to high speed resulting in a tremendous movement energy for the train and when passing on the broken bars the train turns over what it carries and this is considered Terrible material human catastrophe

2. Literature Review

In [5]; authors depend on using EMTP “Electromagnetic Transient Program” to present time-domain electric circuit simulation packages which is designed for power systems application like the railway track networks. The paper is good to present an accurate simulation for the time-domain transmission line parameters. The paper lacks more details about the transmission line model before conducting the simulation that makes the reader doesn’t know the driven steps of the used model in the paper.

In [6]; authors depend on using MATLAB/SIMULINK software to study the track circuit for urban/suburan transit systems. They present an electrical model for the running rails then it introduce a simulation for transmitter, receiver, boosting unit and train occupation circuit by SIMULINK. The paper improves specified measured and simulated values for the track circuit parameters with taking the skin effect and eddy currents effect on the track circuit parameters. The paper didn’t present the whole mathematic derivation for the electrical model of the running rails.

In [7]; authors studied the rail track behavior as an electromagnetic field model and also they present comparison between the theoretical analysis and the published experimental data. The paper was concentrated on studying the behavior of series and mutual impedance of the railway track based on the electromagnetic field model which measures the estimated and dissipated power for the track during operation and thus gives accurate measurements for the track impedance. The paper didn’t concern with the rest parameters of the railway track because it didn’t give interest to the inductance of the railway tracks and also the capacitance between the railway tracks.

In [8]; authors studied both of leakage resistance and distributed capacitance for the high speed railway tracks which are balletless. The paper introduces high accurate model for the resistance-capacitance model of the balletless railway tracks. The paper didn’t concern with the skin effect and the inductance effect of the railway tracks.

In [9]; authors studied the railway tracks as a short transmission line using the open and short circuit measurements and by following this principles they detect and measure the railway tracks impedance and ballast impedance at different points along the railway tracks. The paper presents a detailed model with measured values for the rail impedance and the ballast resistance at different lengths. The paper didn’t mention any information about the effect of rail-to-rail capacitance.

3. Methodology

3.1. Electric Traction Power and Signaling System

The electric traction power causes the trains (tractors) to move sequentially behind each other which cause a strong friction between the wheels of the tractors and the tracks; and this generates some voltage[10]. The signaling system of the Egyptian railway depends on a constructed track circuits which is used to determine the occupancy state of the railway tracks. The track circuit block is used to determine either the track is occupied by a train or not. The track circuit block diagram is shown in figure (1). The track circuit provides the station with the information about the state of occupancy along the track. Usually the track circuit consists of a power supply which is either AC or DC, the terminals of the power supply, the first terminal is connected to the first track circuit and the second terminal is connected to a detector circuit and from this it is connected to the second track circuit as shown in figure (1). The detector circuit is connected to the signaling system especially the semaphores which give indication about the occupancy state of the track as explained previously[11].

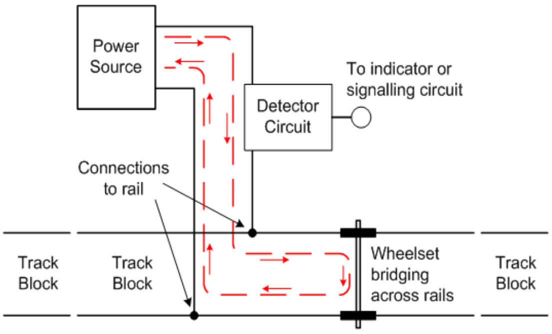

Figure (1): Block diagram of the track circuit block

The track circuit can be classified into:

The first track circuit describe the unoccupied tracks; it can be likened to an open-circuit track circuit and it take place when there aren't any trains on the tracks so it is known as the unoccupied track circuit as shown in figure (2).

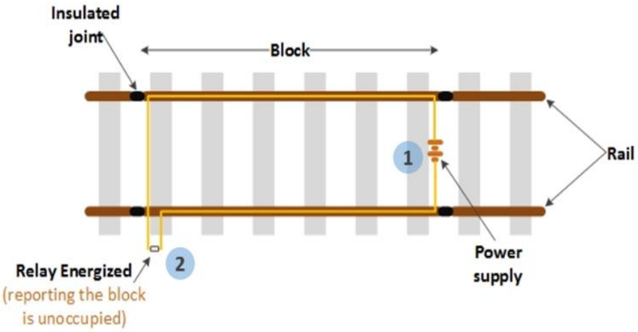

Figure (2): Block diagram of unoccupied the track circuit block

The second track circuit describes the occupied tracks; it can be likened to a short-circuit track circuit and it takes place when there is a train on the tracks so it closes the circuit by the train's wheels; so, it is known as the occupied track circuit as shown in figure (3).

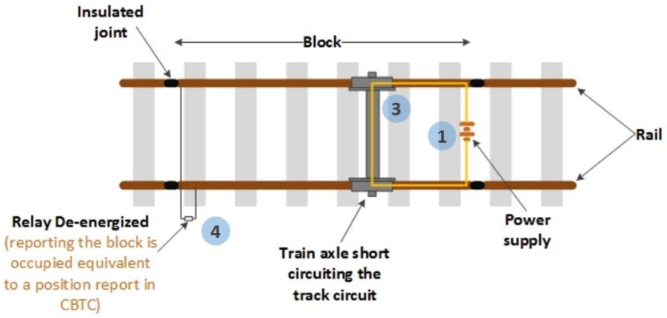

Figure (3): Block diagram of the occupied track circuit block

The paper depends on using the principle of track circuit block with voltage 50 Hz 5 AC V, 5 DC V as a standard voltages[12]. That's because power supply of the track circuit usually is located in the range of 1.5 to 12 DC V[13]. But for the track circuit model purposed in this paper, the model actually doesn't need this value of voltage because there is some voltage already generated due to the electrical traction power. So, the paper depends on a voltage value start from 1.5 to 12 V DC and AC to study the relationship between input-output voltages in case of no crack detected and in case of crack detected[14].

