9. APPLICATION OF THE RBD PROGRAM: EFFECT OF ASYMMETRIC BRAKE FORCES TO BOGIE DYNAMICS

9.1. INTRODUCTION

The RBD program and its formulation developed as part of this thesis could now be regarded as being validated for most practical conditions based on the discussions in chapter 8. This chapter reports on severe bogie dynamics due to the application of asymmetric brake normal forces within a single wheelset in bogies equipped with one-side push brake shoe arrangement. Such a situation could lead to the deterioration of the running performance of the bogie including potential for derailment. Handoko et al. (2004) has reported some limited examination of the effect of asymmetric braking to the curving performance of a wagon negotiating a downhill slope with the brake forces applied to keep the *speed constant*. However, to the best knowledge of the author, no studies of asymmetric braking during *variable speed* have been reported in the literatures. The RBD program has the capability to simulate such severe conditions and in this chapter its potential is reported through examples.

9.2. DEFINITION OF ASYMMETRIC BRAKING

Fig. 9.1 shows the brake rigging arrangement of a simple bogie equipped with one-side push brake shoe arrangement. The braking force produced by the brake cylinder that is mounted on the wagon underframe is distributed to the wheels through a mechanical link arrangement. The mechanical link, called brake rigging, consists of rods and levers suspended from the underframe of the bogies and linked with pins and bushes. This type of brake rigging requires careful installation and regular adjustment to ensure that the forces are evenly distributed to all wheels. It can be seen from the rigging diagram (Fig.9.1) that any bad adjustment of the brake rigging could lead to uneven distribution of braking forces. Such a situation can occur when either the centre-pin on rod AB is slightly off-centred or if the fixed-end pin in the bolster is disorientated and also when the guiding slot is stuck due to some obstacles or dirt.

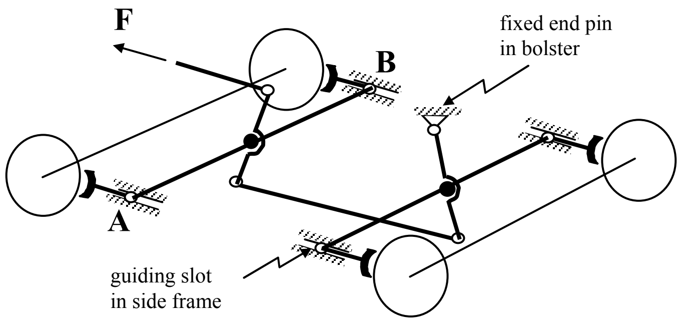


Figure 9.1. Typical Brake rigging arrangement

Fig. 9.2 shows the asymmetric brake shoe normal forces applied to a single wheelset. ΔF is defined as the error in the normal force distribution. It is clear that the asymmetric forces generate yaw torque to the wheelset that could adversely affect the running stability of the bogie. If the distance between the brake shoe is defined as $2b$, the generated yaw torque can be written as

$$T_{yaw} = 2b \cdot \Delta F \qquad (9.1)$$

For simplification, the reaction torque to the bogie frame was ignored (calculation the reaction torque to the bogie frame requires detail geometry data of the brake rigging, which was not available when this investigation was done).

