6. EXPERIMENTAL VALIDATION OF THE EFFECT OF BRAKING TORQUE TO BOGIE DYNAMICS: PART A. DESIGN OF EXPERIMENTAL PROGRAM

6.1. INTRODUCTION

As has been described earlier in this thesis, the RBD program calculates the longitudinal dynamics of bogies including speed profile and the corresponding wheelset pitch due to the application of braking/traction torque. This capability could only be validated using careful experimentation. A full-scale laboratory test was, therefore, designed and commissioned for this purpose at the heavy testing laboratory (HTL) of the Central Queensland University (CQU). This chapter describes the design of the experimental program. Analysis of the dataset and validation of the simulated response of the bogie dynamics are reported in the subsequent chapters.

6.2. EXPERIMENTAL DESIGN

6.2.1. The Concept

The primary objective of the test was to examine the dynamics of bogies subjected to brake torque. A bogie running on a tangent track was considered for this purpose. A three-piece bogie (QR30) provided by Queensland Rail (QR) was used. Due to space limitation in the laboratory a 24m long track could only be constructed, thus restricting the maximum speed of the bogie to 4 m/s (14.4 km/h). The bogie was braked using its own brake system. Traction was not specifically considered as a test parameter. Only the rear wheelset was braked and the front one was left un-braked to allow comparison of the dynamic characteristics of the braked and the un-braked wheelsets. The brake force was controlled using a pneumatic circuit that maintained the brake pressure and brake application time (time needed to reach maximum pressure) to the required levels. A set of measurement equipment and devices was installed on the bogie in order to gather data of the applied brake force, the longitudinal, the vertical and the lateral dynamics (travel distance, velocity and acceleration), as well as the wheelset rotation (pitch).

Andrews (1986) reported a similar experiment carried out in the early 1960's by British Railway Electrical Laboratory in Willesden, with a particular focus on traction effects to locomotive bogie dynamics. A single bogie powered with a traction motor and loaded appropriately to simulate the static axle load was used in their test. A sketch and photo of the test setup are shown in Fig. 6.1 and Fig. 6.2 respectively. Their test did not pay any attention to braking as adhesion and traction torque induced slip were the major study parameters. The test described in this thesis was primarily developed for examining the effect of brake torque to bogie dynamics. To the best knowledge of the author, no other similar experiment was found in the literature.

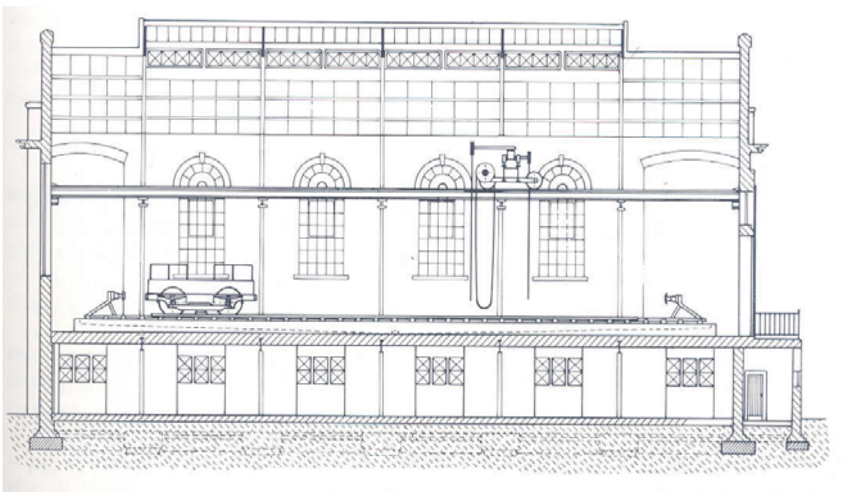


Figure 6.1. Sketch of traction test at British Railway Electrical Laboratory (Andrews (1986))

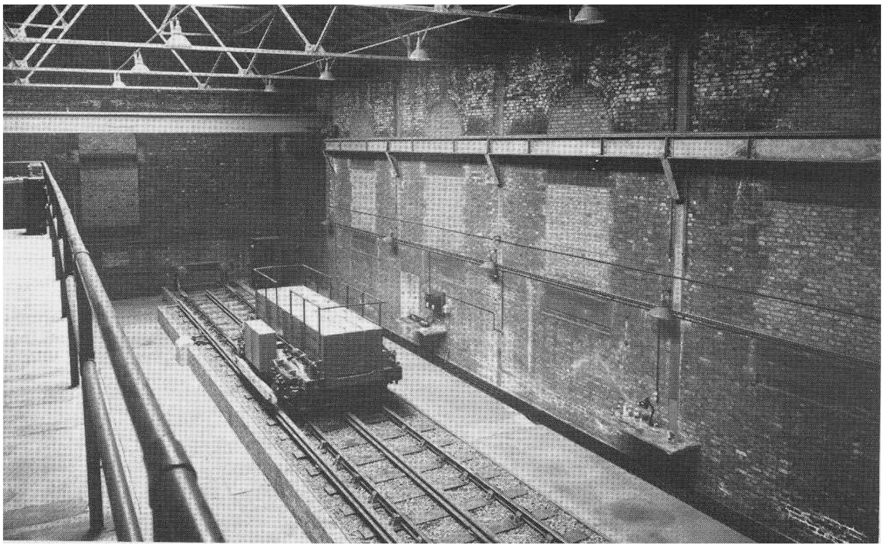


Figure 6.2. Photo of traction test at British Railway Electrical Laboratory (Andrews (1986))

6.2.2. Track Section and Estimated Speed Profile

The 24m long track was divided into zones of acceleration, steady-state rolling (coasting) and deceleration, followed by a safety zone as shown in Fig. 6.3. Choice of maximum length of these zones was constrained from the safety perspective. The estimated speed profile shown graphically in Fig. 6.3 has been used as a base to define the range of the traction force (pulling force) and brake force required for safe operation of the bogie.

The acceleration a_a and deceleration a_b were assumed to be maintained at 1 m/s^2 to avoid excessive slip. Assuming linear change in speed in the acceleration and braking zones, the relation between the maximum speed and the distance travelled in each zone is written as shown in Eq. (6.1) and (6.2):

$$a_a = \frac{1}{2}\frac{v^2}{s_a} = 1 \cdot m/s^2, \tag{6.1}$$

$$a_b = \frac{1}{2}\frac{v^2}{s_b} = 1 \cdot m/s^2, \tag{6.2}$$

Substituting longitudinal distance travelled $s_a = s_b = 8m$ into the above equations, $v = 4 \cdot m/s$ was obtained as the maximum permissible safe speed.

