IMPLEMENTATION OF ALTERNATIVE INTERSECTIONS IN SOUTH AFRICA: OPERATIONAL CONUNDRUM OR COST EFFECTIVE INFRASTRUCTURE SOLUTION

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ABSTRACT

The existing Diamond Interchange at the crossing of the N1 with Sefako Makghato Drive (Route K14) in the City of Tshwane Metropolitan Municipality was recently, in 2015, upgraded to a Diverging Diamond Interchange (DDI). The Diverging Diamond Interchange is one of the so-called alternative intersections based on innovative approaches to avoid or minimise opposing traffic flows. The paper presents the results of capacity and operational analyses by means of analytical techniques (SIDRA 7.0 Plus), and also evaluates the cost-effectiveness. Typical operational challenges of the urban environment, i.e. non-motorised transport, disorderly taxi behaviour, power outages, etc. were also addressed.

1. INTRODUCTION

1.1 Background

Peak period congestion in South African urban areas has little prospect of significant relief in the near future. Funding for systems wide urban transport infrastructure improvements has come to a standstill after the spending spree leading up to the 2010 Soccer World Cup tournament. The implementation of a number of Bus Rapid Transport projects since 2010 have had localised and mixed results. Although many urban and metropolitan areas – most notably in Gauteng – are blessed with well-planned major road networks that can serve the province, and the country, for the next few generations, many critical bottlenecks will probably remain due to lack in adequate funding to implement the planned network.

In general, the South African National Roads Agency (SANRAL) is responsible for Class 1 national roads, the Provincial Road Authorities for Class 2 and Class 3 regional roads, and the Local Authorities for Class 3, 4, and 5 urban roads. It is common knowledge that the Provincial Road Authorities are not receiving adequate funding for new road construction from the national fiscus, but even more problematic is the construction and management by Local Authorities of the Class 3 urban road network where the impacts of land use development and urban growth manifest most severely.

Due to funding and capacity constraints, the development of the urban road network is left to the private sector, i.e. developers, who improve these networks following a piecemeal, localised and short term approach.

The intersection of major roads, i.e. Class 2 and Class 3 roads, in and on the fringes of urban areas are often critical bottlenecks in our urban road networks. Major arterials can potentially be upgraded to six-lane carriageways with dual turning lanes (eight-lanes given the provision of dedicated public transport lanes), after which the grade-separation of one or more major movements is the next logical step.

The intersection of PWV-routes with K-routes and metropolitan arterials are potential bottlenecks in the PWV Major Road Network in Gauteng (now called the Gauteng Strategic Road Network). PWV-routes are freeways (Class 1 roads) and K-routes are conventional dual carriageway arterials (Class 2 roads) that form the backbone of the Pretoria-Witwatersrand-Vereeniging (PWV) Major Road Network for which planning by the former Transvaal Provincial Administration (TPA) started in the mid 1970's.

A recent high-level investigation by GAUTRANS (March 2015, Jeffares & Green) identified about 40 intersections in Gauteng where grade-separation are likely to be required in future. The cost of grade-separation, given that extensive road works and bridge structures are required, is prohibitive (the construction cost of a directional is about R60m and an urban diamond interchange about R250m) which makes it very unlikely that we can "build ourselves out of trouble" in future. Very few urban interchanges are currently being constructed.

1.2 Alternative Intersections and Interchanges

The development of unconventional solutions was the forerunner of Alternative Intersections as summarised by Hummer, 2014:

''*Unconventional solutions provide a menu of other options that highway agencies can explore to overcome the pitfalls associated with conventional solutions. Unconventional intersections and interchanges typically involve rerouting one or more movements—often left turns—to reduce the number of conflict points remaining in the middle of the intersection or interchange. This allows a reduction in signal phases, less lost time, fewer opportunities for crashes, and a host of other potential benefits. Unconventional intersections design probably originated with the jug handle intersection in New Jersey, USA in the 1950's, followed by the median u-turn intersection in Michigan, USA in the*

1960's. Interest in unconventional designs surged in the US beginning in the early 1990's as traffic demands and project costs soared while project funding grew tighter. Roundabout interchanges and single-point diamond interchanges became so popular through the 1990's that today they are considered conventional. The most prominent unconventional service interchange design with no loops and no weaving at the moment is the double crossover diamond (DCD), also known as the diverging diamond. The DCD contains two places where the through directions of the surface street cross each other''.

