CHAPTER 5   RESULTS OF FNN

This chapter develops a fuzzy neural network (FNN) approach to detect freeway incidents. The traffic simulator--Paramics is calibrated against the observed traffic flow data before, during, and after a deliberate incident specially arranged on the freeway mainline. The calibrated Paramics is then employed to generate sufficient samples under various incident scenarios in order to train and validate the FNN approach. Off-line validation tests have demonstrated that our proposed FNN approach is capable of detecting the freeway incidents with rather high accuracy. Sensitivity analysis further shows that altering the FNN structure by reducing the number of detectors or number of input traffic parameters only slightly deteriorates the detection performance, implying a high fault tolerance of the proposed FNN incident detection approach. Section 5.1 demonstrates the off-line test results of FNN. The statistical tests of incident detection performance are shown as section 5.2. Furthermore, the sensitivity of FNN network structure is elaborated in section 5.3 and the brief findings is summarized in section 5.4.

5.1 Off-line Test Results

The off-line tests of FNN are evaluated by simulating various incident scenarios, which is based on the 30-seconds traffic flow data collected in 45 minutes covering a typical afternoon peak hours at the experimented site. The six scenarios of the two-lane freeway mainline section and fifteen scenarios of the three-lane freeway mainline section contain a combination of incidents taking place in different lanes (inner/center/outer), in different incident severity (one or two lane blocked, and incident duration is 15 minutes), and at different locations (250, 500, or 750 meters from the upstream detectors) by placing upstream and downstream detectors one kilometer apart. Each scenario has 200 sets of simulation data, 100 of which are used for training, and the other 100 for off-line validation. The interval of detection time is set as 30 seconds and 60 seconds.

According to Table 5-1, the FNN approach has performed well with average DR 89.50%, FAR 0.0681%, and TTD 78 seconds. The best DR is 97.23%, the best FAR is 0.0337%, and the shortest TTD is 49 seconds while interval of detection time equals 30 seconds. Moreover, the average DR is 88.57%, FAR is 0.0572%, and TTD is 153 seconds. The best DR is 96.98%, the best FAR is 0.0192%, and the shortest TTD is 99 seconds while interval of detection time equals 60 seconds. The results reveal that the shorter detection time intervals (30-seconds) have better reaction to incident detection than the longer ones (60-seconds). Figure 5-1, 5-2 and 5-3 also demonstrate that the detection performance of the FNN approach in two different detection time intervals under various scenario.

From Table 5-1, we find that the detection performance for FNN approaches consistently depend on the location of the incident. In general, if the incident takes place near the detector, either upstream (the 250-meter scenarios) or downstream (the 750-meter scenarios), the DR is higher and the TTD is shorter than the one occurring farther away from the detector (the 500-meter scenarios). The overall detection performance for an inner-lane incident is slightly better than that for an outer-lane incident because more traffic volumes are observed in the inner lane than in the outer lane. Notice that the detection performance may be influenced by the detection time interval and number of lanes of the mainline section. The statistical tests are further examined as follows.

Table 5-1 The Off-line test results of the FNN incident detection

Incident location			30-second time interval			60-second time interval		
	Lane position	Distance from upstream detector (meter)	DR (%)	FAR (%)	TTD (sec)	DR (%)	FAR (%)	TTD (sec)
Two-lane mainline section	Inner	250	93.19 (0.03999)	0.0958 (0.000077)	74 (3.6556)	91.87 (0.03561)	0.0521 (0.000082)	148 (12.6089)
		500	87.90 (0.02867)	0.0628 (0.000076)	89 (4.5762)	86.61 (0.02459)	0.0760 (0.000062)	162 (13.4675)
		750	89.31 (0.03495)	0.0589 (0.000073)	71 (5.8212)	90.53 (0.03725)	0.0418 (0.000072)	143 (12.7128)
	Outer	250	88.25 (0.03721)	0.0337 (0.000083)	83 (6.4183)	88.15 (0.02961)	0.0408 (0.000086)	136 (10.2581)
		500	82.62 (0.02968)	0.0437 (0.000073)	95 (8.1292)	84.07 (0.03569)	0.0591 (0.000093)	181 (14.1007)
		750	91.35 (0.03725)	0.0380 (0.000068)	76 (4.2318)	90.91 (0.02115)	0.0627 (0.000071)	147 (12.3317)
	Average		88.77	0.0555	81	88.69	0.0554	153
Three-lane mainline section	Inner	250	87.38 (0.03611)	0.0482 (0.000069)	82 (5.2719)	87.76 (0.04107)	0.0381 (0.000081)	155 (11.1058)
		500	81.06 (0.04210)	0.0697 (0.000076)	97 (5.8705)	80.70 (0.03179)	0.0192 (0.000075)	190 (13.9213)
		750	89.93 (0.03518)	0.0582 (0.000067)	84 (5.6475)	87.65 (0.02195)	0.0682 (0.000086)	157 (12.0566)
	Inner and center	250	97.23 (0.02217)	0.0963 (0.000063)	56 (2.8733)	96.98 (0.04060)	0.0965 (0.000090)	99 (8.1282)
		500	92.59 (0.02592)	0.0901 (0.000081)	62 (3.2388)	92.65 (0.02586)	0.0712 (0.000079)	120 (10.5731)
		750	96.84 (0.02387)	0.0822 (0.000078)	49 (2.2971)	94.38 (0.03961)	0.0814 (0.000081)	113 (9.0058)
	Center	250	82.59 (0.03720)	0.0748 (0.000069)	79 (4.3561)	83.32 (0.02990)	0.0892 (0.000069)	169 (11.0822)
		500	80.28 (0.03208)	0.0624 (0.000072)	93 (4.4819)	81.23 (0.04068)	0.0753 (0.000064)	202 (15.0024)
		750	86.47 (0.03376)	0.0574 (0.000081)	86 (3.9337)	84.09 (0.03271)	0.0651 (0.000070)	184 (12.0872)
	Outer and center	250	95.56 (0.02102)	0.0803 (0.000082)	53 (2.2028)	94.78 (0.02915)	0.0721 (0.000091)	112 (9.7405)
		500	93.02 (0.02561)	0.0957 (0.000072)	67 (3.3128)	91.06 (0.03007)	0.0288 (0.000076)	128 (10.9892)
		750	95.00 (0.02378)	0.0405 (0.000071)	52 (2.3967)	95.19 (0.03389)	0.0508 (0.000071)	107 (8.9078)
	Outer	250	91.23 (0.02762)	0.0816 (0.000076)	93 (4.8209)	86.56 (0.03842)	0.0259 (0.000088)	178 (13.1270)
		500	83.75 (0.03889)	0.0885 (0.000086)	102 (6.950)	81.90 (0.04217)	0.0395 (0.000075)	196 (14.1328)
		750	93.86 (0.03128)	0.0716 (0.000072)	91 (6.1938)	89.64 (0.02892)	0.0478 (0.000083)	185 (13.7821)
	Average		89.79	0.0732	76	88.53	0.0579	153