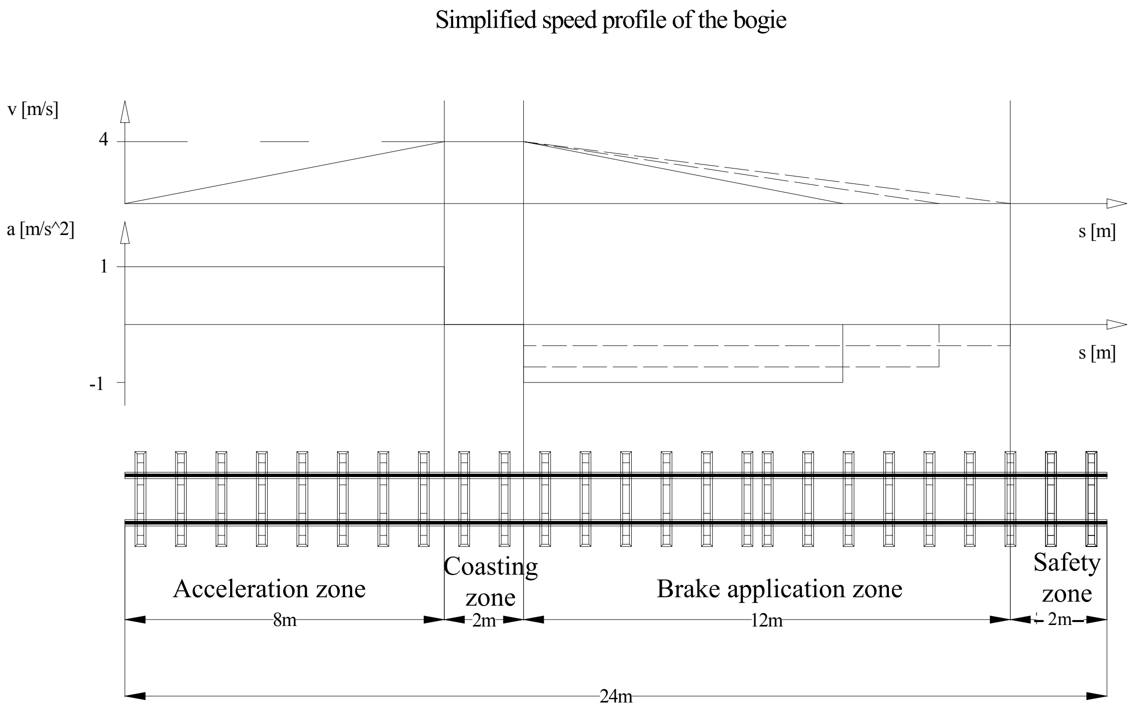


Figure 6.3. Track section and estimated speed profile

However, as a constant braking rate of 1 m/s^2 was most likely not achievable using the available brake equipment (lower acceleration was also considered), the braking section was chosen longer than ideally necessary. Effect of potential lower deceleration rate to stopping distance is shown by the dashed lines in the speed profile curve of Fig. 6.3

6.2.3. Specification of Equipment

Braking force

A reliable and accurate measurement of brake force applied to the wheelset was needed. In the QR30 bogie, the brake torque is transmitted through tangential friction force due to the contact of the brake shoes onto the wheel tread. Force on the brake shoes is provided by a cross-beam that is on one side connected to the brake shoes and on the other side attached though pistons to the actuators (brake cylinders) as shown in Fig. 6.4. The movement of the brake beam is guided by slots provided in the side frame.

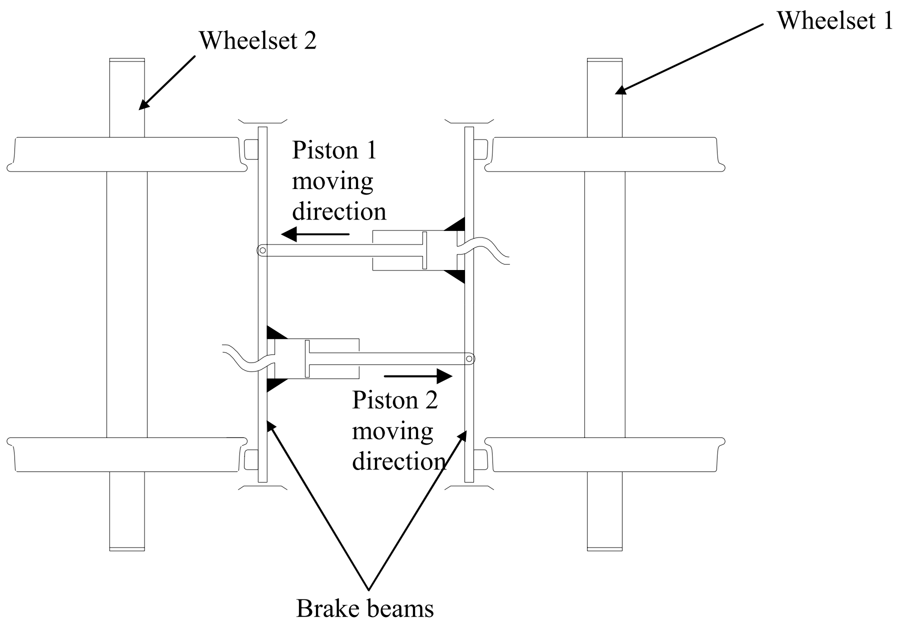


Figure 6.4. Schematic diagram of QR30 brake system

Fig. 6.5 shows the forces applied to the system; due to symmetry only half of the system is shown. It is, therefore, very important to measure the forces exerted by the actuators F_{CT1} and F_{CT2} as well as the tangential force F_T produced due to friction between the shoes and the wheels as accurately as possible. By knowing the magnitude of the tangential force produced, the actual torque applied to the wheels can easily be calculated from the geometric data of the wheelset.