Alternative Intersections in the USA are primarily the result of funding constraints. An Alternative Intersection refers to an intersection which is uncommon or "alternative" and although numerous types and configurations are available, they all have one thing in common; namely measures to reduce the critical opposing movements through diversion, division, distribution, or rerouting of the opposing movements which often results in fewer traffic signal phases. The "magic" of fewer signal phases are illustrated in Figure 1.

Alternative Intersections refer to alternative configurations for both at-grade intersections and the terminals of interchanges.

Some typical *Alternative Intersections* are the following:

- Median U-turn intersection;
- Restricted crossing U-turn intersection;
- Quadrant roadway intersection;
- "Alternative" roundabout;
- Displaced right-turn intersection / Continuous flow intersection;
- Diverging (double crossover) diamond interchange;
- Other "Alternative" interchange configurations;

Although alternative intersections can provide higher capacity than conventional intersections, they cannot replace grade-separation in the long-term but are economical interim solutions that delay the implementation of costly grade-separation until the required expenditure becomes economically viable.

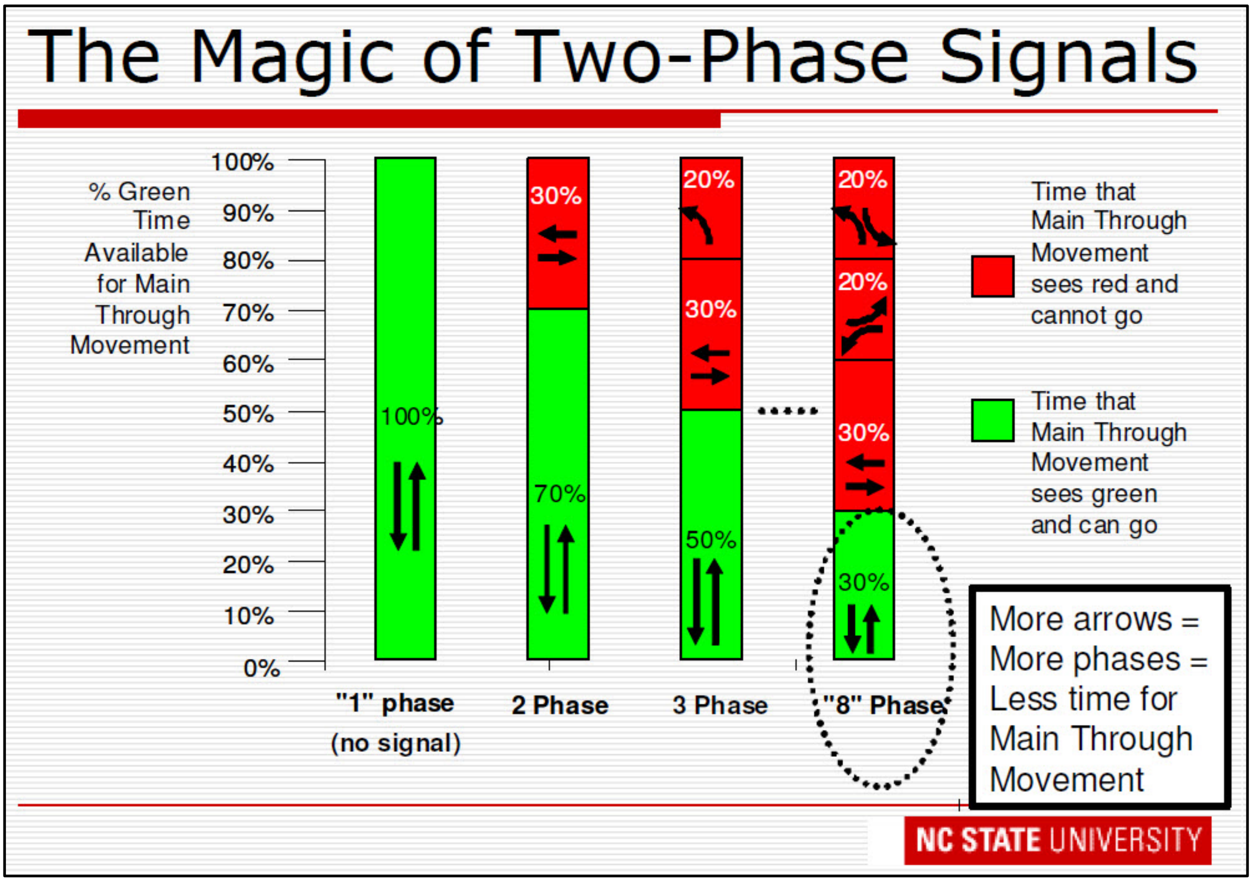


Figure 1: The Magic of Less Opposing Movements / Fewer Signal Phases (Hummer, JE, 2011)

Figure 2 shows the required change in traffic control and configuration with an increase in traffic volumes. The available green time for through movements can easily be reduced with 20% up to 40% because of multiple phases and lost inter-green times.

This paper specifically deals with one type of an Alternative Intersection; namely a Diverging Diamond Interchange (DDI) also known as a Double Crossover Interchange (DCDI) based on recent experience with the analyses, planning, design, and implementation of such an interchange in the City of Tshwane Metropolitan Municipal area.

The first DDI in South Africa, the KwaMashu Interchange, has been implemented in KZN at the crossing of the N2 with the R102 Curnick Ndlovu Highway (completed in August 2013). Feedback from both SANRAL and AURECON (consultants) has generally been positive (AURECON Team, December 2014).