Note: 1. Distance of incident location is measured from the upstream detecting point.

2. Each scenario is simulated for 100 times. The values in this table are the average of 100 simulation runs with standard deviation in parenthesis.

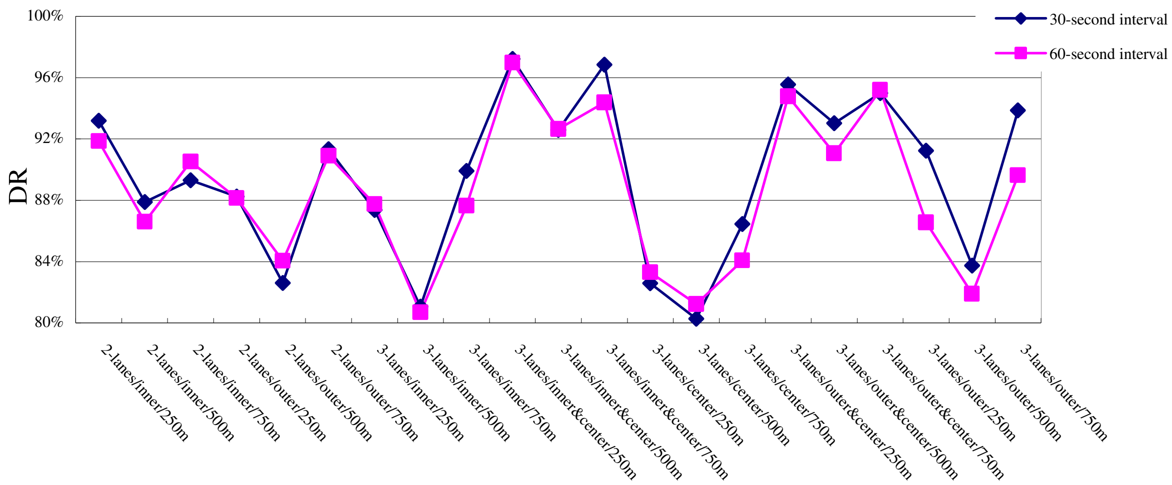


Figure 5-1 The detection rate of different incident locations

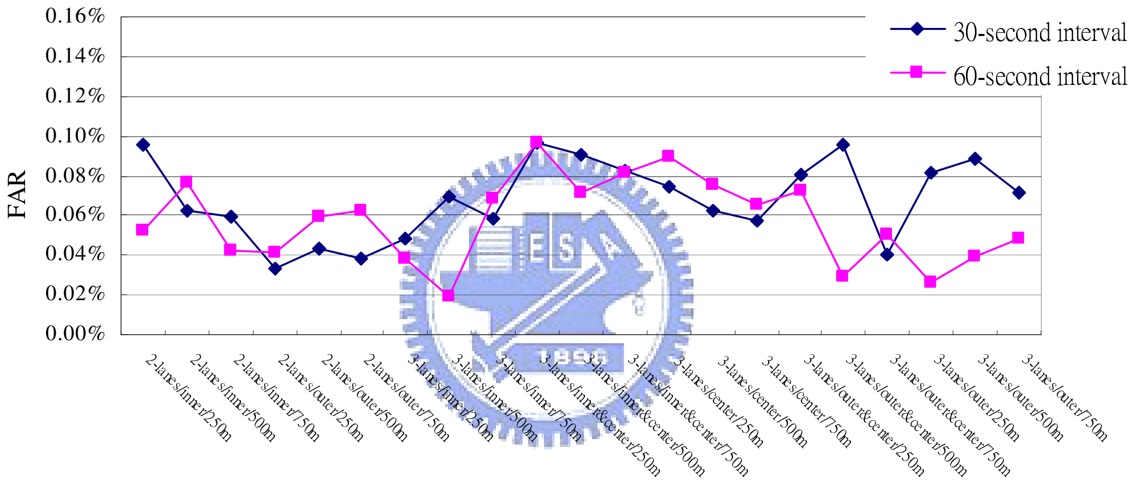


Figure 5-2 The false alarm rate of different incident locations

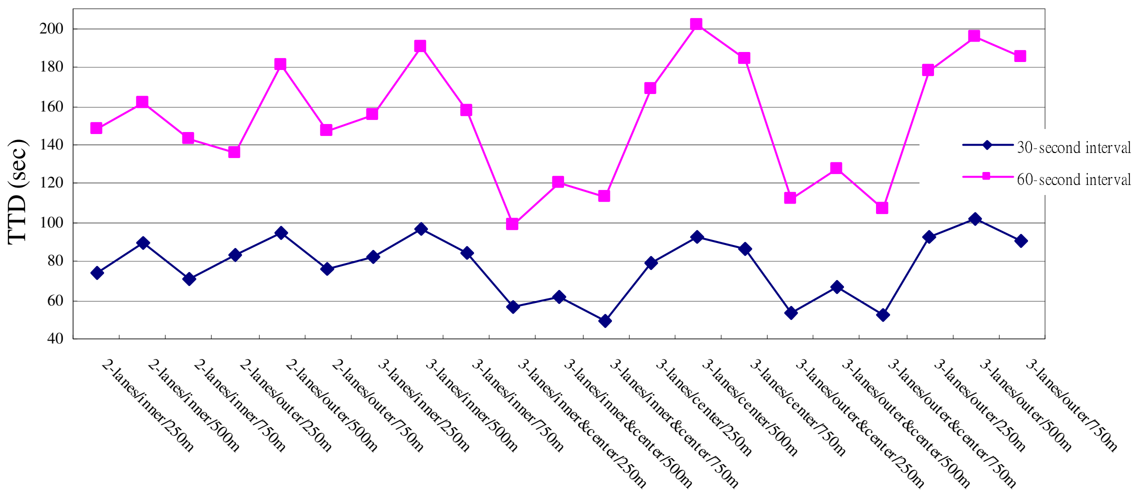


Figure 5-3 The time to detection of different incident locations

5.2 Statistical Tests

For further understanding if the performance of FNN incident detection is affected by interval of detecting time, number of lanes or location of incident, this section demonstrates the statistical tests for the detection rate, false alarm rate and time to detection with significance level α=0.05. The result is shown as Table 5-2, and the explanation is as following:

- **Test for detecting time intervals**

There is no significant difference (P-value=0.5294) for interval of detection time is 30 seconds and 60 seconds, neither is the false alarm rate (P-value=0.0776), but there is significant difference (P-value=0.0019) for time to detection. The time to detection of 30-second detection time interval has better performance.

- **Test for number of lanes of the mainline section**

Detection rate:

When an incident blocks single lane, there is significant difference (P-value=0.0056) for average detection rate of two-lane and three-lane mainline section. The detection rate of two-lane section is slightly higher than three-lane section.

Time to detection:

When blocking one lane, there is significant difference (P-value=0.0037) for average time to detection of two-lane and three-lane mainline section. It also shows that two-lane mainline section have shorter detection time.

- **Test for two-lanes mainline section**

Detection rate:

When an incident is located on the outer lane and inner lane, there is significant difference (P-value=0.0289) for the average detection rate. The incident occurs in inner lane is easier detected than occurs in outer lane. When the incident location is 250, 500, 750 meters away from upstream detector, there is significant difference (P-value=0.0187) for the average detection rate. The nearer of detectors have the higher detection rates.

Time to detection:

When an incident is located on the outer lane and inner lane, there is no significant difference (P-value=0.1096) for the average time to detection. Notice that it is the different results from the performance of detection rate. When incident location is 250, 500, 750 meters away from upstream detector, there is significant difference (P-value=0.0058) for the average time to detection. The incident location is near detectors may be detected earlier.

