Traffic Micro-Simulation Assisted Tunnel Ventilation System Design

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1 Introduction

Road tunnels have recently been built in Sydney. One of key issues addressed during the construction of the tunnels was air quality. The design of the tunnel ventilation system played an important role in meeting the air quality requirements. Two key elements are to be considered in the system design: the emission rates of vehicles and the traffic occupancy levels in tunnel. One traditional method to derive the traffic occupancy levels is the interpolation of the PIARC guide in Swiss Design Code. A key challenge to the application of the guide is a lack of knowledge of variations of vehicle speed within a tunnel. An assumption of uniform tunnel vehicle speed and traffic density has to be made.

Computerized micro-simulation methods have been more and more used in the traffic world. Typical applications of the methods include assistance of road infrastructure designs and traffic scenario assessment. This paper looks into the use of the traffic micro-simulation method to assist the tunnel ventilation system capacity design, challenging the traditional traffic assumption of uniform speed and traffic density within a tunnel where grades, on and off-ramps are often introduced. With the micro-simulation method, the vehicle behaviour in tunnel in terms of natural variability in the traffic flow and shockwave movements under super congestion can be fully analysed. Slow speeds produced in the micro-simulation can match the worst scenarios around 2 km/h, which are not effectively achieved in traditional ways.

This paper starts to discuss the method of PIARC, and then introduces the traffic micro-simulation software Paramics. A Paramics traffic micro-simulation model was developed for Cross City Tunnel to assist the tunnel ventilation system design. The comparison of the traffic results between PIARC and Paramics is made. The advantages of using a traffic micro-simulation method to identify traffic characteristics and create scenarios are demonstrated.

2 PIARC

The Permanent International Association of Roads Congress (PIARC, 1995) in Swiss Design Code is an important guide for tunnel ventilation system designs in the world. The design of a ventilation system needs to accommodate for the worst traffic scenarios or super congestion conditions where the maximum ventilation capacity would be required. PIARC provides traffic information corresponding to the worst traffic scenarios in terms of slow speeds and high vehicle density. A typical example of the traffic information provided in PIARC is presented in Table 1

Table 1 Traffic Flow and Density in PIARC

Speed (km/h)	Flow (pcu/hr/lane)	Density (pcu/km/lane)
0	0	165
5	600	120
10	1100	110
15	1500	100
20	1600	80

Source: PIARC95, Swiss Design Code and pcu = passenger car unit

For the speeds under 5 km/h, users often need to interpolate the traffic information provided in PIARC. One example of the interpolation is presented in Table 2.

Table 2 Interpolation of Traffic Flow and Density

Speed	0 km/h	1 km/h	2 km/h	3 km/h	4 km/h	5 km/h
Flow (pcu/hr/lane)	-	156	294	414	516	600
Density (pcu/km/lane)	165	156	147	138	129	120

The key challenge in applying the PIARC traffic information is a lack of the dynamic information of traffic flows on different tunnel sections. The assumptions of stable traffic conditions in terms of uniform flow and traffic density need to be made.

Vehicle behaviour in tunnels is not stable and uniform. When an incident occurs causing super tunnel congestion, vehicles can only move through the lanes left open, consequently becoming slower and the speeds vary on different tunnel sections. The slow speeds and an incident are among the scenarios the tunnel ventilation system should be able to cope with. In addition, the behaviour of heavy vehicles is different from that of light vehicles on tunnel ramps. Heavy vehicles normally have the lane climbing effects, delaying the speed of other traffic on high gradient uphill sections.

In the tunnel ventilation system design, there is a need to identify the varying vehicle behaviour and reassess the assumptions in applications of the PIARC traffic guide to provide realistic traffic information needed for the ventilation system capacity design. The traffic micro-simulation method is able to identify the details of tunnel vehicle behaviour and create scenarios targeted by the ventilation system capacity design.