3.2. Transmission Line Theory and Two Port Network Principles

3.2.1. Transmission Line Theory

Transmission line is a medium connecting between the generating stations and the distribution stations for any system. Its main responsibility is to carry transmitted power to be distributed in different distribution points. For the railway; it represents the railway tracks which carry the train and help it to move from station to station. For any transmission line; there are four main parameters which affect its operations. Those parameters are resistance, inductance, capacitance and conductance as shown in figure (4).

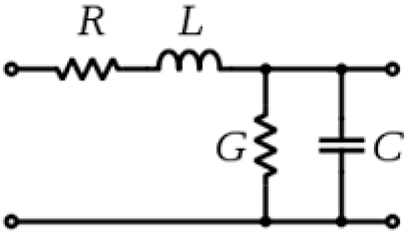

Figure (4): Equivalent circuit of the transmission line

The resistance and inductance are uniformly distributed along the transmission line forming a main parameter of electrical model which is called series impedance.

The resistance of the line usually is responsible for the power loss in the line, the inductance of the line is produced because of the flux linkage in the conductor. Both of resistance and inductance are distributed along the transmission line forming series impedance. Series impedance per unit length (z, Ω/m) can be calculated from equation (1) and the total series impedance (Z, Ω) can be calculated from equation (2). Where R refers to the track resistance, ω refers to the angular velocity, L refers to the rail inductance and l refers to the track length.

$$z=R+j\omega L \quad (1)$$

$$Z=z*l \quad (2)$$

The capacitance of the line usually is produced because of the potential difference of charge on the conductors, the conductance of the line because of the leakage current overhead the line and here it refers to the conductance of the ballast surface. Both of capacitance and conductance are distributed along the transmission line forming shunt admittance. Shunt admittance (y, ℧/m) can be calculated from equation (3) and the total shunt admittance (Y, ℧) can be calculated from equation (4). Where G refers to the ballast conductance and C refers to the shunt capacitance between tracks.

$$y=G+j\omega C \qquad (3)$$

$$Y=y*l \qquad (4)$$

Usually; the leakage current is neglected for specific conductors so that the conductance between the conductors is taken as zero value[15], the shunt admittance of short transmission line has non-effective value on the performance of the line[16]. It is enhanced by the results of the scientific papers; that's because the value of shunt admittance are 257pF/m and 6.67*10-7 S/m respectively[6]. Depending on this, the transmission line approximation for the railway track is considered in figure (5).

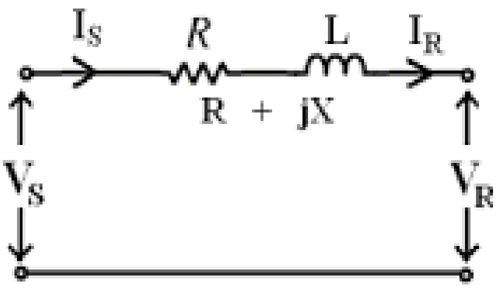

Figure (5): Equivalent circuit of the short transmission line

3.2.2. Two Port Network Principles

Finite length transmission line consists of the two terminals, input port terminal and output port terminal and it is called two port network as shown in figure (6). Usually the two port network is studied using variety of parameters z-parameters (impedance parameters), y-parameters (admittance parameters), h-parameters (scattering parameters) and ABCD parameters (a-parameters) which is called the transmission parameters[17].

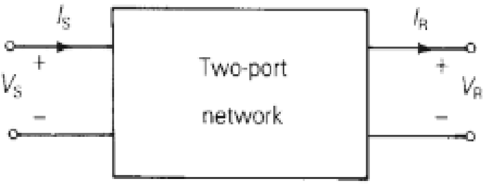

Figure (6): Equivalent circuit of two-port network

3.2.3. The ABCD Parameters along the Track

Transmission parameters are an important subsystem which consists of two or more cascaded two port networks in which the output of one network is connected to the input of the next network and so on as shown in figure (7).

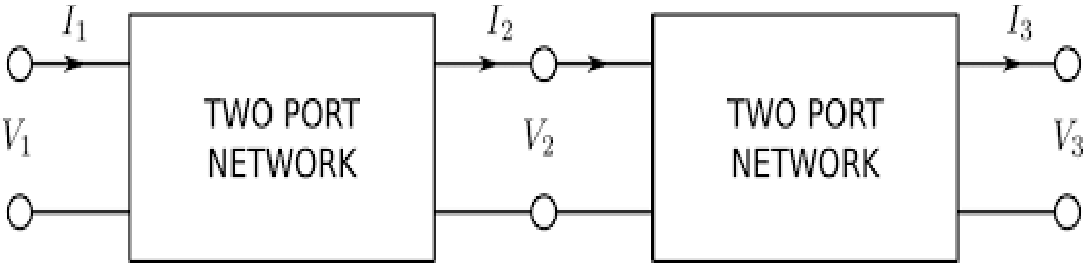

Figure (7): Cascaded two port network

The ABCD matrix of figure (7) is defined as shown below in equation (5).