- **Test for three-lane mainline section**

Detection rate:

There is significant difference (P-value=0.0034) for average detection rate of incidents blocked single lane and two lanes. While blocking single lane, there is no significant difference (P-value=0.0719) for the average detection rate of blocking inner lane, center lane, and outer lane. When blocking two lanes, there is no significant difference (P-value=0.6999) either for the average detection rate for blocking inner lane, center lane, and outer lane. When incident location is 250, 500, 750 meters away from upstream detector, there is significant difference (P-value=0.0187) for the average detection rate.

Time to detection:

There is significant difference (P-value=0.0021) for average time to detection of incidents blocked one lane and two lanes. When blocking one lane, there is also significant difference (P-value=0.0399) for the average time to detection of blocking inner lane, center lane, and outer lane. When blocking two lanes, there is no significant difference (P-value =0.7069) for the average time to detection for blocking inner lane, center lane, and outer lane. When incident location is 250, 500, 750 meters away from upstream detector, there is significant difference (P-value=0.0030) for the average time to detection.

Table 5-2 Summary of the statistical tests

Tests	Null hypothesis	Statistics	P-value	Result[1]
Detection time interval	**DR** H_0 : μ(average DR under 30-second detection interval)=μ(average DR under 60-second detection interval)	t=0.6403	0.5294	NSD
	FAR H_0 : μ(average FAR under 30-second detection interval)=μ(average FAR under 60-second detection interval)	t=1.5062	0.0776	NSD
	TTD H_0 : μ(average TTD under 30-second detection interval)=μ(average TTD under 60-second detection interval)	t=3.7318	0.0019	SD
Lanes of the mainline section (blocked single lane)	**Number of lanes** H_0 : μ(average DR of two-lanes mainline section)=μ(average DR of three-lanes mainline section)	F=11.9091	0.0056	SD
Detection rate of two-lane mainline section	**Lane-specific** H_0 : μ(average DR while incident occurs on inner lane)=μ(average DR while incident occurs on outer lane)	t=2.4063	0.0289	SD
	Incident location H_0 : μ(average DR while incident occurs 250m from upstream detector)=μ(average DR while incident occurs 500m from upstream detector)= μ(average DR while incident occurs 750m from upstream detector)	F=8.2775	0.0187	SD

Note: 1. NSD represents no significant difference and SD represents significant difference ($\alpha=0.05$).

Table 5-2 Summary of the statistical tests (cont.)