3 Paramics

A traffic micro-simulation method widely used in NSW is the Paramics product (Quadstone, 2005). The Paramics software models the behaviour of individual vehicles and their interactions with other traffic under network constraints. It governs the vehicle behaviour by rules defined in the car following, lane changing and gap acceptance models while the network constraints can cover a variety of specifics such road geometry, lane restrictions, turn bans, angle of turn and length of turning lane. For vehicle moving through tunnels, Paramics can model the effects of the high gradients of the tunnel entrances and exits on vehicle movements to reflect the variations of traffic flow, speed and density.

The road network in Paramics models is often developed by matching node and link positions to a background map or design such as a 3D road design. Accurate matching of the model nodes and links to the template provides all the necessary information for Paramics to calculate geometry such as the gradient of a link. The link information details the type of road (urban or highway), the speed limit and the number of lanes and width of each lane.

Paramics can be used to develop speed scenarios under 5 km/h, to identify vehicle behaviour and generate the traffic information needed for the ventilation system capacity design under the worst traffic conditions.

4 Cross City Tunnel models

The Cross City Tunnel is the latest tunnel open for traffic in Sydney metropolitan region. It has two sub-tunnels: westbound tunnel and eastbound tunnel. The design for each of the tunnels includes several sections which are presented in Figures 1 and 2.

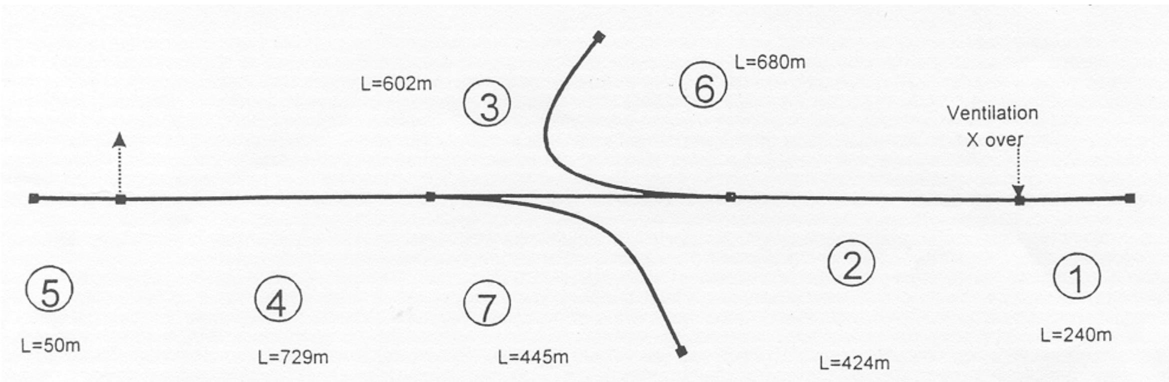

Figure 1 The Sketch Westbound Tunnel

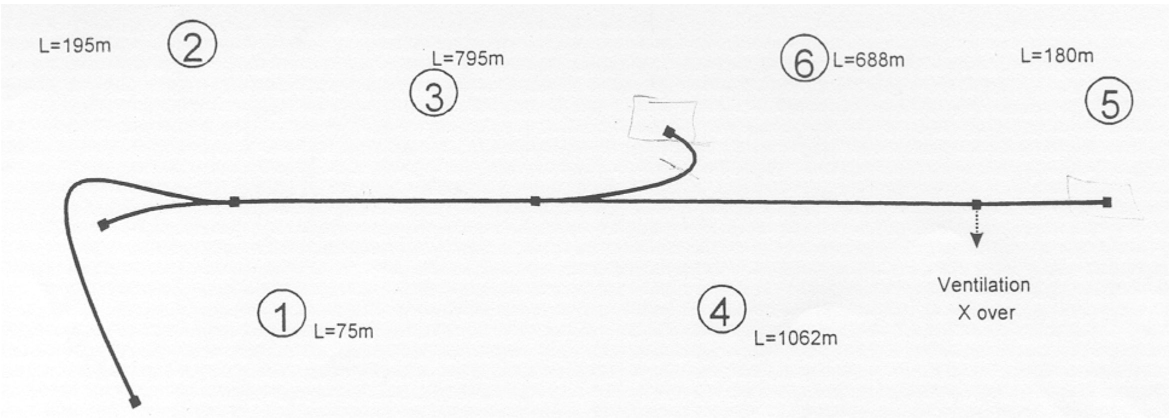

Figure 2 The Sketch Eastbound Tunnel

To assist the design of the Cross City Tunnel ventilation system, two 3D Paramics models were developed based on the two 3D designs: one matching the westbound tunnel and the other matching the eastbound tunnel. The Paramics models reflect the length, the number of lanes, the speed limit and the gradient of each section in the designs.