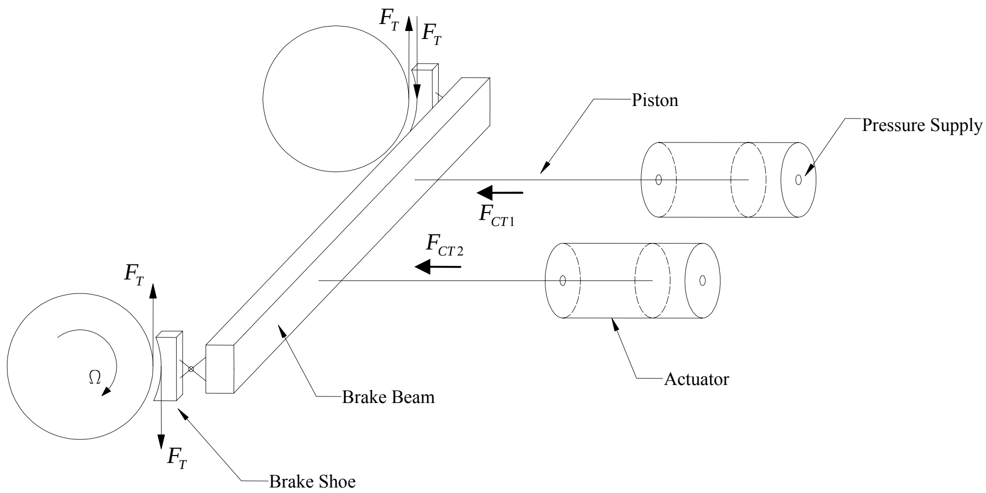


Figure 6.5. Forces acting on brake system of QR30 bogie

According to the QR30 bogie specification, total brake shoe normal force that can be generated by the bogie brake system is 0.164 kN for each kPa of air pressure supplied to the brake cylinders. The brake cylinder can receive a maximum of 350 kPa air pressure that could produce a total of 57.4 kN. However, due to the requirement of low load, during the test the pressure supplied to the brake cylinder was required to be maintained low, say below 200 kPa, to keep the force lower than 32.8 kN. This magnitude of the force is the sum of the normal forces applied to each of the four shoes. Therefore, the force acting on each wheel would be less than 8.2 kN. Due to symmetry, the same magnitude force would act on the brake cylinder rod (see the diagram of the brake force distribution in Fig. 6.6). The calculation of the applied brake tangential force to the wheelset requires knowledge of the friction coefficient between the brake shoes and the wheels. Assuming the friction coefficient in the range of 0.2 to 0.4, the tangential force would be in the range of 1.64 kN to 3.28 kN.

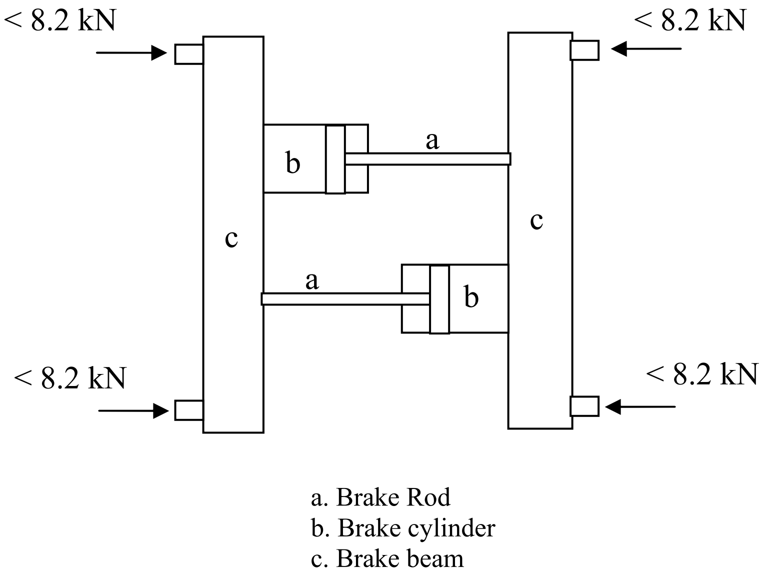


Figure 6.6. Distribution of brake normal force

Longitudinal dynamics of the bogie

In general the bogie dynamics in the longitudinal direction can be defined in terms of the following quantities:

- *Longitudinal acceleration*

- *Longitudinal velocity*

- *Longitudinal travel distance*

- *Wheelset rotation and angular velocity relative to its lateral axis*

As the purpose of the experiment was to investigate the longitudinal dynamics of the bogie under braking condition, the above quantities have to be measured accurately during the test. The brake torque application to the wheel creates longitudinal slip or creepage in the wheel rail contact patch, the definition of which has been described in Section 2.3. The creepage generates the longitudinal contact force that decelerates the bogie. Therefore the measurement equipment should detect this longitudinal slip to validate the creepage-creep force relationship used in the model.

Based on the creepage formulation presented in Section 2.3.1 of Chapter 2, longitudinal slip could be written as in Eq. (6.3):

$$\xi_x = \frac{v_c - v}{v} \tag{6.3}$$

where v_c and v are the circumferential velocity at the wheel-rail point of contact and the longitudinal velocity of the wheel respectively. Predicting the values of longitudinal slip $\xi_x = 0.02$ during the braking, while the circumferential and longitudinal velocities $v_c \approx v = 4 \cdot m/s$, the relative velocity to be measured can be calculated as in Eq. (6.4).

$$|v_c - v| \approx 0.02 \cdot 4 \cdot m/s = 0.08 \cdot m/s\,. \tag{6.4}$$

However, when the speed reduces to zero, relative velocities that are much lower than 0.08m/s could occur. Therefore, to increase the accuracy of the measurements, the relevant specification of the speed was set as 0.1 m/s and the relative velocity to be measured becomes

$$\left|v_c - v_x\right| \approx 0.02 \cdot 0.1 \cdot m/s = 0.002 \cdot m/s \tag{6.5}$$

The value of relative velocity in Eq. (6.5) was then used as a reference value to choose the resolution of the devices for the measurement of the wheel rotation and the longitudinal movement. Including the resolution specifications/tolerances of the sensors in operation, the measured slip or creepage could be written as Eq. (6.6):

$$\xi_{\exp} = \frac{\left(v_c \pm d\Omega_{Sensor} \cdot r_w\right) - \left(v \pm dv_{Sensor}\right)}{\left(v \pm dv_{Sensor}\right)} \tag{6.6}$$

where $d\Omega_{sensor}$ is the resolution tolerance of the sensor measuring the wheelset rotation, dv_{sensor} is the resolution tolerance of the sensor measuring longitudinal movement and r_w is the nominal radius of the wheel.