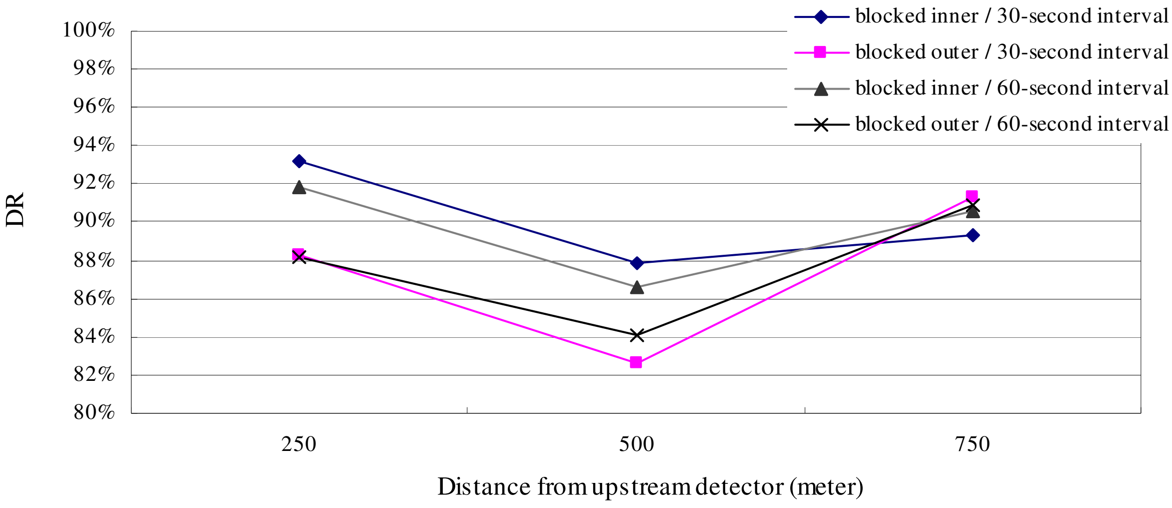
Tests	Null hypothesis	Statistics	P-value	Result[1]
Detection rate of three-lane mainline section	**Number of lane blocked** H_0 : μ(average DR while incident blocked single lane)=μ(average DR while incident blocked two lanes)	F=10.4172	0.0034	SD
	Lane-specific I H_0 : μ(average DR while incident occurs on inner lane)= μ(average DR while incident occurs on center lane)=μ(average DR while incident occurs on outer lane)	F=5.2896	0.0719	NSD
	Lane-specific II H_0 : μ(average DR while incident occurs on inner and center lane)=μ(average DR while incident occurs on outer and center lane)	t=0.3912	0.6999	NSD
	Incident location H_0 : μ(average DR while incident occurs 250m from upstream detector)=μ(average DR while incident occurs 500m from upstream detector)= μ(average DR while incident occurs 750m from upstream detector)	F=8.5910	0.0164	SD
Lanes of the mainline section (blocked single lane)	**Number of lanes** H_0 : μ(average TTD of two-lanes mainline section)=μ(average TTD of three-lanes mainline section)	F=12.0022	0.0037	SD
Time to detection of two-lane mainline section	**Lane-specific** H_0 : μ(average TTD while incident occurs on inner lane)=μ(average TTD while incident occurs on outer lane)	t=1.4185	0.1096	NSD
	Incident location H_0 : μ(average TTD while incident occurs 250m from upstream detector)=μ(average TTD while incident occurs 500m from upstream detector)= μ(average TTD while incident occurs 750m from upstream detector)	F=9.2587	0.0058	SD

Note: 1. NSD represents no significant difference and SD represents significant difference (α=0.05).

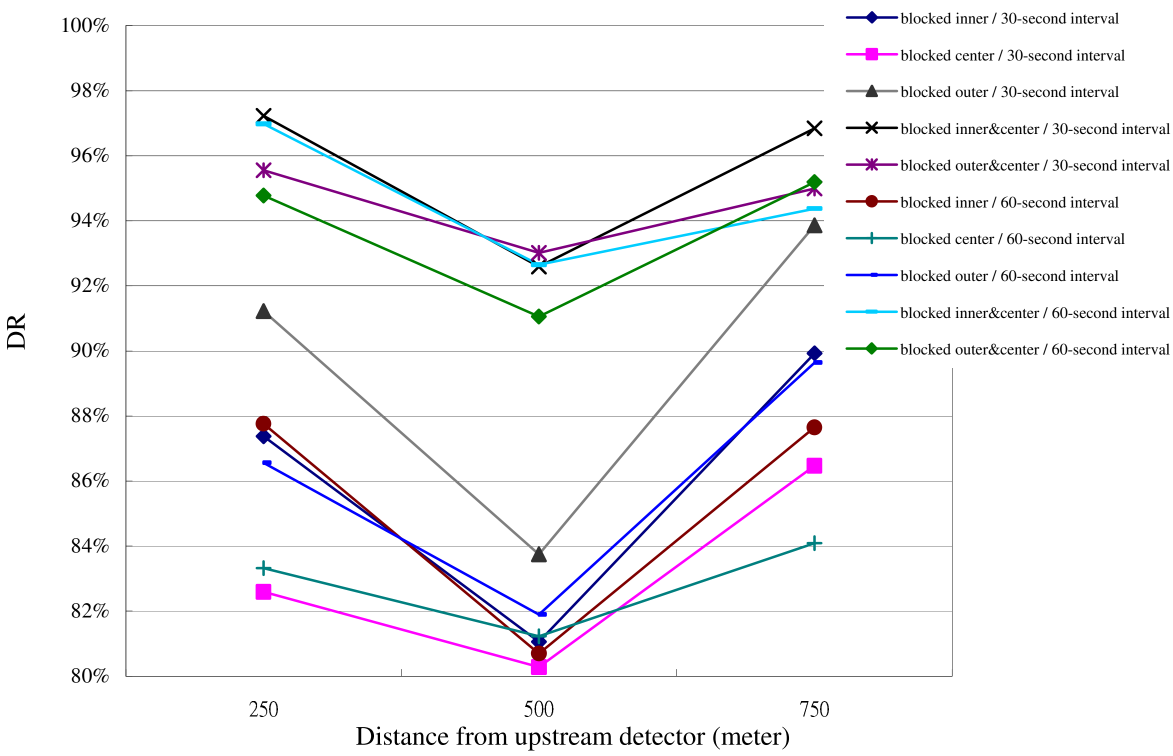
Table 5-2 Summary of the statistical tests (cont.)