The developed Paramics models are presented in Figures 3 and 4. Before the tunnel entrances, “pouches” were added into the entrance links in order to let heavy vehicles to be released in the predefined order. In the slow speed conditions and super-congestion, heavy vehicles may not be properly released into the network due to its physical size.

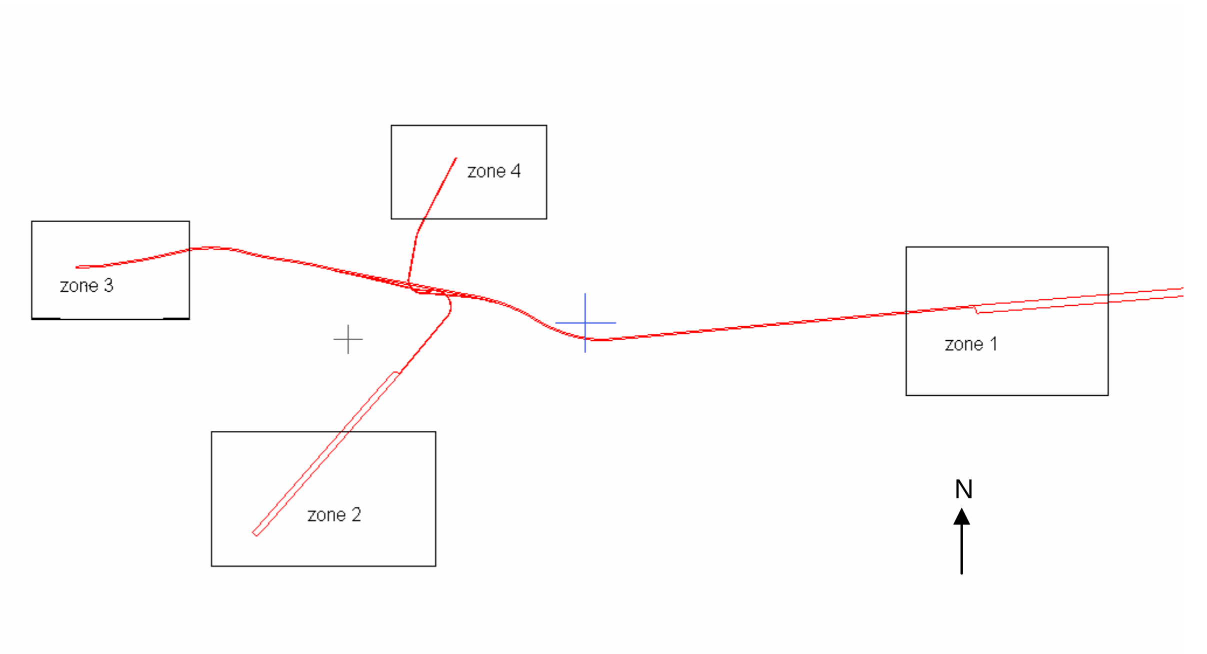

Figure 3 Westbound Paramics Model

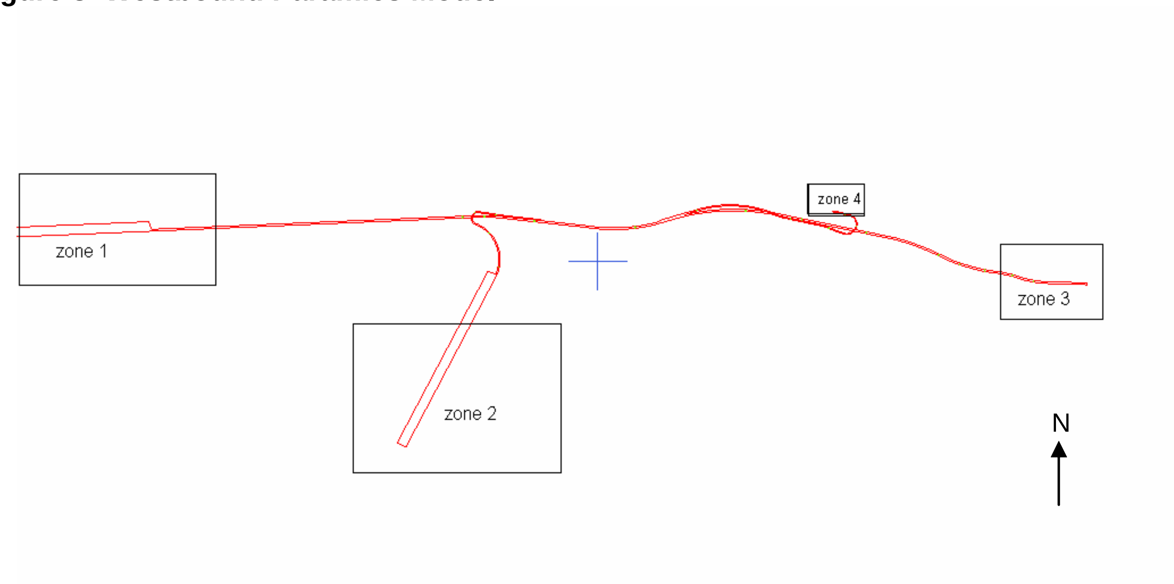

Figure 4 Eastbound Paramics Model

As the traffic patterns between the morning and afternoon were expected to be different, to represent the peak flow directions, the westbound model was focused on the morning peak period and the eastbound model was focused on the afternoon peak period. The choice of peak directions related to the demand estimation for the tunnels.

In each Paramics model, four demand zones were created corresponding to the tunnel entrance and exit portals. They are presented in Figures 3 and 4.

Based on the hourly link flows for cars and heavy vehicles forecast from the tunnel patronage forecasting model (Consultants, 2001), two hourly demand matrices in 2005 were developed for each of the models: one representing the car demand and the other representing the heavy vehicle demand. The characteristics of heavy vehicles were particularly specified in the vehicle emission estimation and their demands were separately estimated. The demand matrices estimated are presented in Tables 3 and 4.

Table 3 2005 Westbound Demand Matrices

Car OD	To Zone 3	To Zone 4	Total
From Zone 1	1,981	2,125	4,105
From Zone 2	528	0	528
Heavy Vehicle OD	To Zone 3	To Zone 4	Total