The error of slip detection in relation to the analytical values of slip is defined as shown in Eq. (6.7).

$$e_{\xi} = \frac{\left|\xi_{\exp} - \xi_{analytical}\right|}{\xi_{analytical}} \cdot 100\%. \tag{6.7}$$

Typical measurement equipment for longitudinal or rotational speed detection is based on resistive, inductive (analogue) or incremental (digital) principles. High accuracies demand exact inductive conditions in the case of analogue equipment like tachometers and precise adjustable resistors in the case of potentiometers. For the incremental devices, precise and small switching events are required. Table 6.1 exhibits a comparative study of the measurement devices for measuring longitudinal motion of the bogie and the angular measurement of wheelset rotation. As can be seen from Table

6.1, inductive devices are used for the measurement of velocities and resistance and optical devices are used for the measurement of position signal. As time (clock) is independently recorded during data acquisition, the calculation of velocities from position data is also possible. Thus, resistance and optical based devices could also be used for measuring the angular and the longitudinal velocities.

Table 6.1. Comparison of measurement devices for longitudinal and angular motion

Device	Signal	Longitudinal		Angular	
		Position	Velocity	Position	Velocity
Inductive	Voltage		Tachometer (Gear)		Tachometer
Resistance	Voltage	Potentiometer		Potentiometer	
Optical/Magnetic	TTL (Transistor-Transistor Logic)	Encoder (absolute or incremental)		Encoder (absolute or incremental)	

<u>General motion of wheelsets</u>

Besides the longitudinal dynamics of the bogie there is also an interest to examine the braking torque's influence to the lateral dynamics and furthermore to yaw and roll motions of the wheelset. To decide on the quantities to be measured for the purpose, it is important to understand how the wheelsets move relative to the track and relative to the bogie frame to which they are connected. Fig. 6.7 shows the end view of a wheelset linked to the side frame. Vertical and lateral motions are restricted by bump-stops and influenced by dry friction between the surfaces in contact. If the axle boxes are assumed to be in permanent vertical contact with the pedestals on the side frames, the wheelsets will have two of their six degrees of freedom (vertical and roll) follow the corresponding degrees of freedom of the side frames. Permanent vertical contact between axle boxes and side frames can be assumed due to expected low vertical accelerations.

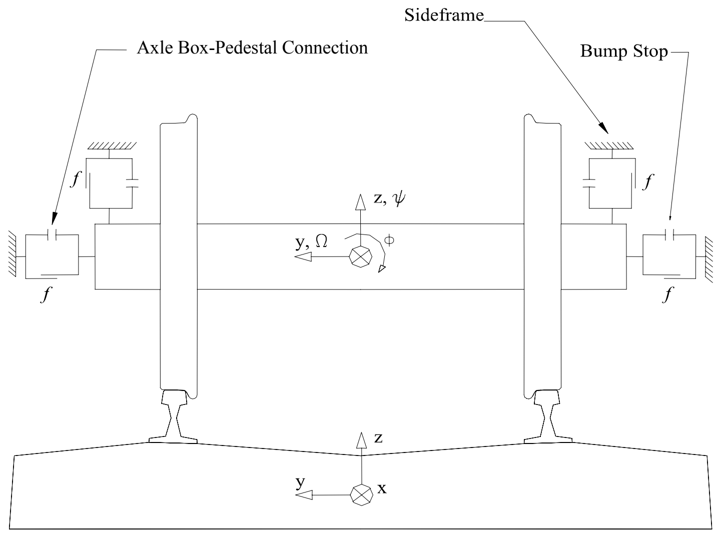


Figure 6.7.Wheelset connection to side frame

As the primary interest of the experiment is the movement of the wheelsets on the rail and *not* the displacements in relation to the bogie's side frame, the accelerations with respect to the three directions of space are required on each axle box. Placing accelerometers here and assuming permanent vertical connection between the side frame and the axle box allowed the detection of vertical running behaviour and pitch of the side frames of the bogie and the bogie itself. By obtaining acceleration data of the axle boxes in all three directions, yaw and lateral motions as well as roll of the wheelsets can be calculated as long as the set-up is held symmetric to the bogie frame.

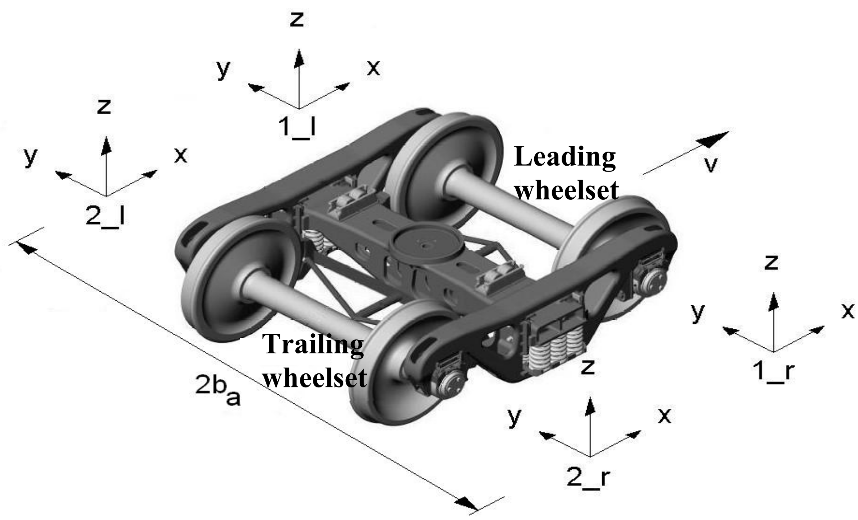


Figure 6.8. Axial acceleration to be measured on the bogie

The accelerometer directions are presented in Fig. 6.8[1]. The four Cartesian coordinate systems shown in Fig. 6.8 represent the directions of the accelerometers fitted at each axle end. If the angular displacements of the wheelset are assumed to be small, the roll and yaw accelerations can be calculated as follow (approximation):

$$\ddot{\phi} = \frac{1}{b_a}\left(\ddot{z}_{1,l} - \ddot{z}_{1,r}\right), \text{ roll,} \tag{6.5}$$

$$\ddot{\psi} = \frac{1}{b_a}\left(\ddot{x}_{1,r} - \ddot{x}_{1,l}\right), \text{ yaw.} \tag{6.6}$$

The variable b_a denotes half of the lateral distance between the accelerometer positions on the axle boxes. Lateral motion of the wheelset would ideally cause identical signals on both of the lateral accelerometers on one axle; thus only one accelerometer is necessary in the lateral direction. Therefore, only five accelerometers per wheelset (a total of 10 accelerometers) were used in the experiment.

[1] Picture taken from Standard Car Truck manual, modified

6.3. EQUIPMENT, INSTALLATION, AND DATA ACQUISITION

Based on the specification described in Section 6.2, a set of measurement equipment was chosen. Other factors such as the cost and the delivery time were also considered when selecting the equipment supplier. This section presents briefly the chosen measurement devices and their installation on the bogie.