Tests	Null hypothesis	Statistics	P-value	Result[1]
Time to detection of three-lane mainline section	**Number of lane blocked** H_0 : μ(average TTD while incident blocked single lane)=μ(average TTD while incident blocked two lanes)	F=13.0284	0.0021	SD
	Lane-specific I H_0 : μ(average TTD while incident occurs on inner lane)= μ(average TTD while incident occurs on center lane)=μ(average TTD while incident occurs on outer lane)	F=4.5028	0.0399	SD
	Lane-specific II H_0 : μ(average TTD while incident occurs on inner and center lane)=μ(average TTD while incident occurs on outer and center lane)	t=0.5170	0.7069	NSD
	Incident location H_0 : μ(average TTD while incident occurs 250m from upstream detector)=μ(average TTD while incident occurs 500m from upstream detector)= μ(average TTD while incident occurs 750m from upstream detector)	F=10.7058	0.0030	SD

Note: 1. NSD represents no significant difference and SD represents significant difference (α=0.05).

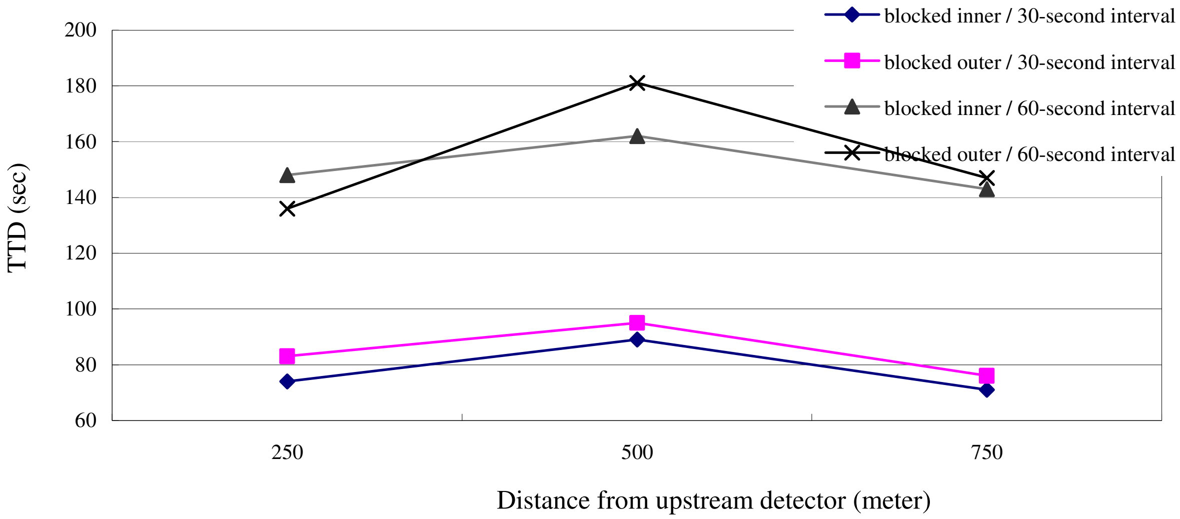


（a） 2-lanes

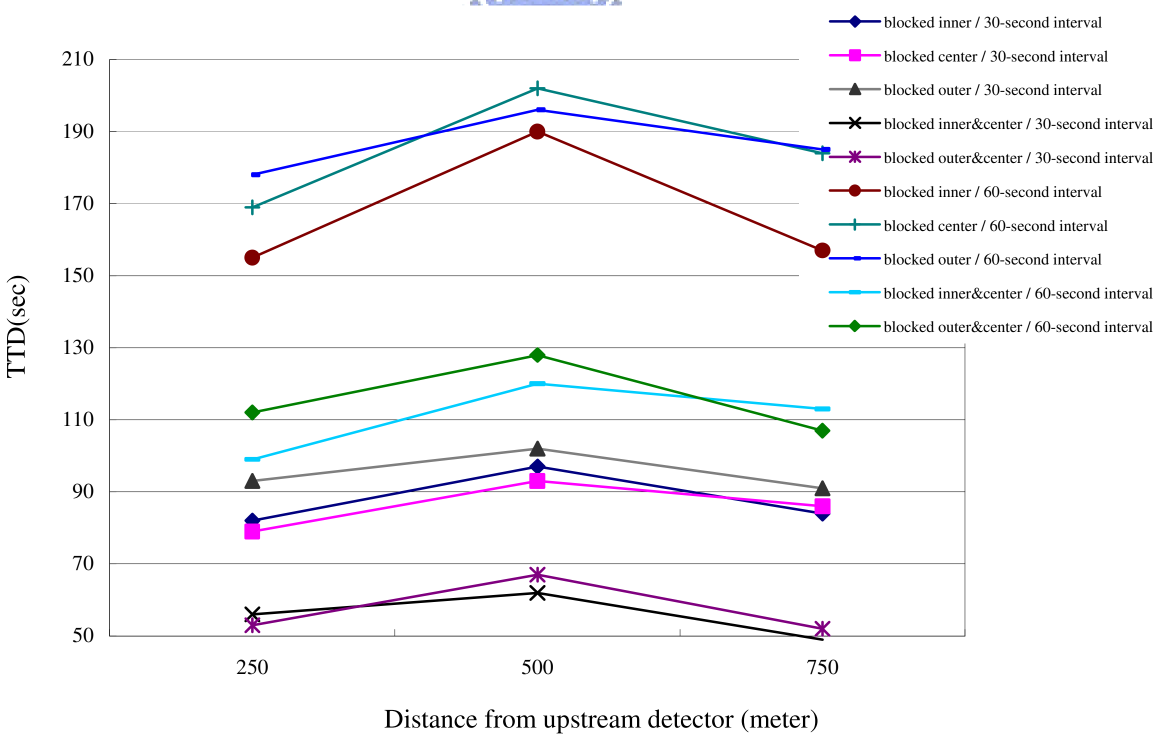


（b） 3-lanes

Figure 5-4 The relation of detection rate and incident location



（a） 2-lanes



（b） 3-lanes

Figure 5-5 The relation of time to detection and incident location

5.3 Sensitivity of Network Structure

FNN incident detection approach in this research includes four layers: the input layer, which is processing original input data, the membership layer which is mapping input data into fuzzy degree through the fuzzy membership function and adjusting the parameters of fuzzy membership function by training process), the rule layer which is containing the fuzzy inference process, and the output layer which is revealing the revealing the incident occurrence by employing the center of area method to defuzzify the fuzzy number into a crisp binary value. Each layer is important and cannot be omitted. Although we can add more FNN layers, but too complicated system will increase computing and training time. Therefore, the sensitivity analysis in this section is generated by remaining number of layers, and only examines the impact of modification of FNN network structure which, for instance, changing the activation functions of the nodes or changing the number of parameters in the input layer, on incident detection performance. Because that some detector data sets are unrealistic and unusable due to detector malfunction and some interferes on sensors and communication media and flow and occupancy parameters are mainly collected by inductive loop detectors. The sensitivity analysis of detection performance in adjustment of number of parameters in the input layer is considered.

According the off-line tests and statistic tests, detection rate and false alarm rate of FNN incident detection approach are not affected by the length of interval of detecting time. Consequently, this research uses 30-second detection time interval and two-lane mainline section as the base condition to process the sensitivity analysis. By changing the number of input layer parameters and use only downstream single detector, the simulation off-line test is re-built and results are shown in Table 5-3 and Figure 4-6. From the table, we can find that when we change detector number from two to one, the average detection rate decreases from 88.77% to 84.71%, false alarm rate falls from 0.0555% to 0.1384%, and time to detection remains 81 seconds. The detection rate and false alarm rate deteriorated a bit sharply, but the time to detection remained.