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \qquad (5)$$

Where V_S ,I_S, V_R and $I_R$refer to the input voltage, input current, output voltage and output current respectively. The source voltage (V_S,v) can be calculated by using the ABCD matrix in equation (6) and also the source current (I_S,A) can be calculated in equation (7). Where $V_R$refers to the receiving voltage, $I_R$refers to the receiving current, A refers to the voltage ratio of two port network, B refers to short circuit resistance of two port network, C refers to open circuit conductance and D refers to current ratio of two port network.

$$V_S=AV_R+BI_R \quad \text{(volts)} \qquad (6)$$

$$I_S=CV_R+DI_R \quad \text{(amperes)} \qquad (7)$$

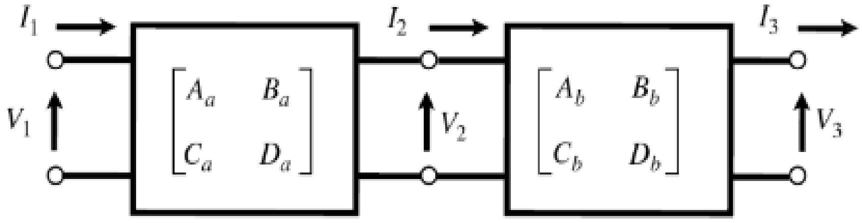

Figure (8): Current flow in the cascade two-port network

In the case of passing I_R into the two port network and in the same time I_S pass out of the two port network as shown in figure (8), the ABCD parameters for the two cascaded networks is given as given [18]:

From the principles of two port network[16];

$$I_S = I_R \qquad (8)$$

$$V_S= AV_R+BI_R \qquad (9)$$

For cascaded two port network, the ABCD matrix can be calculated as following in equation (10)

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_a & B_a \\ C_a & D_a \end{bmatrix} \begin{bmatrix} A_b & B_b \\ C_b & D_b \end{bmatrix} \qquad (10)$$

When the two port network consists of more than two identical networks; the following formula in equation (11) can be used;

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = n * \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \qquad (11)$$

Where n refers to the number of network cascades.

It is required to evaluate the behavior of ABCD parameters along the track circuit orders.

For short transmission line;

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \qquad (12)$$

From equation (5) and equation (12); the short transmission line parameters is:

A=D=1, B=Z ohm and C=0.

So, main circuit representing the railway tracks consists of cascaded RL circuits as shown in figure (9). The model targets to study the track circuit from the electrical RL and ABCD parameters along the track.

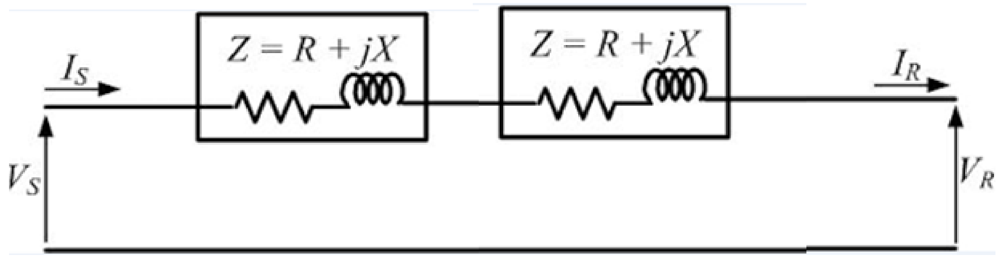

Figure (9): Block diagram of cascaded track circuits of the railway.

3.2.4. Input-Output Characteristics along the Track

For the sending or source end voltage and sending or source current can be calculated from equation (13) and (14).

$$V_S = AV_R + BI_R \qquad (13)$$

$$I_S = CV_R + DI_R \qquad (14)$$

For open circuit;

$$I_R = 0 \qquad (15)$$

$$V_S = AV_R \qquad (16)$$

$$A = \frac{V_S}{V_R} \Big| \, I_{R=0} \qquad (17)$$

But A=1 for short transmission line

So,

$$V_S = V_R \qquad (18)$$

And

$$I_S = I_R = 0 \qquad (19)$$

For short circuit;

$$V_R = 0 \qquad (20)$$

$$V_S = BI_R \qquad (21)$$

$$B = \frac{V_S}{I_R} \Big| \, V_{R=0} \qquad (22)$$

By following the principles of open-short circuit calculations for voltage and current, the input-output characteristics can be studied. By comparing results of the standard case of no crack detected with the measured values; the crack existence can be detected when values of voltage and current are changed.

3.2.5. Crack Distance Detection along the Track

Actually the railway track isn't a continuous track and it consists of metal sub-tracks jointed with each other forming the whole track as shown in figure (10).

Figure (10): Jointed sub-tracks forming the whole track

This sub-track has the length of 180 m in the Egyptian railway. In the same time the used track circuit blocks detect the occupancy state along 2300 m for the train speed around 120 Km/hr [19]. The model gives the standard values for ABCD parameters for the 2300 m track length and by using the mathematical proportionality principle especially the reciprocal multiplication rule; the distance of the crack from the sending end can be detected as shown in equation (23) and equation (24). Figure (11) shows a one transmission line element of length x within a track circuit of length L fed from left to right. Where $|Z_{in}|_{\text{At L=2300m}}$ refers to the input (series) impedance of the 2300 meters track circuit and $|Z_{in}|_{\text{At x}}$ refers to the input (series) impedance at the detected crack distance.