From Zone 1	103	32	136
From Zone 2	80	0	80

Table 4 2005 Eastbound Demand Matrices

Car OD	To Zone 3	To Zone 4	Total
From Zone 1	1,676	351	2,028
From Zone 2	621	139	760
Heavy Vehicle OD	To Zone 3	To Zone 4	Total
From Zone 1	100	49	148
From Zone 2	6	3	9

With the hourly demand matrices, the Paramics base models were calibrated against the link flows forecast in the tunnel patronage model under the designated tunnel speed limits. The results show that the Paramics base models can reasonably represent the base conditions. The values of the Paramics parameters adopted in the calibrated base models in terms of headways, gap acceptance and lane changing were used in the modelling scenarios.

5 Modelling Scenarios

The scenarios targeted in the ventilation system capacity design are the vehicles moving at low speeds with serious tunnel congestion. The scenarios were created in the Paramics models. Speed constraints were imposed at each of the two exit portals in each of the models to create slow speed scenarios. Complete stationary vehicles with an engine running are actually not the worst scenario for tunnel ventilation.

The six speed scenarios at the exit portals modelled in Paramics were:

- Scenario 1 - 1 km/h limit
- Scenario 2 - 2 km/h limit
- Scenario 3 - 3 km/h limit
- Scenario 4 - 4 km/h limit
- Scenario 5 - 5 km/h limit
- Scenario 6 - 6 km/h limit

The first 30 minutes of the model operation was for "warming up" the model. Then the speed constraints would cause congestion over the entire tunnel. The start of assessing the traffic situation was the time when the tunnel was full of slow vehicles.