Furthermore, the performance of the reduction of the traffic parameters obtained by single detector is examined. When the amount of input layer parameters changes from three parameters, which are speed, flow, and density, to two parameters, which are speed and flow or density and flow, average detection rate is 83.97%, false alarm rate is 0.1528% and time to detection is 80 seconds; to single parameter, namely flow, average detection rate is 84.65%, false alarm rate is 0.1523% and time to detection is 79 seconds. The detection rate and false alarm rate declined slightly, but the time to detection remained.

In summary, changing the number of detector from two to one or reduce the amount of input parameters will decrease average detection rate, increase false alarm rate and reduce time to detection, but the degree is relative low. On the other hand, the result of this sensitivity analysis shows that if we only use one detector and only flow parameter, FNN approach still accomplishes the good detection performance, and it means that the FNN approach has high fault tolerance and satisfied stability.

Table 5-3 The result of sensitivity analysis

(a) Detection Rate (%)

Incident location			Variables of input layer				
Lane position		Distance from upstream detector (meter)	Two Detectors Speed, Flow, Density	One Detector Speed, Flow, Density	One Detector Speed, Flow	One Detector Flow, Density	One Detector Flow
Two-lane mainline section	Inner	250	93.19 (0.03999)	86.62 (0.02882)	85.12 (0.02751)	85.82 (0.03577)	84.36 (0.03552)
		500	87.90 (0.02867)	84.02 (0.03107)	83.08 (0.03067)	84.43 (0.02411)	82.11 (0.01767)
		750	89.31 (0.03495)	83.75 (0.01996)	82.33 (0.01832)	83.74 (0.02600)	81.24 (0.02093)
	Outer	250	88.25 (0.03721)	85.57 (0.02251)	84.90 (0.03287)	86.02 (0.03188)	84.08 (0.02159)
		500	82.62 (0.02968)	85.09 (0.03001)	84.95 (0.03566)	84.69 (0.02468)	82.45 (0.03024)
		750	91.35 (0.03725)	83.23 (0.02836)	83.41 (0.02908)	83.22 (0.03310)	82.13 (0.03252)
	Average		88.77	84.71	83.97	84.65	82.73

(b) False Alarm Rate (%)

Incident location			Variables of input layer				
Lane position		Distance from upstream detector (meter)	Two Detectors Speed, Flow, Density	One Detector Speed, Flow, Density	One Detector Speed, Flow	One Detector Flow, Density	One Detector Flow
Two-lane mainline section	Inner	250	0.0958 (0.000077)	0.1606 (0.000171)	0.1624 (0.000171)	0.1667 (0.000200)	0.2006 (0.000217)
		500	0.0628 (0.000076)	0.1199 (0.000098)	0.1197 (0.000099)	0.1478 (0.0001388)	0.1598 (0.000111)
		750	0.0589 (0.000073)	0.1257 (0.000166)	0.1248 (0.000166)	0.1298 (0.0001250)	0.1732 (0.000209)
	Outer	250	0.0337 (0.000083)	0.1508 (0.000122)	0.1702 (0.000182)	0.1700 (0.000209)	0.1818 (0.000198)
		500	0.0437 (0.000073)	0.1364 (0.000117)	0.1885 (0.000190)	0.1501 (0.000183)	0.1907 (0.000187)
		750	0.0380 (0.000068)	0.1372 (0.000175)	0.1514 (0.000152)	0.1492 (0.000165)	0.1334 (0.000104)
	Average		0.0555	0.1384	0.1528	0.1523	0.1733