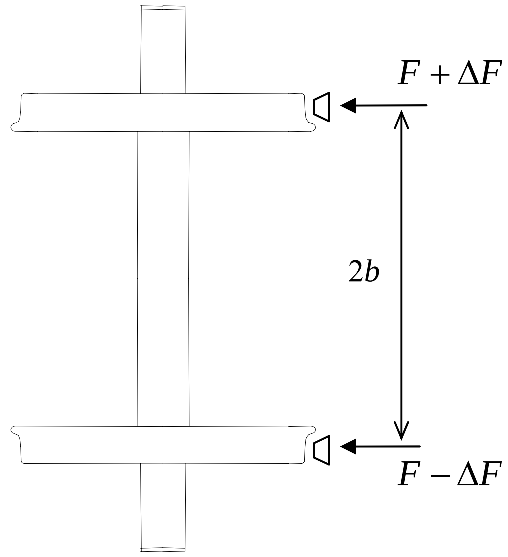


Figure 9.2. Asymmetric brake shoes normal forces

9.3. CASES STUDIED

Several cases of asymmetric brake force (the error ΔF) in the leading wheelset and trailing wheelsets were studied. Table 9.1 shows some selected important cases reported in this chapter. The bogie arrangement, including the mass and the spring constant, was assumed to be the same as that for the bogie model reported in Chapter 5 (see Section 5.2). The wheel-rail friction coefficient was assumed to be 0.3 for all cases. The brake torque applied was assumed to be 20 kNm that produced a constant 1.1 m/s^2 deceleration. These values are considered as common operational parameters in practice. All cases reported correspond to the initial speed of 25 m/s (90 km/h) although other initial speeds were examined. As the initial speed was found to have no significant effect, the cases corresponding to other initial speeds were disregarded in this chapter.

Table 9.1. Cases of Asymmetric Braking

Item	Error Magnitude	Application Time
#1. Asymmetric braking at leading wheelset only	25%	1s, 5s,10s
	50%	1s, 5s, 10s
	75%	1s, 5s,10s
#2. Asymmetric braking at trailing wheelset only	25%	1s, 5s,10s
	50%	1s, 5s, 10s
	75%	1s, 5s,10s

Three levels of error magnitude (25%, 50%, 75%) and application time (normal: 5s / fast: 1s / slow: 10s) were considered as the input control parameters (Table 9.1). Cases of asymmetric braking to the leading and trailing wheelset were also examined, thus a total of eighteen cases were studied. The resulting speed profile and lateral displacement of the wheelsets (leading and trailing) were examined to understand the response of bogies under severe dynamics.

9.4. RESULTS

For simplicity, only detailed results of two (out of the 18) cases for each major items (Items #1 and #2 in Table 9.1) are reported. Results of all cases are compiled in Tables 9.2 and 9.3. Detail plots are included in Appendix IV.

9.4.1. Asymmetric Braking of Leading Wheelset

Fig. 9.3 shows the result of the simulation of the case of 25% error on the leading wheelset at 10s of brake application time (the least severe case of Item #1). From Fig. 9.3 (a), it can be seen that the brake torque linearly increased from zero to 20 kNm within 10 seconds. The application of the brake caused the bogie to come to rest (from its initial speed of 25 m/s) within 22.9 seconds as shown in Fig. 9.3 (c).

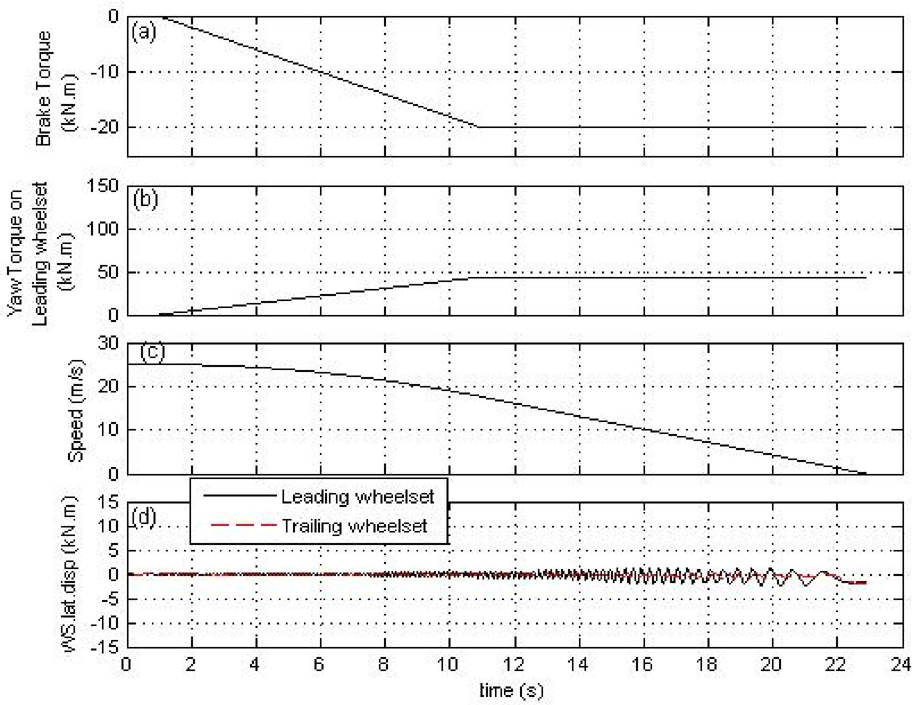


Figure 9.3. 25% error on leading wheelset, 10s brake application time (the least severe case)