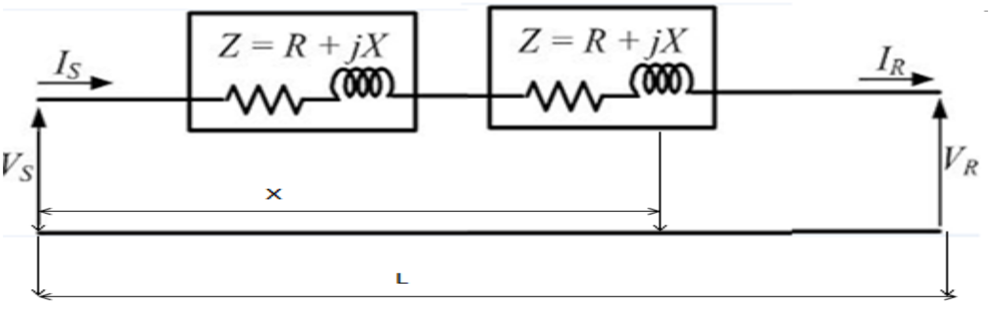

Figure (11): One transmission line element of length x within a track circuit of length L fed from the left to right

$$|Z_{in}|_{\text{At L=2300m}} \longrightarrow \text{L} = 2300\text{m} \tag{23}$$

$$|Z_{in}|_{\text{At x}} \longrightarrow \text{X} = ? \tag{24}$$

By multiplying the two sides in the middle, the value of the distance at which the crack exists can be detected[20].

3.2.6. The Model Algorithm and flow chart

The paper develops an electrical model to detect the cracks on the railway tracks by using the theory of transmission line followed by using the principles of two port network theory especially the ABCD parameters which give the standard values of the normal railway tracks. This will help to recognize the existence of cracks on the tracks when the standard values of ABCD change. After crack detection; data with crack location will be transmitted to the control room to the right decision whether slow down the train or stop it.

The algorithm of working can be explained by the following steps:

1-Turn on the power supply connected to the track
2-Measure sending end and receiving end voltage and current by RLC meter when no crack is detected
3-Calculate ABCD parameters by applying equations from equation (13) to equation (22) when no crack is detected
4- Measure sending end and receiving end voltage and current by RLC meter when crack is detected
5- Calculate ABCD parameters by applying equations from equation (13) to equation (22) when crack is detected
6-Compare values of either voltage and current or ABCD matrix in the two conditions
7-Give alert that crack is detected
8-Calculate the crack distance by applying equation (23) and equation (24)
9-Stop the train

The algorithm can be represented by the flowchart shown in figure (12). This

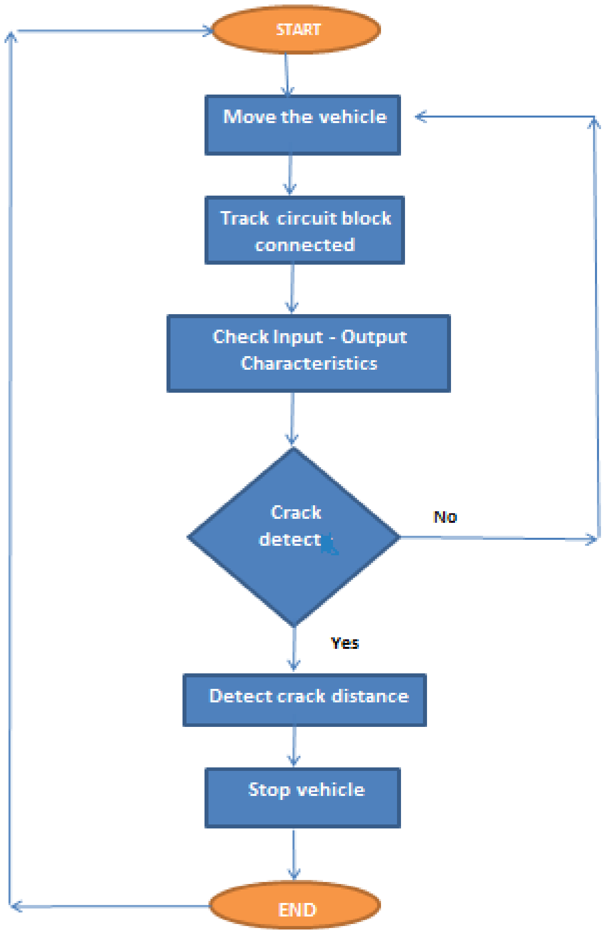

Figure (12): The Model Flowchart

4. The Results

The results described below were obtained by using MATLAB and SIMULINK software.

4.1. ABCD Parameters along the track

According to MATLAB results, this point can be classified into two cases; the first case when no crack is detected on the track and the second case when crack is detected on the track.

4.1.1. Case I: No crack detection

For this case; no track circuit is removed, opened, shorted or change on its parameters. So, the results are studied as the relationship between the RL parameters and ABCD parameters as a function of the track circuit order.

The changes in all results refer to no change on A, C, D parameters because it is a short transmission line. And it agrees with the theoretical theory about short transmission line as explained previously. The changes occurs only on the B parameter which indicates the equivalent impedance of the transmission line and it is affected by the values of resistance and inductance of the track respectively. This is shown in table (1);

Table (1): ABCD & RL parameters when no crack is detected

Track Circuit Order	**R** Ω/m	**L** μH/m	**B** Ω/m
$track\ circuit_1$	0.976	1.321	0.000976+j0.000415
$track\ circuit_2$	0.976	1.321	0.0020+j0.0008
$track\ circuit_3$	0.976	1.321	0.0029+j0.0012
$track\ circuit_4$	0.976	1.321	0.0039+j0.0017
$track\ circuit_5$	0.976	1.321	0.0049+j0.0021

From the above results, we can conclude that the model is applicable to estimate the ABCD parameters for the track circuits and the final result in the absence of any cracks in the railway tracks is equal to the multiples of the final result in the case of a single track circuit. Therefore, we can rely on the equation (11) as the main formula;

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = n^* \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix}$$

4.1.2. Case 2: Crack detection

For this case; the changes occurs in RL parameters in one or more track circuit and they affect the ABCD parameters. The changes influence B parameters. Table (2) shows the effect of changes in track circuit on the ABCD parameters. The results are obtained from applying a change on the RL values for half of its values and double of its values.