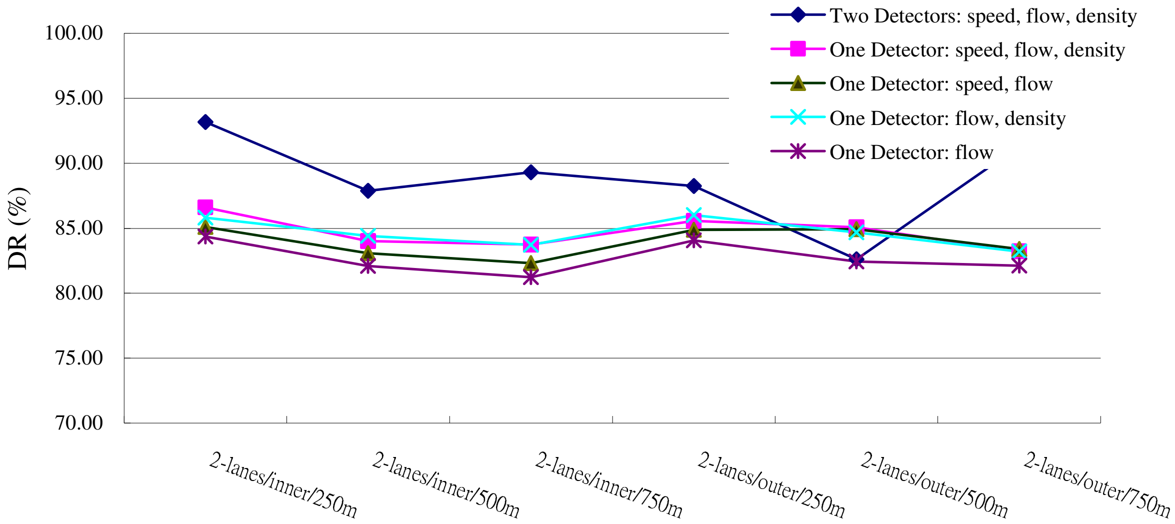
(c) Time To Detection (seconds)

Incident location			Variables of input layer				
Lane position		Distance from upstream detector (meter)	Two Detectors Speed, Flow, Density	One Detector Speed, Flow, Density	One Detector Speed, Flow	One Detector Flow, Density	One Detector Flow
Two-lane mainline section	Inner	250	74 (3.6556)	69 (3.7892)	71 (4.1943)	67 (3.5769)	66 (3.1801)
		500	89 (4.5762)	90 (4.9237)	90 (4.8430)	92 (5.7618)	91 (5.1862)
		750	71 (5.8212)	70 (4.9985)	72 (3.9149)	68 (3.5031)	71 (4.8840)
	Outer	250	83 (6.4183)	85 (5.3571)	83 (5.6730)	82 (6.6392)	81 (6.0230)
		500	95 (8.1292)	95 (7.8323)	96 (8.6928)	93 (8.6094)	95 (7.9405)
		750	76 (4.2318)	73 (4.9363)	73 (5.2507)	70 (4.6008)	71 (3.7128)
	Average		81	81	80	78	79

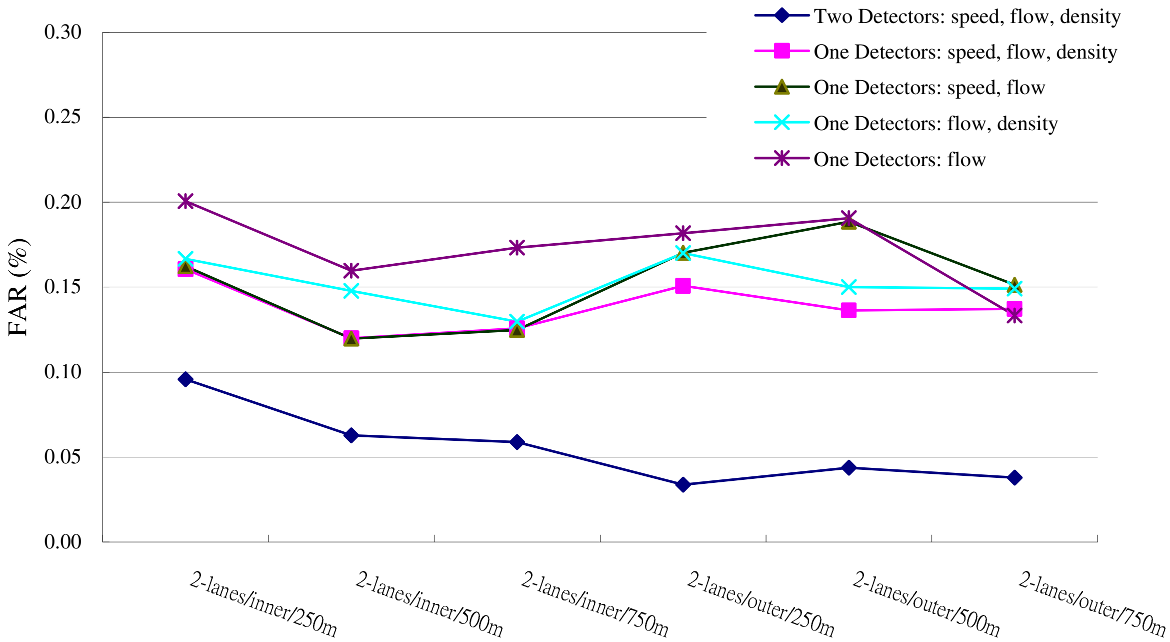
Note: 1. Distance of incident location is measured from the upstream detecting point.