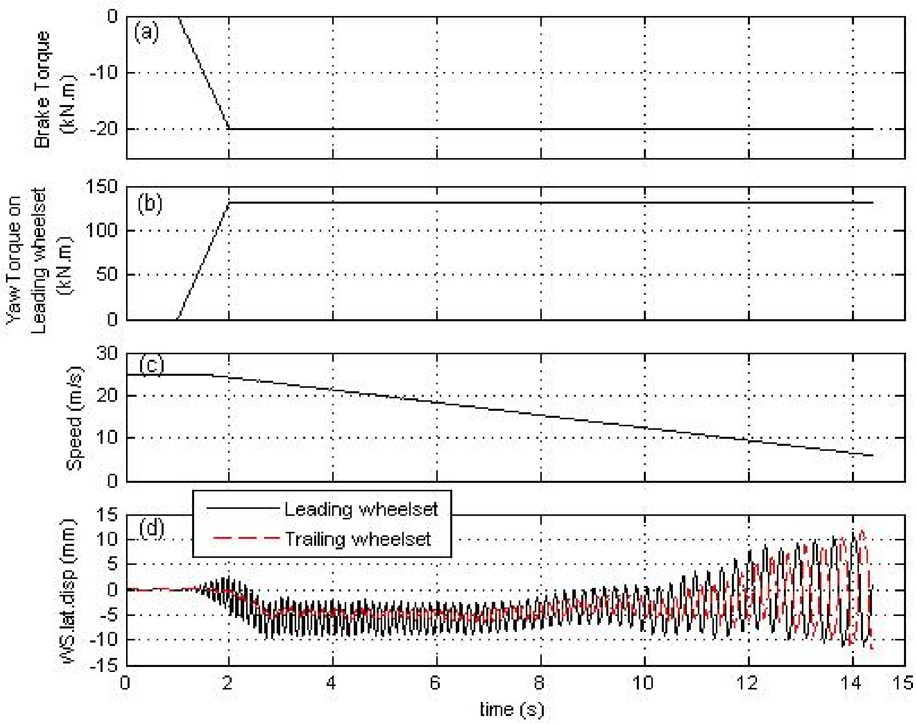
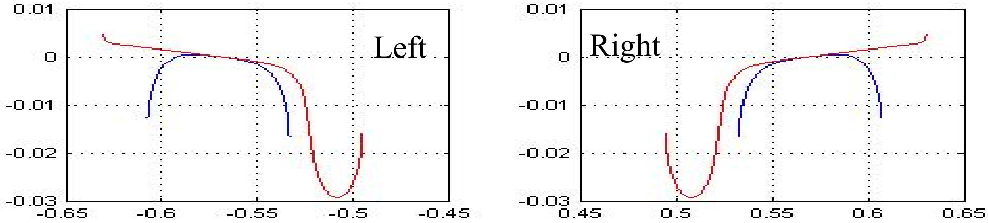


Figure 9.4. 75% error on leading wheelset, 1s brake application time (the most severe case)