6.3.1. Brake Force Measurement – Strain Gauge

As introduced in Section 6.2 the brake force was applied to one wheelset only; the trailing wheelset was braked while the non-braked leading wheelset was used as a reference. Originally the brake beam was supported and guided by slots in a slider housing provided in each side frame, which adversely affected the measurement of the tangential force. Therefore, the brake beam of the braked wheelset was cut as shown in Fig. 6.9 and hangers were then used to replace the function of the slots to support and guide the movement of the brake beam. The tangential brake force was measured from the strain in the hanger.

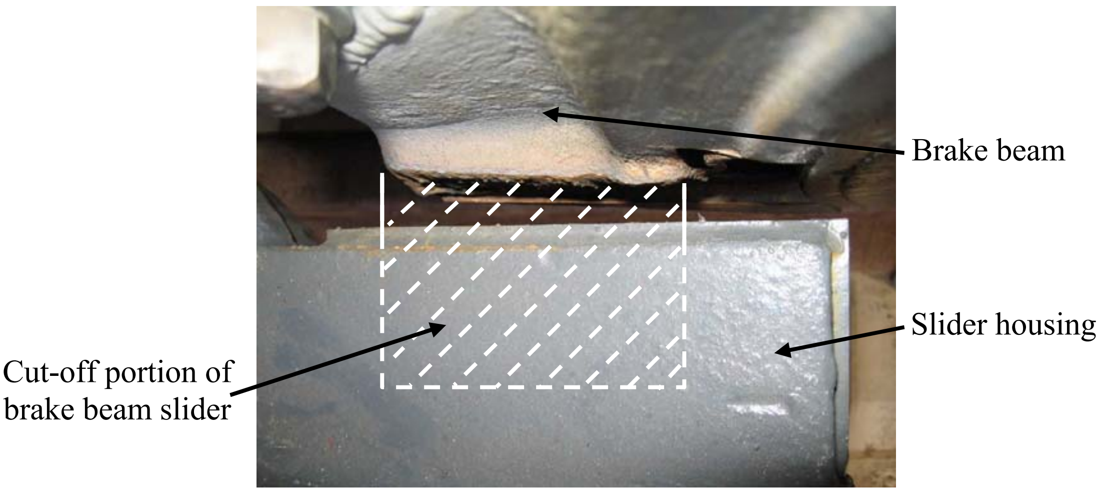
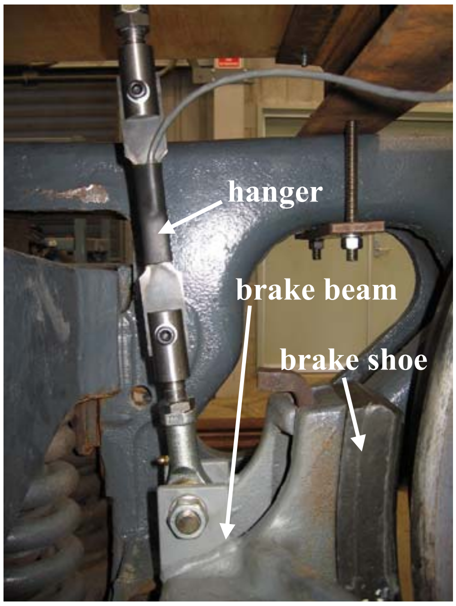


Figure 6.9. Modification (cutting) of the brake beam slider

Fig. 6.10 (a) shows part of the hanger fitted with a strain gauge and Fig.6.10 (b) shows its installation on the bogie. The design of hanger installation assembly allowed accurate positioning of the brake beam relative to wheelset both vertically and laterally.

(a) part of the hanger with strain gauge



(b) installation on the bogie

Figure 6.10. Tangential brake force measurement

In the non-braked leading wheelset, the movement of the brake beam was restricted by a plate welded onto the slot providing a thread to allow adjustment of the longitudinal clearance using a bolt (Fig. 6.11). The force exerted by the brake actuator was measured by fitting a strain gauge on the brake rod as shown in Fig. 6.12.