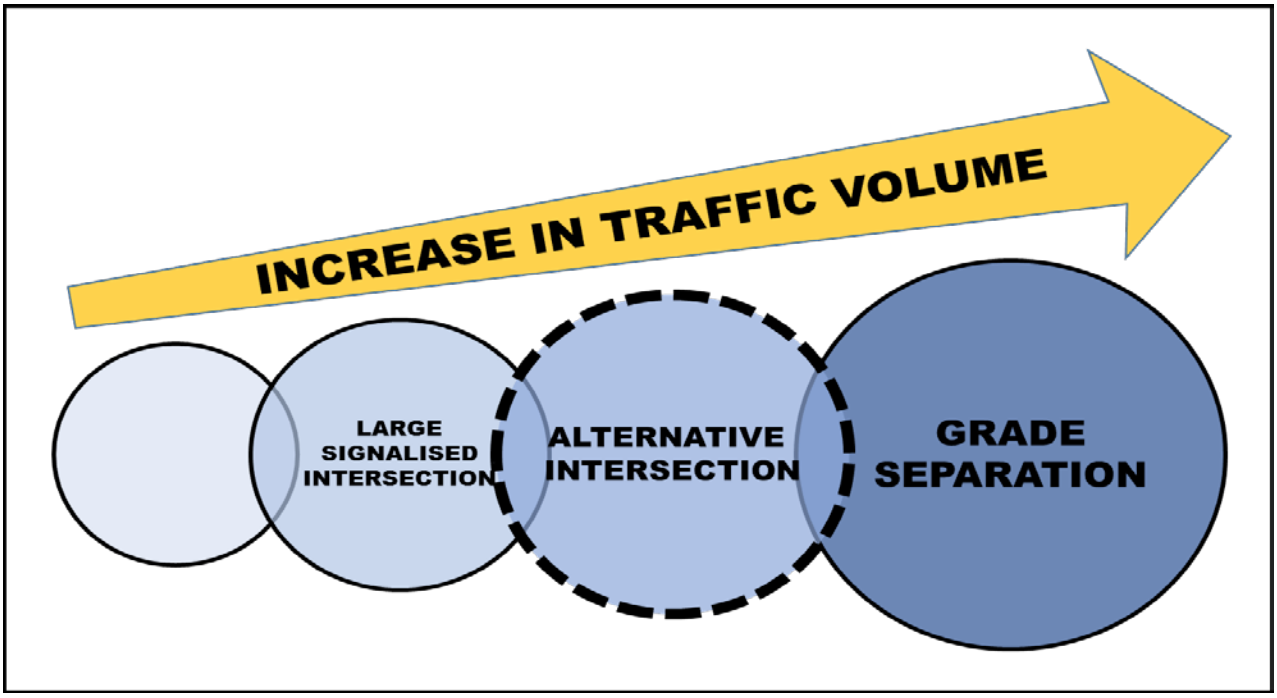


Figure 2: Change in Control and Configuration with Increase in Traffic Volumes (FHWA, 2014)

The following photograph, Figure 3, shows an example of a DDI from the USA (right-hand drive rule) where the alternative intersection/interchange concept originates from.

Figure 3: Example of Diverging Diamond Interchange in the USA (Hughes, W, 2010)

2. IMPLEMENTATION OF A DDI AT N1/SEFAKO MAKGHATO DRIVE (K14)

2.1 Background

The Diverging Diamond Interchange (DDI) between the N1 and Sefako Makghato Drive (K14) along the N1 immediately north of the Magalies Mountain Range was done as an upgrade of the existing Diamond Interchange (DI) by BAKWENA, the concessionaire for the N1/N4 Platinum Highway. The upgrade was done in terms of an obligation of the concession contract to ensure minimum performance standards.

The Magalies Mountain Range forms a natural barrier that separates the northern residential suburbs of Pretoria from employment opportunities in the south. High traffic demand along Sefako Makghato Drive (K14) for origins and destinations in the south (i.e. via the N1 Eastern Bypass) is the result of limited access routes through the mountains. Figure 4 - the Gauteng Strategic Road Network – shows that only Lavender Rd (in addition to the N1) provides access through the Mountain Range.