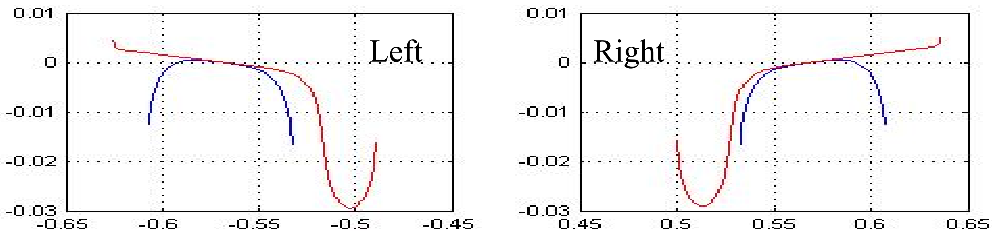
Due to 25% error in the distribution of the brake shoe normal forces, yaw torque was generated on the leading wheelset as shown in Fig. 9.3 (b). The maximum yaw torque was 43.92 kNm which occurred when the brake torque attained its maximum value. As revealed in Fig. 9.3 (d), the yaw torque initiated unstable lateral oscillation of the leading wheelset followed by the lateral oscillation of the trailing wheelset. The magnitude of the lateral oscillation of the trailing wheelset remained smaller (maximum 1.5 mm) compared to the lateral oscillation of the leading wheelset (maximum 2.4 mm) throughout the time history.

Fig. 9.4 shows the result of the simulation of the case of 75% error on the leading wheelset at one second of brake application time (the most severe case of Item #1). From Fig. 9.4 (a), it can be seen that the brake torque linearly increased from zero to 20 kNm within one second. The 75% error in the distribution of the brake shoe normal forces generated yaw torque (maximum 131.8 kNm) on the leading wheelset as shown in Fig. 9.4 (b). The yaw torque initiated severe unstable lateral oscillation of the leading wheelset and the trailing wheelset. When the bogie attained the speed of 6.1 m/s, the lateral displacement of the wheelset attained a large enough value to cause abrupt termination of the RBD program. This was due to the diverging contact constraint equations that failed to determine the position and the orientation of the wheel-rail contact point. This condition is regarded as the onset of "*derailment*" in this thesis.

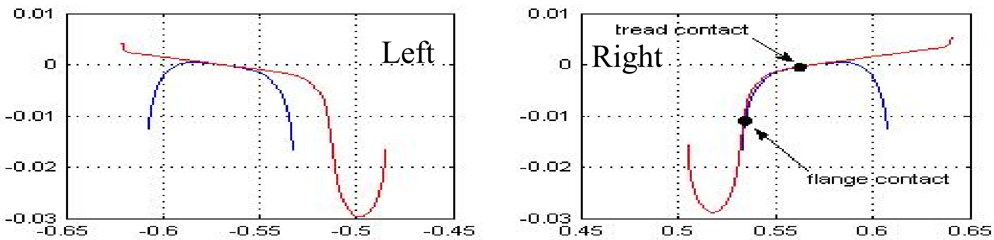
Fig. 9.5 presents several situations of wheel-rail contact predicted by the RBD program during lateral shift of the wheelset. Fig. 9.5 (a) shows the condition when the wheelset is in the centre position (equilibrium state). Fig. 9.5 (b) shows the condition when the wheelset is displaced 5 mm to the right. This figure shows that the clearance between the flange of the right wheel and the right rail head is narrowing while the clearance between the flange of the left wheel and the left rail head is enlarging.



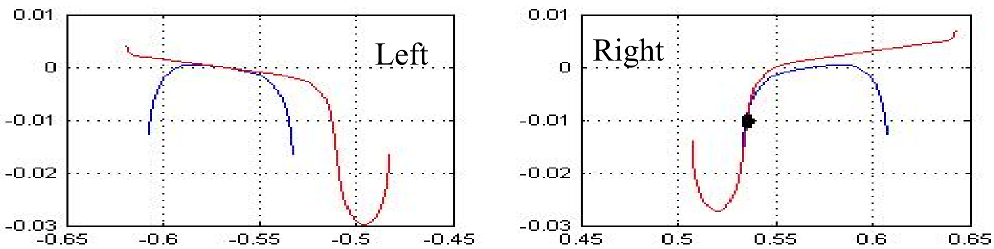
a. centre position



b. 5 mm lateral displacement (towards right rail)



c. 9.5 mm lateral displacement (towards right rail)



d. loss of right tread contact (on the right rail)

Figure 9.5. Wheelset lateral displacement and W/R contact point

When the lateral displacement attains 9.5 mm, the flange contact between the right wheel and the right rail is encountered while the tread contact is still maintained (Fig. 9.5 (c)). This situation leads to lateral impact. When the wheelset continues moving to the right, the flange of the right wheel starts to climb up the right railhead. As the right wheel continuously climbs up the right railhead, at certain lateral displacement, the tread contact between the right wheel and the right railhead is lost (Fig. 9.5 (d)). It is the point where the contact constraint equation in the RBD program failed to converge. With the profiles used in this thesis, the wheel-climb mechanism of derailment occurred at the lateral displacement of around 11.5 mm.