Change 1: Short Circuit in track circuit_1
Change 2: Increase RL values to double in track circuit_1
Change 3: Decrease RL values to half in track circuit_1

Table (2): ABCD & RL parameters when crack detected

Track Circuit Order	Change 1 B Ω/m	Change 2 B Ω/m	Change 3 B Ω/m
track circuit_2	0.000976+j0.000415	0.0029+j0.0012	0.0015+j0.0006
track circuit_3	0.002+j0.0008	0.0039+j0.0017	0.0024+j0.001
track circuit_4	0.0029+j0.0012	0.0049+j0.0021	0.0034+j0.0015
track circuit_5	0.0039+j0.0017	0.0059+j0.0025	0.0044+j0.0019

From the above results we can conclude that the model can determine the incidence of cracks in the railway tracks when the final result changes in contravention of the formula (11) which express that the total ABCD matrix for a certain track circuit sections doesn't equal to the multiplication of single ABCD matrix of one track circuit section by the number of track circuit sections. By this way, the crack incidence can be detected.

4.2. Input – Output Characteristics along the track

To study the input – output characteristics along the track especially for the voltage – current characteristics the track circuit signaling is studied when it consist of 5 track circuit sections and also 28 track circuit sections which indicate to 500 meter single track circuit type. According to SIMULINK results, this point can be classified into two cases; the first case when no crack is detected on the track and the second case when crack is detected on the track.

4.2.1. Case 1: No crack detection

The 5 track circuit sections shown in figure (13) show the block diagram of equivalent track circuit when no crack is happen in the track. Figure (14) shows the input – output voltage of the equivalent circuit.

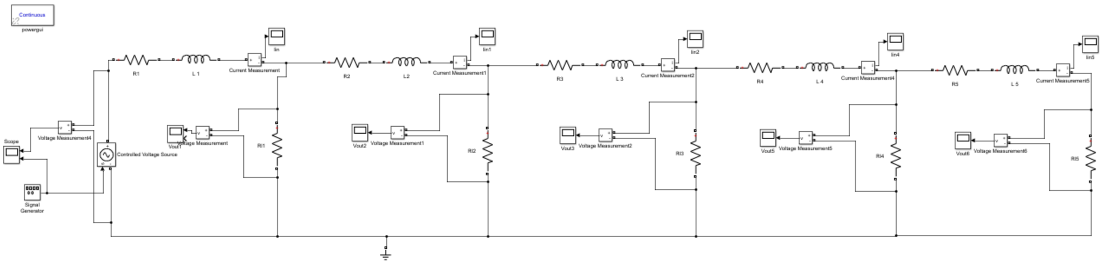

Figure (13): Five sections track circuit when no crack is detected.

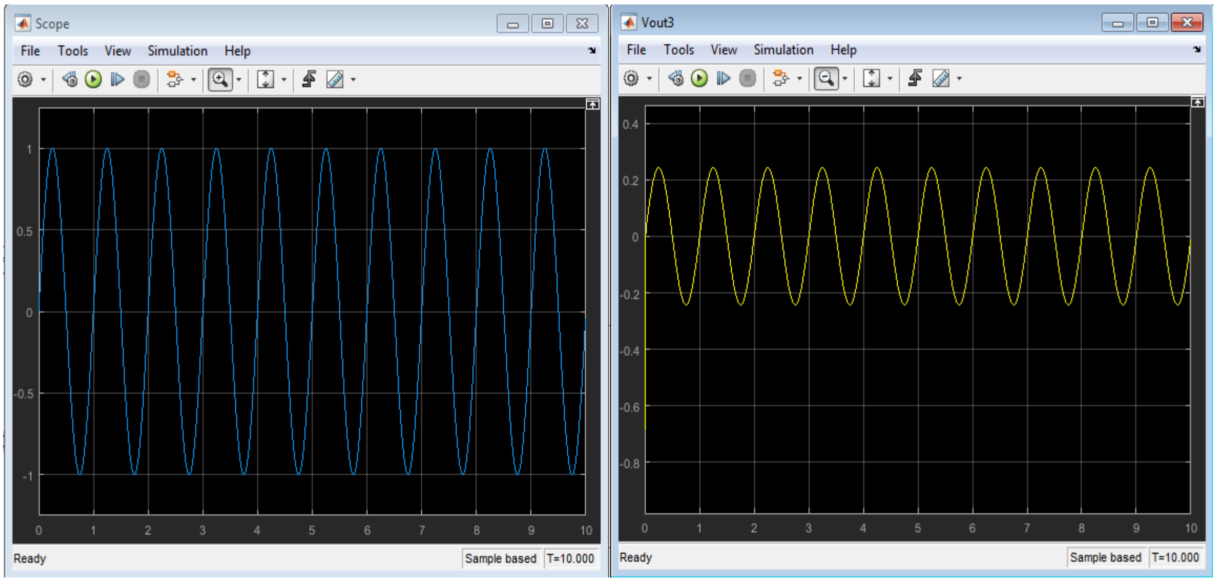

Figure (14): Input – Output Voltage relationship when no crack is detected

From this it can be concluded that the output voltage is decreased along the track because of the series impedance of the track. Figure (15) shows the input – output current of the equivalent circuit.