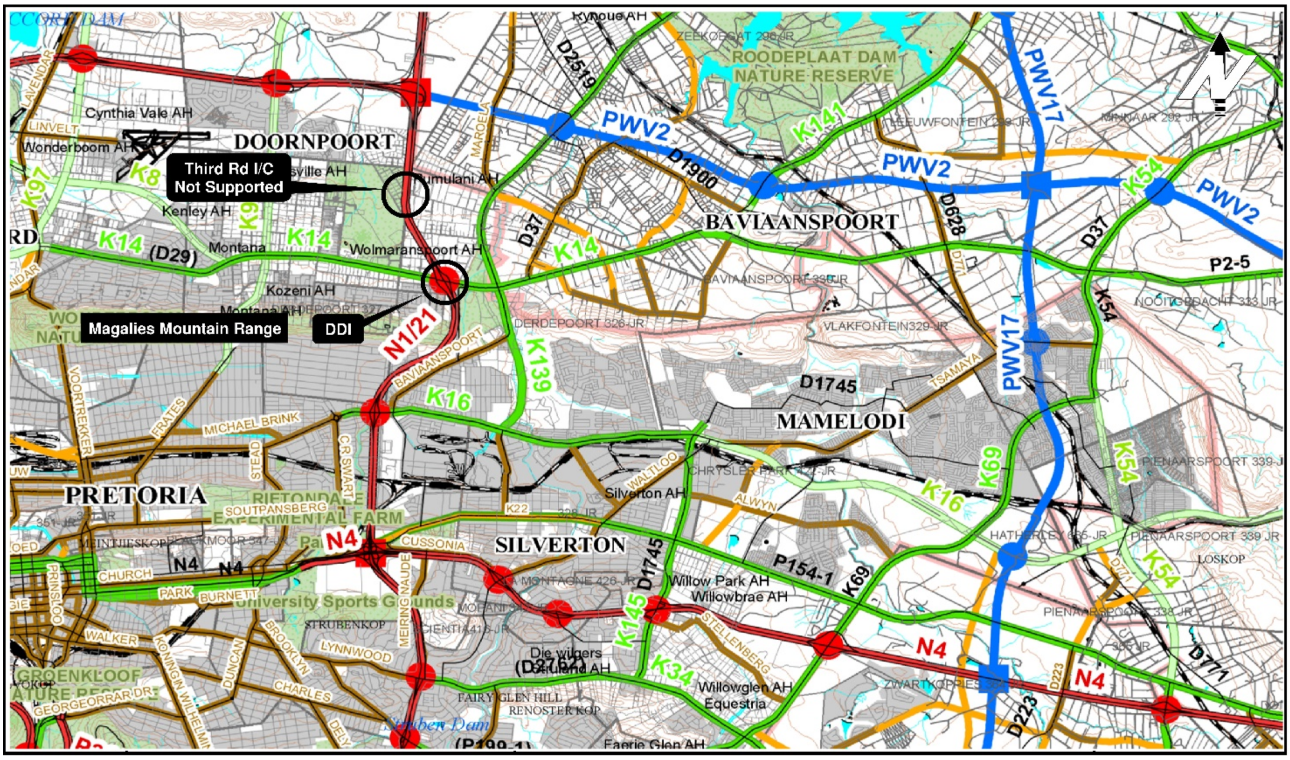


Figure 4: Gauteng Strategic Road Network

The previous DI at the N1 was blamed by many motorists for ruining their early morning journeys to work (angry e-mails and telephone calls to the Traffic Engineer at BAKWENA testify to this). The large right-turn movement of about 2400 vph from west-to-south during the morning peak hour at the eastern terminal (i.e. feeding the Zambezi On-Ramp Plaza) was the biggest bottleneck. At the end of 2015 the "tweaking" of green time at the interchange did not bring relief anymore and it became clear that more drastic measures were required.

Figure 5 shows the 2015 – adjusted to 2017 - weekday peak hour demand at the DI.

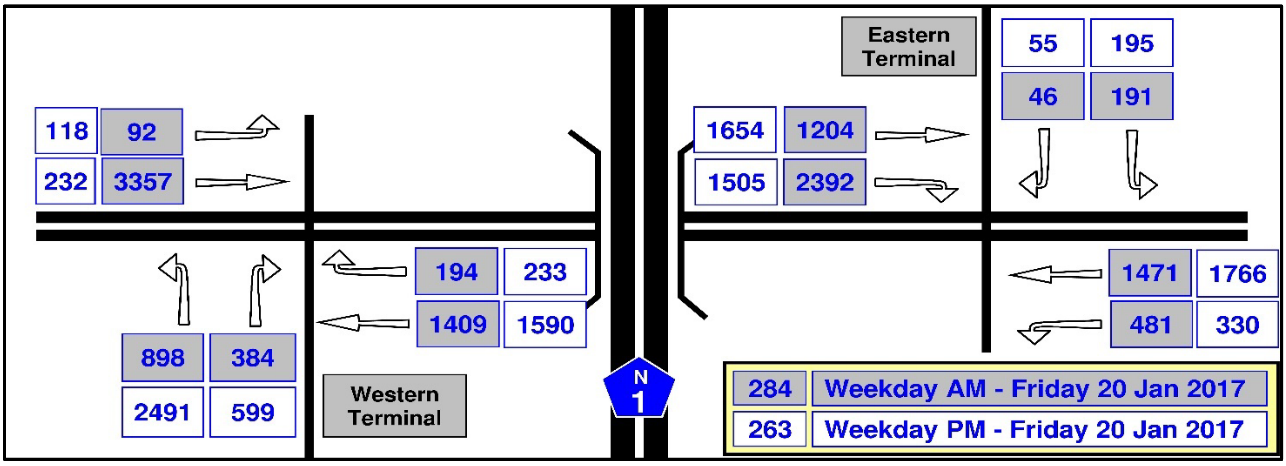


Figure 5: 2017 Weekday Peak Hour Traffic Demand

Several alternative solutions to this problem were investigated before a DDI become the chosen option. Alternative solutions that were investigated included the following:

- New interchange with the N1 at Third Street – immediately north of Sefako Makghato Drive - to reduce the traffic loading at the congested DI. This new interchange was not supported by SANRAL due to sub-standard spacing of the on- and off-ramps;
- Introduction of a loop in the north-eastern quadrant of the DI would have changed the major right-turn into a left-turn movement. The loop was abandoned based on technical difficulties to firstly toll this movement and secondly to provide adequate merging and weaving distances along the N1 given the existing two-lane on-ramp;
- Upgrading of the critical right-turn lanes to multiple lanes, i.e. four lanes. The geometry, reduction in saturation flow rate, and thus reduced capacity of multiple right-turn lanes counted against this solution.