The results of all cases of the simulation of the asymmetric braking on the leading wheelset are compiled in Table 9.2.

Table 9.2. Results of asymmetric braking on leading wheelset at initial speed 25 m/s

	Input		Output		
Error (%)	Maximum Yaw Torque in Leading Wheelset (kNm)	Application Time (s)	Time to Stop (s)	Maximum Lateral Displacement (mm)	
				Leading Wheelset	Trailing Wheelset
25%	43.92	10s	22.9s	2.4 mm	1.5 mm
		5s	20.4s	2.5 mm	1.7 mm
		1s	18.3s	2.5 mm	1.9 mm
50%	87.84	10s	22.9s	8.3 mm	6.1 mm
		5s	20.4s	9.2 mm	6.5 mm
		1s	18.3s	9.3 mm	7.3 mm
75%	131.76	10s	derailment at v=5.9m/s and t=19.1s	-	-
		5s	derailment at v=6.1m/s and t=16.3s	-	-
		1s	derailment at v=6.1m/s and t=14.4s	-	-

The input (maximum yaw torque and its time of attainment) and output (time to stop and maximum lateral displacement of both the leading and trailing wheelsets) are presented. At 25% error, the lateral oscillation attained only a small value irrespective of the brake application time. The lateral displacement progressively increased with the increase in yaw torque. At 75% error the program failed to converge at the speed of around 6 m/s, indicating onset of derailment, for all cases of application time.

9.4.2. Asymmetric Brake on the Trailing Wheelset

Fig. 9.6 shows the result of the simulation of the case of 25% error on the trailing wheelset at 10s of brake application time (the least severe case of Item #2). From Fig. 9.6 (a), it can be seen that the brake torque linearly increased from zero to 20 kNm within 10 seconds. The application of the brake caused the bogie to come to rest from 25 m/s within 22.9 seconds as shown in Fig. 9.6 (c). Due to 25% error in the distribution of the brake shoe normal forces, yaw torque was generated on the trailing wheelset as shown in Fig. 9.6 (b). The maximum yaw torque generated was 43.92 kNm which occurred when the brake torque attained its maximum value. As revealed in Fig. 9.6. (d), the yaw torque on the trailing wheelset caused unstable lateral oscillation of the wheelset followed by the lateral oscillation of the leading wheelset. The magnitude of the lateral oscillation of the trailing wheelset was larger (maximum 2.2 mm) compared to the lateral oscillation of the leading wheelset (maximum 1.7 mm).

Fig. 9.7 exhibits the result of the simulation of the case of 75% error on the trailing wheelset at 1s of brake application time (the most severe case of Item #2). Fig. 9.7 (a) shows that the brake torque linearly increased from zero to 20 kNm within 1 second. The 75% error in the distribution of the brake shoe normal forces generated yaw torque (maximum 131.8 kNm) on the trailing wheelset as shown in Fig. 9.7 (b). The yaw torque initiated severely unstable lateral oscillation of the trailing wheelset followed by the leading wheelset.