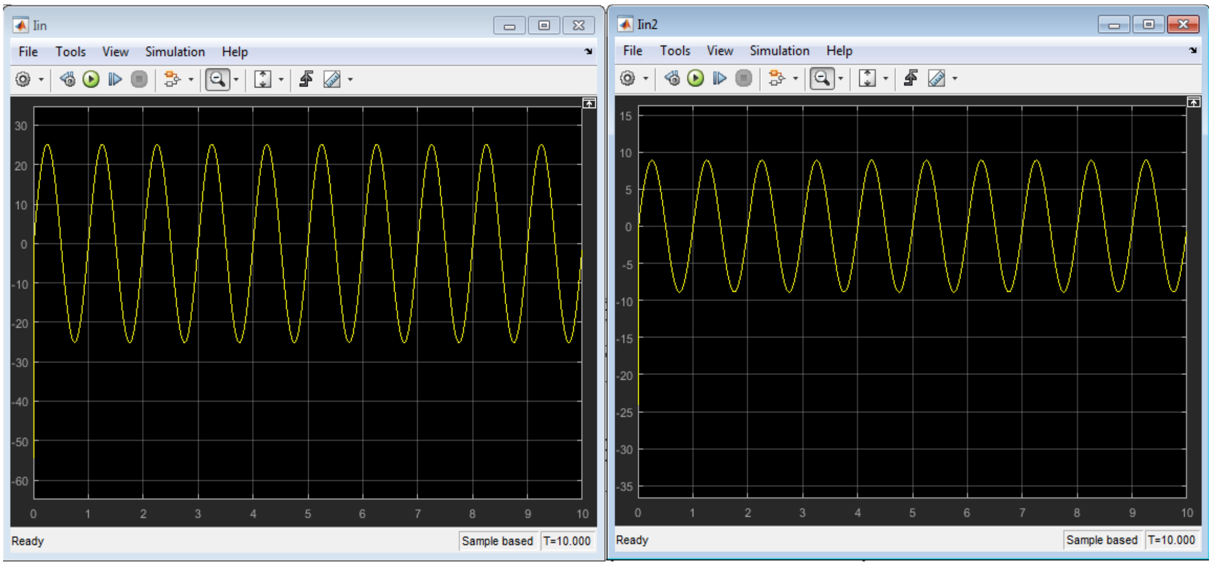

Figure (15): Input - Output Current relationship for no crack.

From this it can be concluded that the output current is decreased along the track and it is logical issue which agree with the principle of Ohm's law which discuss that the current is inversely proportional with the impedance for specific circuit and it can be ensured from the formula in equation (25).

$$V = IR \qquad (25)$$

4.2.2. Case 2: Crack detection

The 5 track circuit sections shown in figure (16) show the block diagram of equivalent track circuit when a crack is detected because of track section number 3 is removed. Figure (17) shows the equivalent circuit input/output voltage.

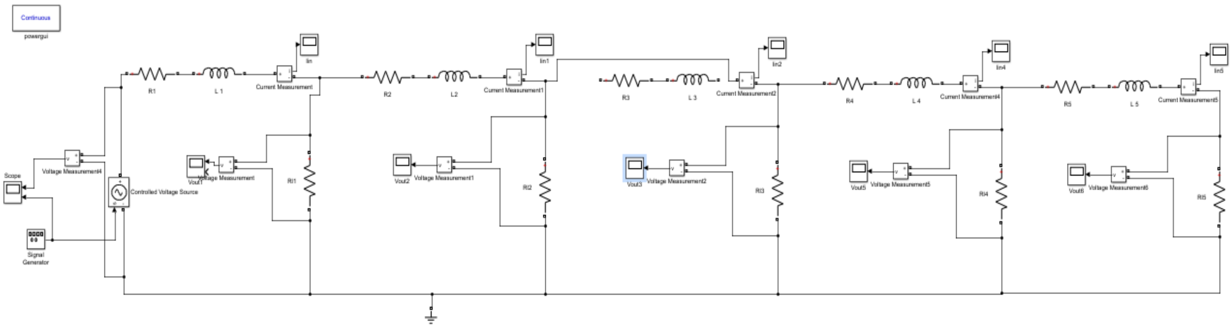

Figure (16): Five sections track circuit when crack is detected.

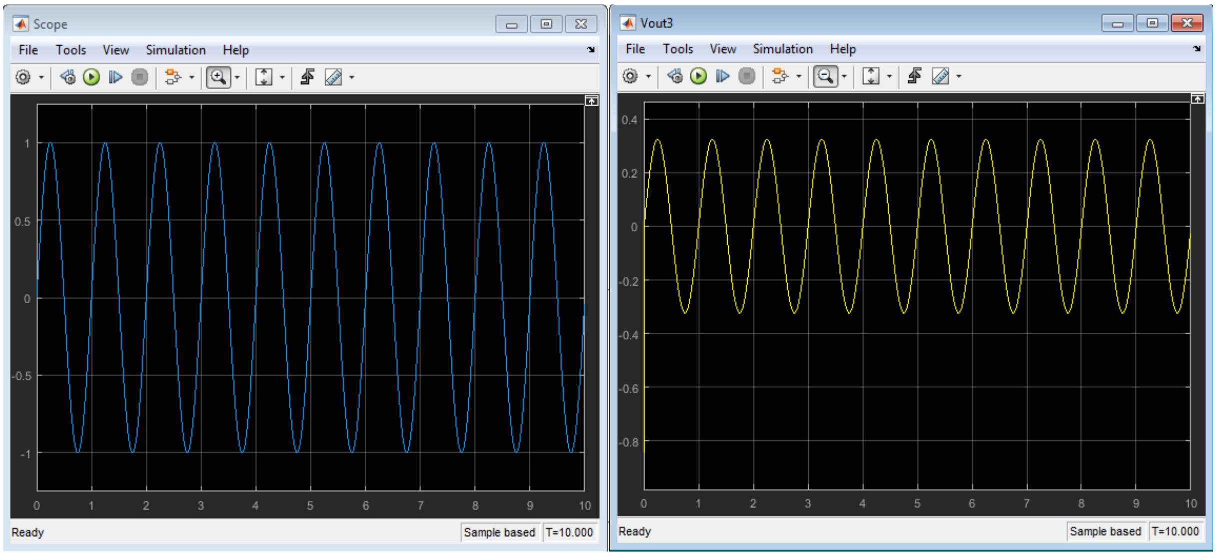

Figure (17): Input – Output Voltage relationship when crack is detected.