2.2 Key Considerations

Figure 6 shows the layout of the DDI that was constructed at the N1 / Sefako Makghato Drive (K14) crossing to replace the existing DI.

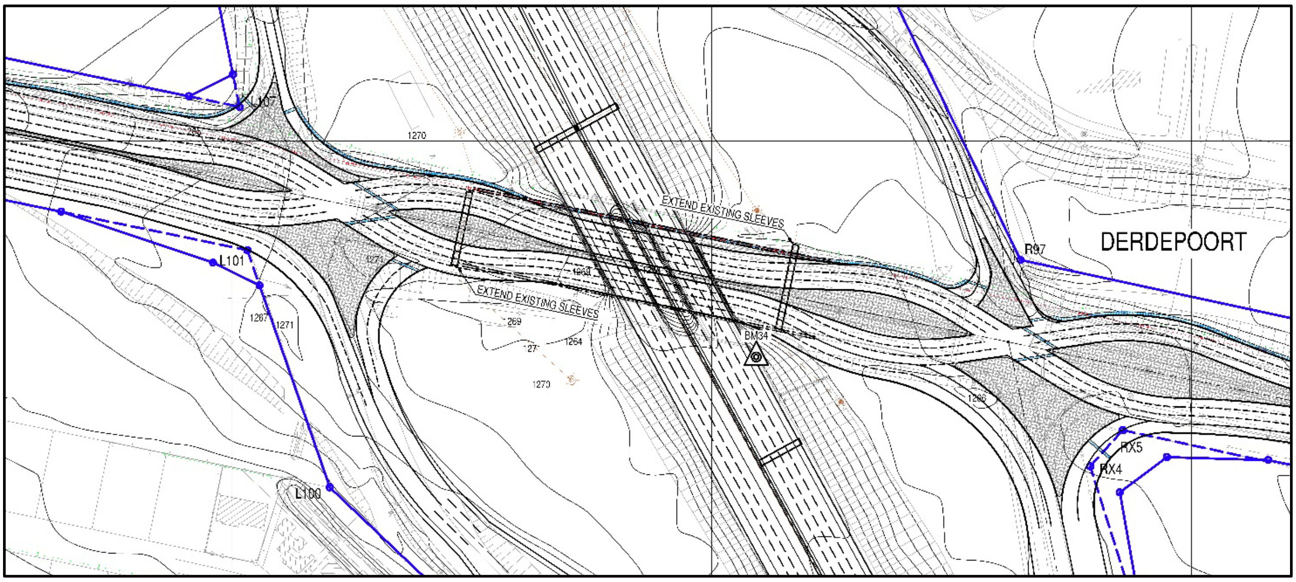


Figure 6: DDI at N1 / Sefako Makghato Drive (K14)

This figure shows the additional road works and road reserve that was required, as well as the pedestrian paths through the interchange.

Alternative Intersections are unconventional, and often more complex from an operational point of view. The primary consideration for the implementation of this DDI was therefore cost-effectiveness, namely an increase in capacity at a relatively low capital cost; generally known as a traffic management solution.

The highway sections of the N1 south of the interchange with Sefako Makghato Drive is approaching capacity during peak periods with no prospect of further upgrading (relief from the current peak hour congestion can however come from the implementation of the planned major road network most notably the extension of PWV2 and the construction of PWV17 towards the south). On the other hand, the major local road network north of the Mountain Range – most notably Sefako Makghato Drive (K14) towards the west - has little prospect for further upgrading. Refer to the Figure 4, the Gauteng Strategic Road Network.

Since the upgrading of this interchange was an obligation in terms of the concession contract, BAKWENA was interested in an affordable cost-effective solution that will result in balanced network from a capacity point of view. The DDI was such a solution.