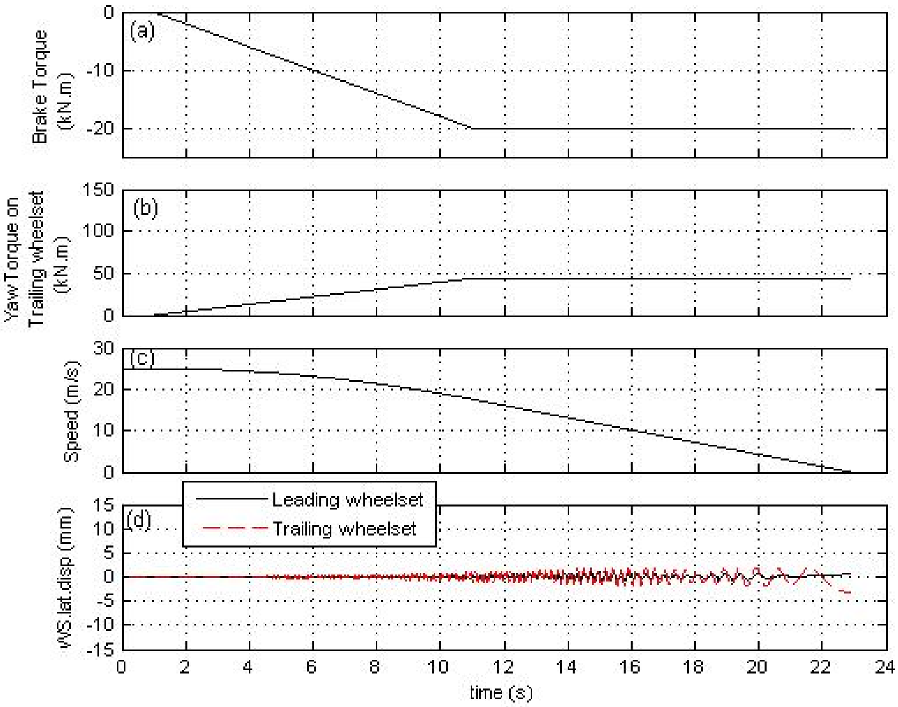


Figure 9.6. 25% error on trailing wheelset, 10s brake application time (the least severe case)

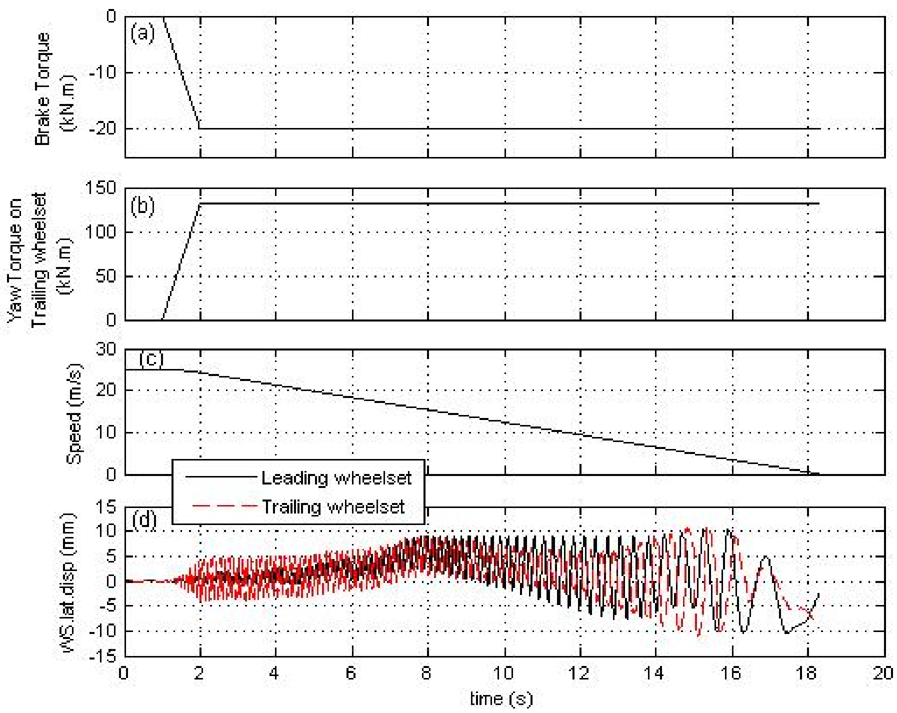


Figure 9.7. 75% error on trailing wheelset, 1s brake application time (the most severe case)