By comparing the input – output voltage in figure (14) and figure (17), it can be concluded that in case of crack occurrence, the output voltage is varied from its normal values for the same number of track circuit sections. And it gives a direct indicator for crack detection. Figure (18) shows the input – output current of the equivalent circuit.

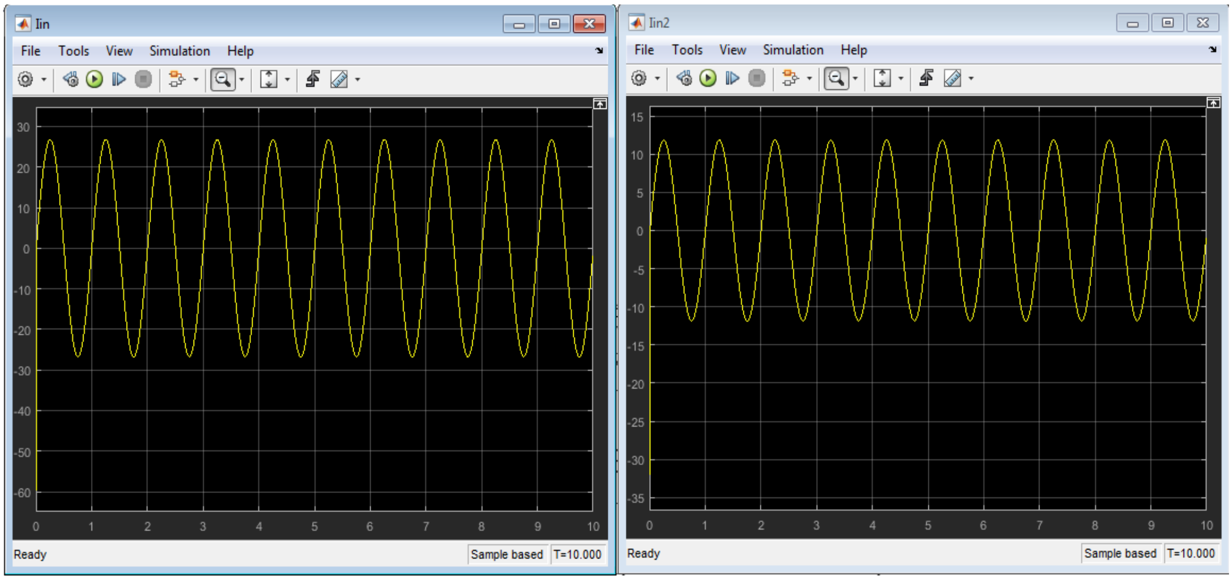

Figure (18): Input – Output relationship when crack is detected.

For the output current, by comparing the results in figure (15) and figure (18); the output current is varied away of its normal values for the same number of track circuit sections which indicates to crack detection.

From the above results we can conclude that the model can determine the incidence of cracks in the railway tracks when the final result changes in contravention of the normal values for both of current and voltage for the same number of track circuit sections. Thus is agree with the principles of Ohm's law shown in equation (25) which illustrate that the more impedance for a circuit is increased it affect inversely on the current and also cause change for voltage. Depending on this result the model success to give indicator about the existence of cracks on the tracks.

4.3. Crack Distance Detection along the track

Consider the case of “change 3” occur and the values of specific track circuit is decreased to half of its value due to a crack in the track so, the results of change 3 case is considered from table (2) and the standard values for inputs impedance is considered from table (1). The crack distance can be obtained from the following formula

$$X=\frac{L*|Z_{in}|\text{At x}}{|Z_{in}|\text{At L=2300m}} \qquad (26)$$

Table (3): Crack distance detection

Track Circuit Order	$\lvert Z_{in}\rvert$ At L = 2300m	$\lvert Z_{in}\rvert$ At x	X m
track circuit$_2$	0.00215	0.00161	1722.3
track circuit$_3$	0.00313	0.0026	1910.5
track circuit$_4$	0.00425	0.00374	2024
track circuit$_5$	0.00533	0.0048	2071.29

From results shown in table (3); it is possible to use the mean of reciprocal multiplication rule to detect the distance at where the crack exist from the sending end of the track circuit block which detect sequential track length equal to 2300 m.

4.4. Relationship between crack distance and barking distance

According to the known barking distance for train; the model success to make early detection for the crack to enable the train driver to stop the train with respect to the barking distance using the emergency breaker.

For a train at a speed of 201 km/hr it needs to operate the emergency breaker at a distance of 1283 m[21]. Using the mean of reciprocal multiplication, the barking distance of the train can be calculated at different speeds. The formula in equation (27) and equation (28) show the calculated barking distance for the air-condition train of the Egyptian Railways which run at speed 120 km/hr:

$$201\text{ km/hr} \longrightarrow L_{\text{barking distance}} = 2300\text{m} \qquad (27)$$

$$120\text{ km/hr} \longrightarrow X_{\text{barking distance}} = ? \qquad (28)$$

$$X_{\text{barking distance}} = \frac{120*1283}{201} = 766\text{ m} \qquad (29)$$

From this, it’s easy to conclude that the mathematical model is successful to detect cracks along the railway track at a distance which is larger than the required barking distance to stop the train and this will give the train driver the chance to stop train once note the crack alarm.