2.3 Benefits from a Capacity Point of View

Table 1 shows the Measures of Effectiveness of the previous DI compared with the new DDI for the weekday peak hours using 2017 traffic volumes.

Table 1: MOE's for Previous DI compared with New DDI

Terminal and MOE			Diamond Interchange (DI)		Diverging Diamond Interchange (DDI)	
			AM	PM	AM	PM
2017	Eastern Terminal	Design Peak Hour Traffic	6406	5478	6406	5478
		Cycle Length (s)	115	115	60	60
		Number of Phases	3	3	2	2
		Worst Movement ito Delay	W-S RT	W-S RT	E-W T	N-E LT
		Worst Movement Delay (s)	69.9	46.1	20.7	26.2
		Worst Movement LOS	E	D	C	C
		Worst Movement V/C	0.984	0.953	0.663	0.683
		Average Delay (s)	50.2	36.1	12.5	13.8
		Average LOS	D	D	B	B
		Ave Queue Length (m)	270	159	60	59
	Western Terminal	Design Peak Hour Traffic	6667	7740	6667	7740
		Cycle Length (s)	115	115	60	60
		Number of Phases	3	3	2	2
		Worst Movement ito Delay	E-N RT	S-E RT	E-N RT	E-N RT
		Worst Movement Delay (s)	78.6	66.6	33.2	24.3
		Worst Movement LOS	E	E	C	C
		Worst Movement V/C	0.957	0.891	0.860	0.707
		Average Delay (s)	30.0	20.8	21.0	14.7
		Average LOS	C	C	C	B
		Ave Queue Length (m)	337	197	121	64

Please note that the two interchanges – analysed in Table 1 - are not fully comparable in terms of the number of lanes per critical movement. SIDRA 7.0 Plus was used to calculate the performance and service levels. Only the worst movement(s) and overall intersection performance is reported due to the space limitations. Inspection of this table shows the following benefits of the DDI:

- Lower V/C ratios and lower delay, and thus higher service levels;
- Shorter cycle lengths and fewer phases resulting in higher capacity;

Table 2 shows a comparison between the modelled capacity – and spare capacity (difference between modelled capacity and current demand) – for the diamond interchange compared with the diverging diamond interchange. SIDRA 7.0 Plus was used to determine the potential maximum critical volumes of these interchange terminals to ensure V/C = 1.0; i.e. termed the spare capacity. Three cases are shown:

- Case 1: The old Diamond Interchange (DI);
- Case 2: The lane configuration of the old Diamond Interchange (DI) adjusted to compare directly with the lane configuration of the Diverging Diamond Interchange (DDI) in terms of the number of lanes on critical movements;

- Case 3: The Diverging Diamond Interchange (DDI) that was constructed;
- Case 2 (DI) is therefore directly comparable with Case 3 (DDI).

Table 2: Capacity of DI compared with New DDI

Terminal and MOE		CASE 1		CASE 2		CASE 3	
		Diamond Interchange (DI)		Diamond Interchange (DI) (comparable with DDI)		Diverging Diamond Interchange (DDI)	
		AM	PM	AM	PM	AM	PM
Eastern Terminal	Modelled Capacity	6406	5587	6663	7340	9481	7559
	Spare Capacity (relative to 2017 demand)	0%	2%	4%	34%	48%	38%
	Cycle Length (s)	120	120	120	120	120	120
	Worst Movement ito Delay	W-S RT	W-E TH	W-S RT	E-W TH	E-W TH	E-W TH
	Worst Movement Delay (s)	73.2	51.2	73.4	68.9	76.6	72.2
	Worst Movement LOS	E	D	E	E	E	E
	Worst Movement V/C	0.990	0.999	0.993	0.991	0.994	0.988
	Average Delay (s)	50.5	42.2	56.2	51.6	50.4	46.8
	Average LOS	D	D	E	D	D	D
	Ave Queue Length (m)	283	192	297	252	528	355
Western Terminal	Modelled Capacity	6667	8824	8668	8359	8668	11920
	Spare Capacity (relative to 2017 demand)	0%	14%	30%	8%	30%	54%
	Cycle Length (s)	120	120	120	120	120	120
	Worst Movement ito Delay	S-E RT	W-E TH	S-E RT	E-N RT	E-W TH	E-W TH
	Worst Movement Delay (s)	97.4	61.7	80.6	61.5	71.6	65.9
	Worst Movement LOS	F	E	F	E	E	E
	Worst Movement V/C	1.008	0.985	0.998	1.00	0.992	0.987
	Average Delay (s)	35.0	32.2	40.8	19.5	52.3	43
	Average LOS	D	C	D	B	D	D
	Ave Queue Length (m)	377	317	395	141	391	324