An additional scenario modelled by the Paramics model was a vehicle breakdown in the westbound tunnel at the western ventilation exit portal. The incident was created after 20 minutes of simulation when the tunnel was operating without any speed constraints at the exit portals. The purpose of the scenario was to examine the capacity of the ventilation system in an incident situation. The start of assessing the traffic situation was the 30 ~ 40 minutes after the incident.

6 Modelling results

Tables 5 and 6 present the vehicle speeds on each tunnel section under each speed scenario. The results show that the vehicle speed in the tunnels was not uniform across all the tunnel sections. The scenario closest to the vehicle speed of 2 km/h on most of the tunnel sections was scenario 3 with a speed limit of 3 km /h at the exit portals.

Table 5 Westbound Tunnel Section Average Speed (km/h)

Section	Scenario No. of Lanes	1 (km/h)	2 (km/h)	3 (km/h)	4 (km/h)	5 (km/h)	6 (km/h)
1 WB	2	1.2	1.5	3	6.8	8.5	10.4
2 WB	2	1.2	1.4	2.8	7.1	9.2	11.7
3 WB	2	0.8	1.1	1.8	3.6	4.5	5.7
4 WB	2	0.6	0.9	1.8	4.6	5.7	7.1
5 WB	2	0.6	0.9	1.7	4.1	5.1	6.1
6 WB	1	0.6	0.9	1.8	5.0	5.5	6.7
7 WB	1	0.3	0.3	0.3	1.1	1.6	3.1

Table 6 Eastbound Tunnel Section Average Speed (km/h)

Section	Scenario No. of Lanes	1 (km/h)	2 (km/h)	3 (km/h)	4 (km/h)	5 (km/h)	6 (km/h)
1 EB	2	0.7	2.0	2.9	6.1	7.2	8.5
2 EB	1	0.2	0.2	1.0	4.3	5.7	7.1
3 EB	2	0.7	1.8	2.8	6.8	8.3	9.9
4 EB	2	0.6	1.1	2.2	5.0	6.2	7.8
5 EB	2	0.6	1.1	2.0	4.3	5.2	6.4
6 EB	1	0.5	2.1	2.4	5.1	6.5	10.0

Tables 7 and 8 presents the tunnel occupation levels on each tunnel section under each speed scenario. The comparison of the average tunnel speeds with the PIARC values shows the difference of the tunnel occupation levels. PIARC would under-estimate the vehicle occupation levels on the tunnel entrance sections and over-estimate the levels on the tunnel middle and exit sections.

Table 7 Westbound Tunnel Occupancy (pcu/h)

Scenario / Average Tunnel Speed / Occupancy	1	2	3	"Study"	PIARC	4	5	6
	0.8 km/h	1.1 km/h	2 km/h	2 km/h	2km/h	4.6 km/h	5.6 km/h	7.2 km/h
	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)
1 WB	290	352	676	676	588	1602	1906	2330
2 WB	284	361	679	679	588	1610	1919	2295
3 WB	179	254	465	465	588	1084	1243	1420
4 WB	180	257	479	479	588	1212	1458	1741
5 WB	180	252	478	478	588	1208	1450	1728
6 WB	93	126	241	241	294	561	707	804
7 WB	8	10	11	11	294	159	235	413

Table 8 Eastbound Tunnel Occupancy (pcu/h)

Scenario	1	2	"Study"	PIARC	3	4	5	6
Average Tunnel Speed	0.7 km/h	1.5 km/h	2 km/h	2 km/h	2.4 km/h	5.6 km/h	6.9 km/h	8.6 km/h
Occupancy	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)	(pcu/h)
1 EB	236	520	656	588	764	1448	1708	1884
2 EB	8	26	82	294	127	511	655	783
3 EB	239	522	720	588	878	1931	2295	2581
4 EB	186	294	425	588	529	1197	1474	1724
5 EB	186	294	425	588	530	1209	1476	1717
6 EB	55	271	303	294	329	645	767	826

The Paramics models produced the traffic outputs in terms of vehicle speed and vehicle occupancy level for estimation of the worst tunnel vehicle gas emissions, which the ventilation systems should have the capacity to meet the tunnel air quality requirements.