5. Discussion and Comparison of the Results

5.1 Discussion of the Results

As mentioned previously in literature studies, many researches handled the problems of railway especially those which tried to study the different characteristics of railway track. In [5]; the authors depend on using EMTP software to analysis the track characteristics of impedance and shunt capacitance. In [6]; the authors presented MATLAB/SIMULINK simulation that studied the main parameters of railway track including the measured impedance, capacitance and shunt conductance of the railway track and the paper ensured that the shunt capacitance and conductance have very small values which have very small effect on the track that can be neglected forming a short transmission line model represent the railway track which is considered the backbone of our model. In [7], [8] and [9] the papers presented a study for the railway track in order to reach a standard model and values of the main parameters of track like series impedance, leakage resistance, distributed capacitance of rail to earth in balletless track and ballast resistance respectively. Our paper is complemented to those papers by identifying the different properties of tracks and the different theories used in it, and then we specialized in studying cracks that occur in railway tracks by relying on both the transmission line theory and the two port network principles.

By using the transmission line theory and the two port network principles, the paper reaches those results;

1- The paper proved that the crack can be detected by studying the analysis of ABCD parameters for the track circuits. That’s because in the normal case when no crack is detected along a specific number of track circuit sections , the total ABCD matrix equal to the ABCD matrix of single track circuit section multiplied by the number of track circuits. So, for the same number of track circuit sections, if the equivalent ABCD matrix is varied away the normal ABCD matrix in case of no crack it mean that there is a crack is detected in specific point on the track.

2- The paper proved that the crack can be detected by studying the analysis of input – output voltage and current characteristics for the track circuit. That’s because in the normal case when no crack is detected along a specific number of track circuits, the output voltage and output current have specific characteristics that express the total voltage and current of the total equivalent circuit. If the measured voltage and current is varied away of the normal total characteristics of the same number of track circuits or distance thus indicate a crack occurrence on a specific point along the track.

3- The paper proved that the mathematical rule of reciprocal multiplication can be used to calculate the distance of crack along the track referenced to the normal standard values.

4- The ABCD matrices method is more applicable when the number of track circuit sections is known that can be said when the distance of detection is small and near to feed point. And also the mean of reciprocal multiplication is useful for crack distance detection in this case.

5- The input – output voltage and current characteristics is more applicable for long distance detection of the railway track. That’s because it is easy to be measured using smart meter like W-454 HV[22] with programmable kit like ioPAC 8500 Series [23]for track circuit control.

6-The paper successes to detect the crack at a sufficient distance to stop the train according to the required barking distance for the train. That’s because the train at speed of 120 km/hr need to 766 m to be stopped by the emergency brake and in the same time, the model in the paper detect the crack at a minimum distance of 1722 m thus guarantee that the train will be stopped within a suitable distance.

5.2 Comparison of the Results

(1) Authors in [5] used EMTP software to make evaluation of the rail track impedance and capacitance of the running rails with respect to the rail-ground effect of the railway track while our mathematical model make evaluation for the track by studying it as a transmission line and two port network. Thus gives the chance to study the transmission line parameters and evaluate the state of the track by examining the obtained values from measurement devices and comparing it with the expected values and this give our model a strong point about the reliability of periodic check of tracks.

(2) Authors in [6] depend on building a MATLAB/SIMULINK model to study the track circuit when there is a running wheel in it. So, they could give a clear calculated and measured values for the track circuit parameters while our model use those obtained track circuit parameters to build a model which can detect the crack occurrence along the track.

(3) Authors in [9] study the ballast resistance of the railway tracks by considering the track as a short transmission line and deriving a mathematical model to calculate the shunt admittance and series impedance at a short and open circuit tests. By this way it study the effect of the ballast on the track while our purposed model use the same idea to study the effect of crack occurrence on the shunt admittance which is neglected for short track circuit transmission line and the series impedance which vary in accordance to the crack occurrence.

(4) Authors in [24] used the IR sensors to perform as an anti-collision detector to detect cracks and trains on opposite directions in the same track. The model was successful to detect trains on the opposite directions but not good for crack detection while our model purposed to detect crack and also detect the crack distance on the track. This is by establishing fixed measurement points with smart RLC meters which give alert when the crack is detected on the track.

6. Conclusions and Future Work

6.1 Conclusion

The paper provide an electrical model detect the existence of cracks in the railway tracks based on the voltage imposed to track circuit blocks which are the backbone of the signaling system of the Egyptian Railway. The model developed in the paper depends on studying the railway tracks as a transmission line then analyzing it using two-port network principles especially ABCD parameters. By evaluating the ABCD parameters for the track circuits; the existence of cracks can be detected when the standard values of ABCD parameters change away of the standard values for the same track circuit numbers. The model studied the input-output voltage and current characteristics of the railway track in case of crack existence and no crack existence. Also the model provides a mathematical derivation to calculate the exact distance at which the crack exists.

6.2 Future Work

(1) The mathematical model for the crack detection will be improved to use some of the mobile cloud computing techniques to send the analysis of the track periodically to either the train drivers or the controlling room members like those technologies used in [25].

(2) The data collected or analyzed for the track will be transferred to the data warehouse and artificial intelligence fuzzy systems by multitasking wireless sensors like those developed in [26] instead of using GSM modules to transfer data because it isn’t cost effective.

(3) The crack detection on the railway track will be detected by trying another technology like using LRTU (Long Range Ultrasonic Testing) techniques and also the RF (Radio Frequency) testing and then compare the results from the three models to specify the best one to detect crack.

(4) Monitor speeds throughout the railway for trains to avoid accidents caused by unattended speeds such as the one that occurred on February 27 of 2019, when a tractor entered at a speed of no less than 80 km / hr to the dock of the Egypt station and resulted in a collision between the tractor and the building of the station, causing an explosion of the fuel tank inside the tractor and resulted in a massive fire that led to the death of 21 people at least and wounding about 52 others [27].

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