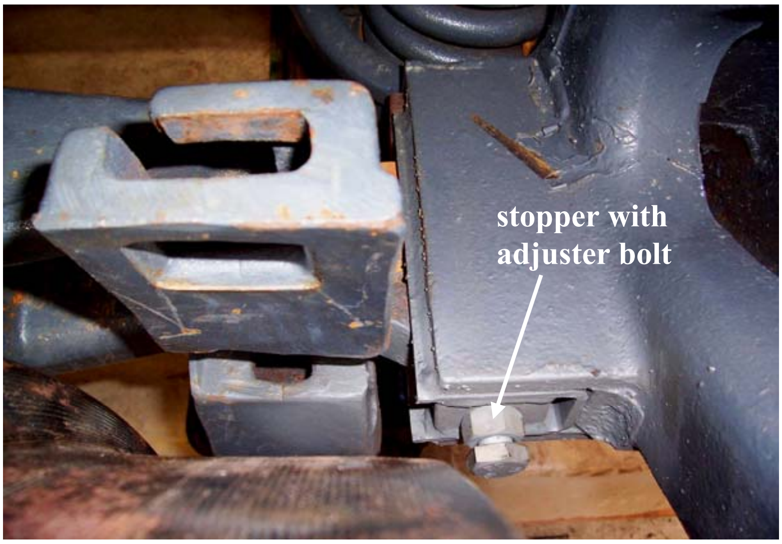


Figure 6.11. Brake beam stopper of the non-braked wheelset

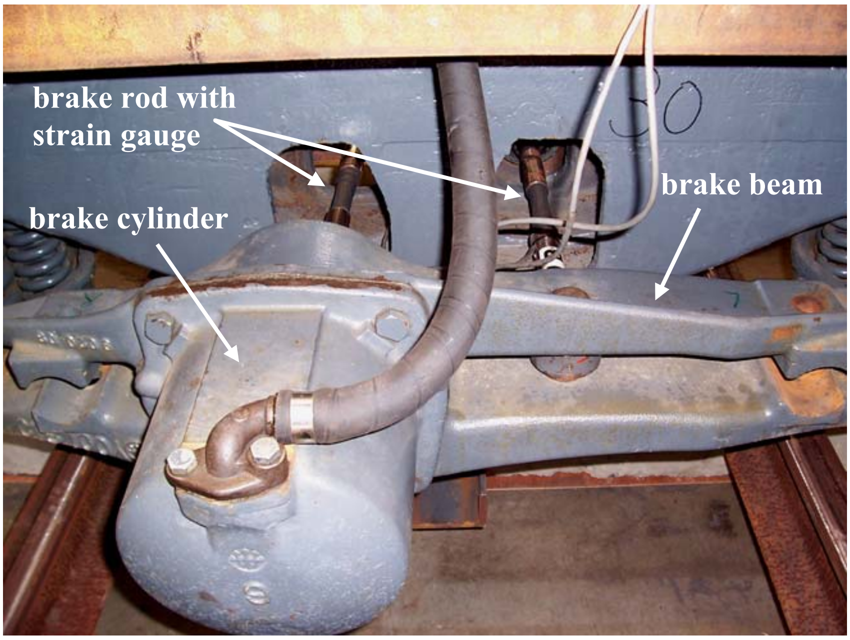


Figure 6.12. Brake cylinder and brake rod with strain gauge

6.3.2. Longitudinal Movement Measurement – Magnetic Linear Encoder

A magnetic linear encoder was used as a sensor to measure the longitudinal motion of the bogie. The specification of the sensor is provided in Table 6.2. The sensor is capable of accurately detecting incremental motion reading on a longitudinally installed magnetic tape. The picture of the sensor and the magnetic tape are shown in Fig. 6.13.

Table 6.2. Specification of linear encoder

Manufacturer	Kuebler
Type	LIMES, K8.L2.122.2211.0005 and K8.B2.10.010.0250
Physical Principle	Detection of inductive currents due to polarity changes on the tape
Characteristic Output	TTL-Signal, 50000 lines per m, 0.02 (single) – 0.005(quadruple) acquisition
Range	0-14m/s

Figure 6.13. LIMES magnetic linear encoder

Based on the specification of the linear encoder, which requires high precision, a special support and guidance system was designed. The system provided longitudinal support for the magnetic tape which also guided a carriage with the sensor located on it ensuring safe signal reception. The sketch of the longitudinal travel distance measurement using LIMES linear encoder is presented in Fig. 6.14. A longitudinally rigid and laterally and vertically free to move link system was installed between the bogie frame and the carriage. The LIMES linear encoder was fitted to the carriage. The mounting system of the sensor allowed for adjustment of the gap between the sensor and the magnetic tape (1 mm gap was required in addition to the adjustment of the lateral position of the sensor above the tape). The carriage and the guide beam containing magnetic tape are exhibited in Fig. 6.15.

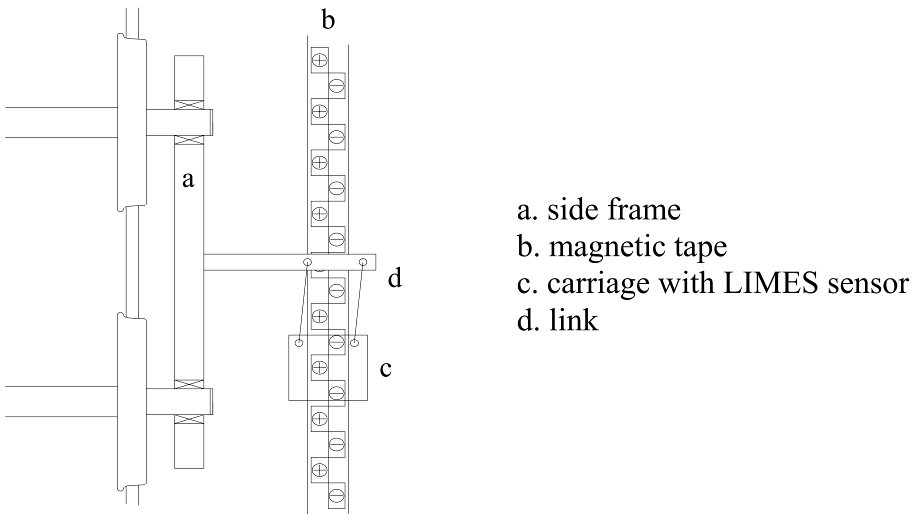


Figure 6.14.Sketch of longitudinal travel distance measurement

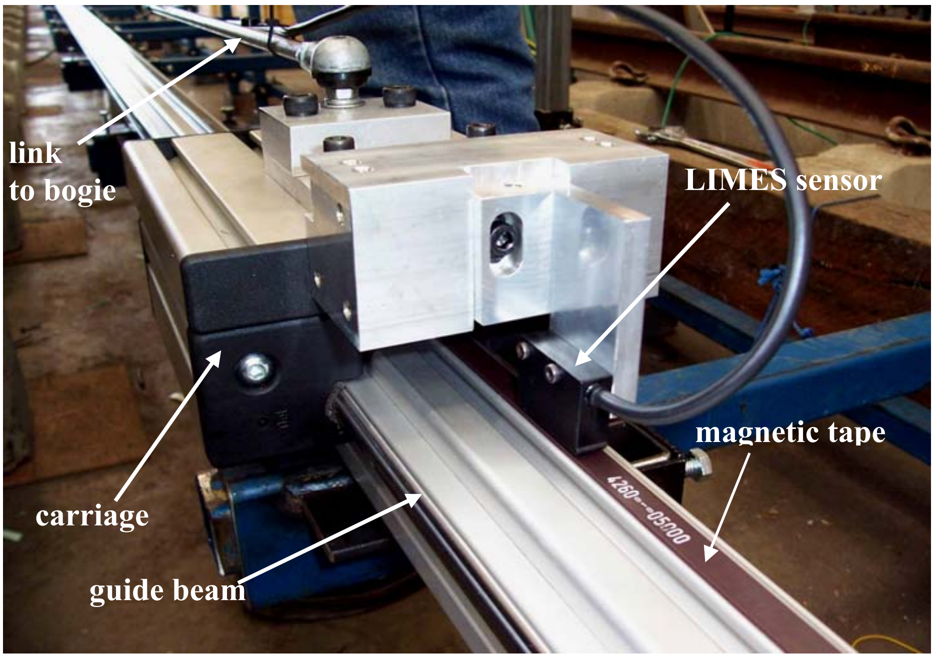


Figure 6.15.The carriage and guide beam for linear encoder

6.3.3. Wheel Rotation Measurement – Shaft Encoder

42mm Hollow Shaft Encoders of 10.000 pulses per revolution were chosen to measure the rotation of both wheelsets. The specification of the shaft encoder is presented in the Table 6.3 and its photo is shown in Fig. 6.16.