The traffic flow under a vehicle breakdown in the westbound tunnel is presented in Figure 5. It shows the dynamic instability of flow, speed and density. In the Figure, it is noted that the maximum tunnel congestion occurred some 35 ~ 45 minutes after the vehicle incident, corresponding with traffic flow reaching a minimum in the Figure.

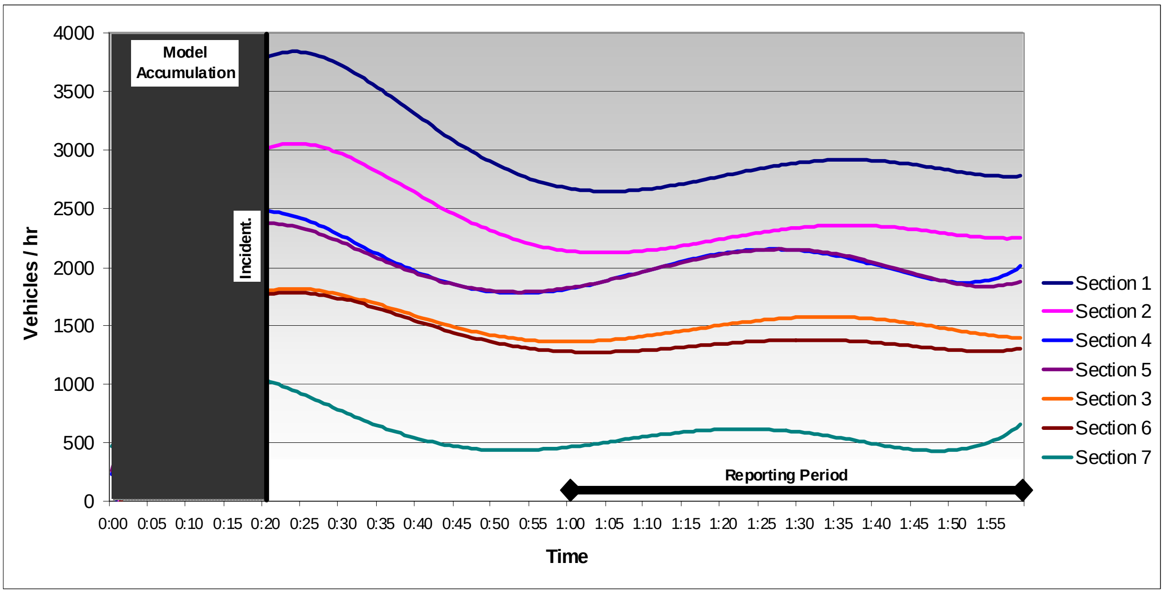

Figure 5 Traffic Flow in Westbound Tunnel Following a Breakdown Incident

Traffic data was extracted for the one-hour period after the first hour of simulation, providing a maximum congested flow. Table 9 presents the traffic information under a breakdown scenario.

Table 9 Westbound Traffic under a Vehicle Breakdown

Section	No. of Lanes	Length (m)	Section Speed (km/h)	Tunnel Occupancy (pcu/h)
1 WB	2	240	14.7	2,916
2 WB	2	424	16.6	2,642
3 WB	2	602	6.4	1,700
4 WB	2	729	11.0	2,226
5 WB	2	50	66.7	2,228
6 WB	1	680	59.6	1,311
7 WB	1	445	5.3	695

7 Conclusions

The vehicle behaviour in a tunnel is dynamic, with varying speeds, flows and densities. The traffic micro-simulation method studied in this paper is able to help understand the dynamic vehicle behaviour in a tunnel and provide better traffic information required for the tunnel ventilation system capacity design.

The traffic micro-simulation method in terms of Paramics has demonstrated its advantages in developing traffic scenarios and capturing specific vehicle behaviour in terms of slow speeds and incidents, which would not be effectively obtained by traditional methods.

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