However, as seen in Fig. 9.7, unlike the severe case Item #1, the contact constraint equations in the RBD program during the severe case of Item #2 always converged as illustrated by the stoppage of the bogie (the bogie stopped from 25 m/s within 18.3 seconds as shown in Fig. 9.7 (c)). The magnitude of the lateral oscillation of the trailing wheelset was initially larger compared to the lateral oscillation of the leading wheelset. After 8s, the magnitude of the lateral oscillation of the leading wheelset became larger than that of the trailing wheelset. At the end of the simulation the lateral oscillation of both wheelsets had more or less the same magnitudes (approximately 11 mm), but they never reached the point where the tread contact was lost (11.5 mm).

The results of all cases of the simulation of the asymmetric braking applied to the trailing wheelset are compiled in Table 9.3.

Table 9.3. Results of asymmetric braking on trailing wheelset at initial speed 15 m/s

	Input		Output		
Error (%)	Maximum Yaw Torque on Trailing Wheelset (kN.m)	Application Time (s)	Time to Stop (s)	Maximum Lateral Displacement (mm)	
				Leading Wheelset	Trailing Wheelset
25%	43.92	10s	22.9s	1.6 mm	2.2 mm
		5s	20.4s	1.7 mm	2.4 mm
		1s	18.3s	1.7 mm	2.7 mm
50%	87.84	10s	22.9s	7.4 mm	5.6 mm
		5s	20.4s	7.5 mm	5.9 mm
		1s	18.3s	7.8 mm	6.2 mm
75%	131.8	10s	22.9s	10.9 mm	10.8 mm
		5s	20.4s	11.1 mm	11.2 mm
		1s	18.3s	11.2 mm	11.1 mm

Similar to the asymmetric braking on the leading wheelset, the 25% error caused only small lateral oscillation and the brake application time was revealed not to have much effect to the magnitude of the lateral oscillation of the wheelset. The magnitude of the lateral displacement of the wheelset was mainly affected by the error that generated yaw torque of the wheelset. Unlike the asymmetric braking on the leading wheelset, the program was found to converge for all cases of asymmetric brake application on the trailing wheelset. Thus, it can be considered that no "*derailment*" occurred for all cases of asymmetric braking on the trailing wheelset considered in this investigation. However, at the error of 75% the lateral displacement was around 11 mm, resulting in flange contact. Any further increase in yaw torque (or more than 75% error) could potentially lead to derailment.

At 25% error, the magnitude of the lateral oscillation of the trailing wheelset where the asymmetric braking was applied remained consistently larger than the magnitude of lateral oscillation of the leading wheelset. However, at larger errors (50% and 75 %), the lateral oscillation of the leading wheelset, at certain periods of the simulation, became larger than the lateral oscillation of the braked trailing wheelset.

9.5. SUMMARY AND CONCLUSION

The effect of asymmetric braking to the dynamics of bogies has been examined using the validated RBD program. The results can be summarised as follows:

- In general, the asymmetric braking due to error in the distribution of brake shoe normal forces adversely affects the lateral dynamics of the wheelset as evidenced by unstable lateral oscillations.
- The case corresponding to 25% error in the distribution of brake shoe normal force on the leading wheelset and/ or trailing wheelset caused only small lateral oscillation of the wheelsets.

- For the cases of asymmetric braking applied to the leading wheelset, the magnitude of lateral oscillation of the leading wheelset remained always larger than the trailing wheelset.

- For the cases of asymmetric braking applied to the trailing wheelset, at small level of error the lateral oscillation of the trailing wheelset was larger than the lateral oscillation of the leading wheelset. However at larger errors (50% and 75 %), the magnitude of lateral oscillation of the leading wheelset, at certain simulation times, could became larger than the magnitude of lateral oscillation of the trailing wheelset.

- The 75% error applied to the leading wheelset has caused the contact constraint equation in the RBD program to fail to converge, a situation that is described as "*derailment*". However derailment did not happen for a similar case of brake shoe forces applied to the trailing wheelset. It is concluded that the error in the brake shoe forces on the leading wheelset is more dangerous than a similar error in the trailing wheelset.