2. Each scenario is simulated for 100 times. The values in this table are the average of 100 simulation runs with standard deviation in parenthesis.

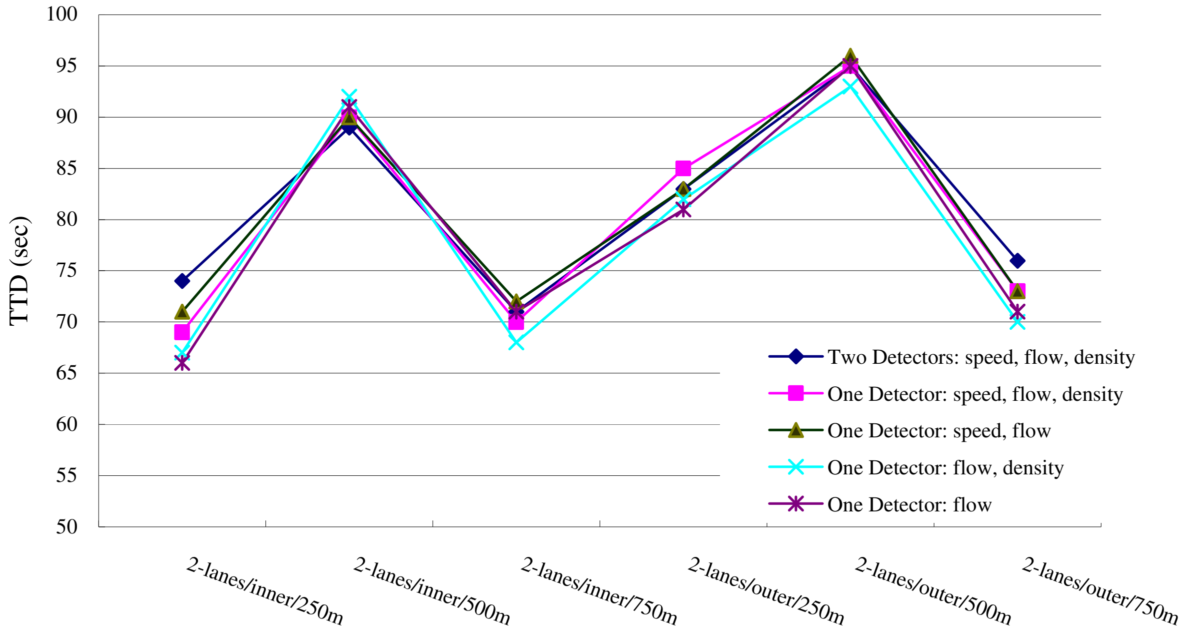
3. Time of the detection interval is 30 seconds



(a) Detection rate



(b) False alarm rate



(c) Time to detection

Figure 5-6 Sensitivity analysis of FNN incident detection

5.4 Summary

The FNN incident detection approach has different detection performance under different incident scenario. The statistics tests show that the interval of detecting time has significant influence on time to detection, but the influence on detection rate and false alarm rate is unremarkable. It means that incident detecting ability of FNN incident detection system is not affected by the length of interval of detecting time (30- or 60-second).

When an incident which is on mainline section with two lanes and three lanes blocked single lane, detection rate and time to detection of FNN have significant difference. There is higher average detection rate and shorter time to detection when incidents occur on two lanes than when incidents take place on three lanes. It means that three lanes with one lane blocked, has more left capacity for vehicles to pass than two lanes with one lane blocked, that is, incidents happen on three lanes have smaller impact on traffic flow and are not easy to detect. That implies that when incidents fall on low flow capacity rate (v/c), they have smaller impact on traffic flow and are not easy to detect.

When the situation is on mainline section with two lanes, where incidents fall on has no significant influence on time to detection, but has significant effect on average detection rate. Detection rate is higher when incidents fall on inner lane shows that it is easier to detect incidents on the inner lane and is mainly because of inner lane flow and density is higher than outer lane. The distance between incident location and upstream or downstream detectors has significant impact on detection rate and time to detection. The farther the distance is the longer detecting time needed. The nearer (from either upstream or downstream) the distance is the easier to detect that it means FNN system is affected by the density of detector deployed.

When the situation is on main lane with 3 lanes, incidents that block one lane or two lanes has significant difference on detection rate and time to detection, and incidents block two lanes has higher detection rate and time to detection is shorter. When incidents block one lane, where the incident falls on has no significant influence on detection rate and time to detection. When incidents block two lanes, whether blocking inner and center lanes or blocking outer and center lanes, has no significant difference on detection rate, but has significant influence on time to detection. The same as two lanes situation, the distance between incident location and upstream or downstream detectors has significant effect on detection rate and time to detection. When incidents occur on the center of two detectors, there is the lowest detection rate but the longest time to detection.

When changing the network structure of FNN system from upstream and downstream detectors to single downstream detector, it will cause detection rate to fall and false alarm rate to rise. It is mainly because of the detection rate is affected by the distance between incident location and detector because the limited distance of double detectors is 500 meters and the limited distance of single detector is 750 meters, and the influence of incidents on traffic flows decreases when distance increases, that implies that the higher density detectors deployed the higher detection rate is. Reducing the amount of input parameters will cause detection rate to decrease and false alarm rate to increase, but the scale is not high, that means FNN incident detection approach has high tolerance and stability when the input traffic data is not integral, so that it has practical implement.