Table 6.3. Specification of shaft encoder

Manufacturer	Hengstler,
Type	RI176TD/10000AH.4A42TF
Physical Principle	Opto-electronic
Characteristic Output	TTL-Signal, 10000 lines per revolution, 0.036°
Range	0-1800 rpm

Figure 6.16. Hollow shaft encoder

Fig. 6.17 shows the installation of the shaft encoder to the axle end of one of the wheelsets. To achieve this installation the axle boxes were required to be cut open to provide access to the fitting of the encoder adaptor. In addition, a rigid link was also attached for the installation of the accelerometer box (also shown in Fig. 6.17).

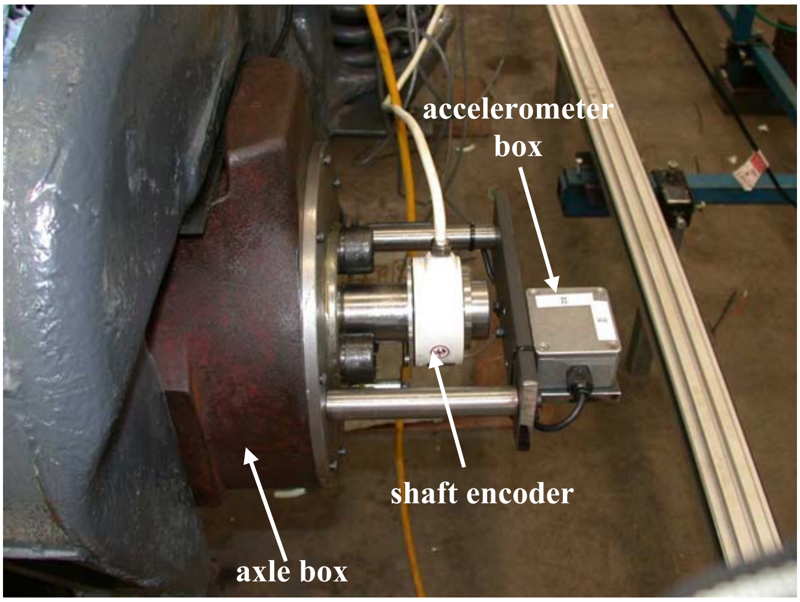


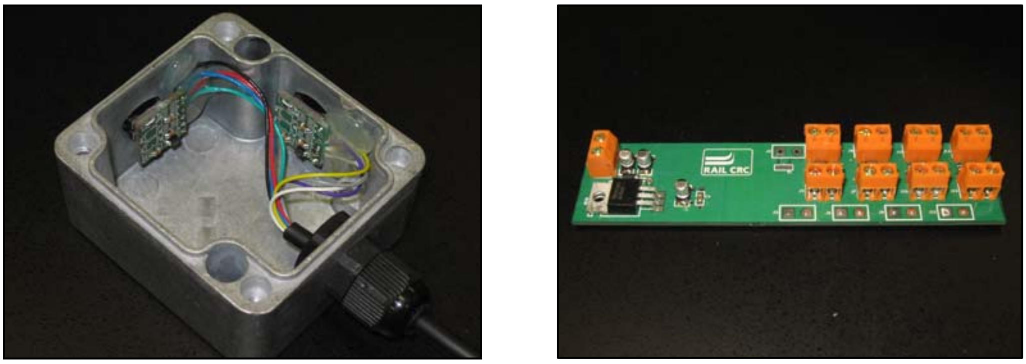
Figure 6.17. Shaft encoder and accelerometer installation through modification of axle box

6.3.4. Accelerometer Measurements

The specification of the accelerometers used for measuring the wheelset motion is presented in Table 6.4. The accelerometers are compactly installed in a small rigid box as shown in Fig. 6.18 (a). A cut-off frequency was chosen and an appropriate filtering device was implemented to facilitate its use for any other application beyond the current test. The accelerometer signal was filtered by a second order Butterworth filter (Fig. 6.18 (b)), cutting off the signal at the frequency of 20 Hz. The accelerometer installation on the bogie is exhibited in Fig.6.17.

Table 6.4. Accelerometer specification

Manufacturer	Analog Devices
Type	ADXL210
Physical Principle	Piezoelectric device
Characteristic Output	Voltage, 100 mV/g
Range	+/- 10g



(a.) Accelerometer (b.) Butterworth filter

Figure 6.18. Accelerometer and CRC Butterworth filter

6.3.5. Wheel-Rail Profile Measurement – MiniProf

Real data of the wheel and the rail profile were measured using MiniProf (a special tool designed to measure wheel and rail profile). The equipment was provided by Queensland Rail (QR). The data of the wheel and the rail profile coordinates provided by the MiniProf was required as the input for the computer simulations (to be discussed in Chapter 8). Figs. 6.19 and 6.20 show the MiniProf tool used to measure the wheel profile and the rail profile respectively.

Figure 6.19. MiniProf tool for measuring the wheel profile

Figure 6.20. Measurement of the rail profile using MiniProf

6.3.6. Track Construction

The test track was carefully constructed to achieve the satisfactory *straightness of the track* along the length of 24 m. It was done by the professionals from the Queensland Rail. Two photos of track welding and grinding activities during the track construction are shown in Fig. 6.21 and Fig. 6.22.

Figure 6.21. Track welding

Figure 6.22. Track grinding

6.3.7. Rail Friction Coefficient Measurement - Tribometer

The friction coefficient of the rail surfaces was determined using a portable hand-pushed tribometer (product of Salient System) shown in Fig. 6.23. The tribometer measures the coefficient of friction at points along the rail head from the top of the running surface to the lower edge of the gauge face. As the experiment was only for a bogie running on the tangent track where the gauge face contact was an unlikely event, only the friction coefficient of the top of rail head was measured. The measurement was conducted by pushing the device at walking speeds to collect readings, while a proprietary algorithm reviewed the data for accuracy. The tribometer was provided by QR.

(a) arrangement on the rails

(b) close up of the sensor wheel and the reader

Figure 6.23. Portable Tribometer

6.3.8. Data Acquisition and Data Analysis

A total 18 channels of data signals were obtained and processed during the experiment. Three of them were digital signals (from two shaft encoders and one linear encoder), and the other 15 channels were analogue signals. These different types of the streams were synchronised with time (computer clock) during the experiment. For this purpose a data acquisition program was developed in Lab View software platform. The program was then installed into the data acquisition (DAQ) computer mounted on the bogie (Fig. 6.24). The output of the DAQ program was provided in two binary files (one for the analogue data stream and the other for the digital data stream), which were then converted and merged into one data text file. To analyse the result, a program in Matlab platform was coded. The program read the data text file and plotted the data as required.

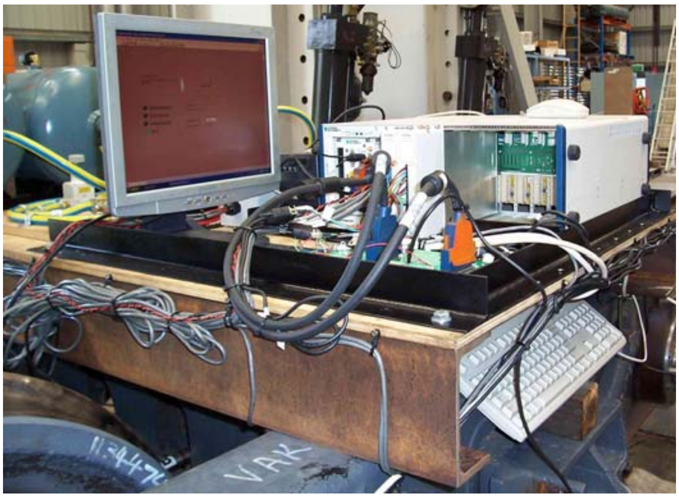


Figure 6.24. DAQ computer mounted on the bogie

6.3.9. Brake Controller

Fig. 6.25 shows the pneumatic system installed on the bogie for the control of the application of the brake force. Experimental conditions did not allow a person to sit on the bogie to control the brakes. Also no external control radio link or other network interaction was available. The pressure supplied to the brake actuators was set up using the pressure regulator while the application time was adjusted using a flow restriction valve.

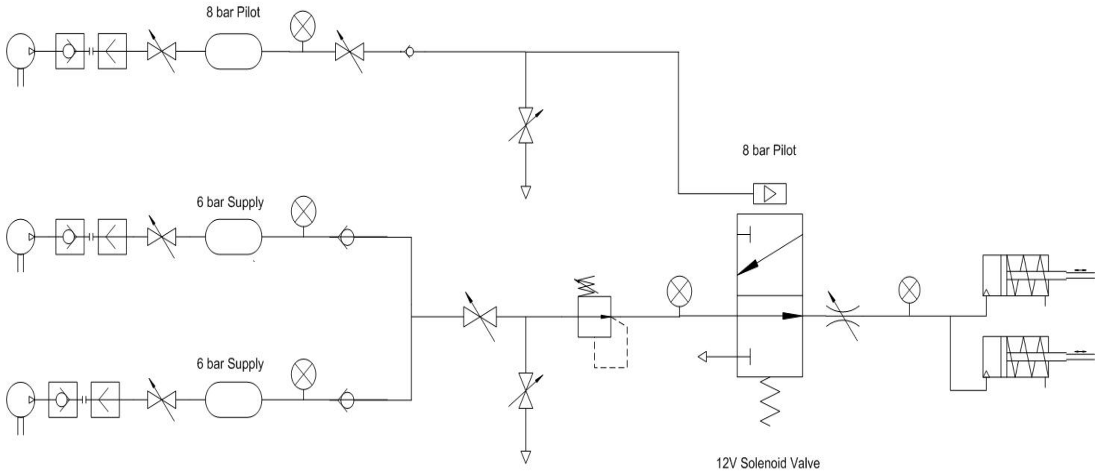


Figure 6.25. Diagram of pneumatic system used for brake controller

To control the event of braking, a solenoid valve was used. The solenoid valve opened the air pressure line to the brake actuators when the electric circuit was de-energised; this provided a fail-safe operation. De-energising of the electric circuit at a certain position along the track was controlled automatically by the DAQ computer system mounted on the bogie. The operator of the experiment was required to just input the distance at which the brake was required to be applied; the DAQ computer system recorded this value and then compared it to the data received from the measurement of the longitudinal movement of the bogie provided by the LIMES system. This process was performed in real time during the test execution.

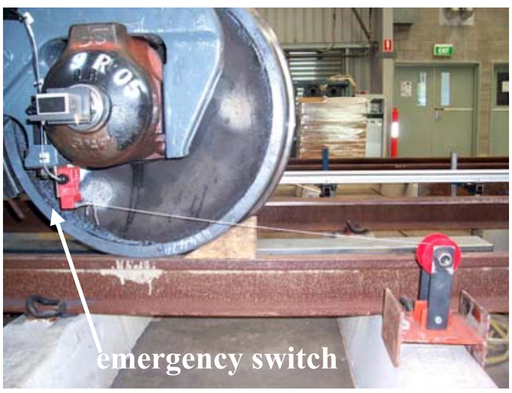


Figure 6.26. Brake emergency switch using string

To deal with any un-anticipated failure in the DAQ computer, a switch was designed and installed so that it could be simply disengaged (cut-off the electric circuit) by pulling a plug connected to a string (Fig 6.26). The length of the string was carefully worked out and the emergency brake was positioned accordingly on the track.

6.3.10. Complete Test Setup

Fig. 6.27 shows the fully instrumented bogie with its data acquisition system ready for commissioning.

Figure 6.27. Instrumented Bogie with DAQ ready for commissioning

Prior to each test trial, the DAQ was supplied with the information on the required brake pressure and the start time and rate of application of brake pressure. A road truck was used to provide the traction.

6.4. SUMMARY

An experimental program was designed to validate the RBD program, in particular the calculated speed profile due to the application of braking torque and the corresponding wheelset pitch. The experimental program design may be summarised as follows:

- Due to the space constraint within the lab, the track length was limited to 24 m.
- Due to the limitation of the test track length, the experiment could only be performed at low speed (i.e. below 4 m/s).
- The test track was carefully divided into four zones namely acceleration zone (8m), coasting zone (2m), braking zone (12m) and safety buffer zone (2m).
- The primary objective of the experiment was to investigate the influence of braking torques to the bogie longitudinal dynamics. In relation to this, to avoid complexity and reduce cost, no traction motor was installed on the bogie. Instead, a small road truck was used to accelerate the bogie. This economical option, although adversely affecting the repeatability issues, was sufficient (discussed in Chapter 7) to achieve very close repeatable experiments.
- A fully controlled and measured brake force was applied to the trailing (rear) wheelset of the bogie.
- Measurement devices were carefully chosen to meet the requirement of high precision data. The mounting details for each of the devices were carefully designed so that the data could be gathered accurately.

- Different types of data streams (analogue and digital) from 18 channels were processed and synchronized by a data acquisition program built in Lab View software platform. The DAQ system computer was mounted on the bogie.

- A fail safe braking system was designed and installed to prevent any unexpected failure in brake circuit and /or DAQ program.