The critical terminal of an interchange determines the overall capacity of an interchange. The old DI was subsequently compared with the DDI assuming that the same traffic transverses both terminals (approximately true) which allows a comparison of the lowest spare capacity of the old DI (i.e. critical terminal) with the lowest spare capacity of the DDI (i.e. critical terminal). Inspection of *Table 2* shows that the DDI trumps the DI with 26% during the morning peak hour (30% versus 4% spare capacity), and with 30% during the afternoon peak hour (38% versus 8% spare capacity).

It can be noted that different terminals are critical (i.e. act as bottlenecks) during the respective peak hours. The benefits of the DDI are more notable if the critical terminals of the DI are compared with the corresponding terminal of the DDI, i.e. the eastern terminal during the weekday morning peak hour and the western terminal during the weekday afternoon peak hour, namely 44% (48% versus 4% spare capacity) during the weekday morning peak hour and 46% (54% versus 8% spare capacity) during the weekday afternoon peak hour.

The relatively smaller or no gains of the non-critical terminals of the DDI compared with the DI (30% versus 30% and 34% versus 38% during the weekday morning and afternoon peak hours respectively) illustrate an important aspect of a DDI. A DDI will provide the most benefits under the following circumstances:

- Large in- and out-flows via the ramps of the interchange;
- Relatively lower straight through movements on the cross-road;

This is easily explained by the critical movements in both cases. The benefits of the DDI stems from changing opposed right-turn movements into unopposed right-turn movements, which simultaneously changes three-phase signal control into two-phase signal control. This however also results in the major disadvantage of the DDI configuration namely that it separates the main through movements in both directions into two opposing movements and thus different phases. A comparison of the critical movements at a DI (Figure 7) and the critical movements at a DDI (Figure 8) illustrates this schematically. This is a detrimental aspect of a DDI that can potentially offset the benefits of unopposed right-turn movements.

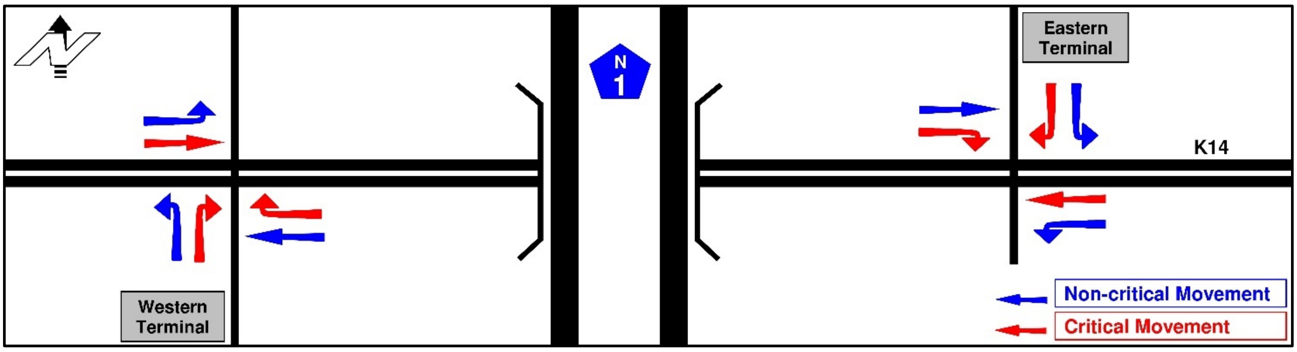


Figure 7: Critical Movements at Diamond Interchange

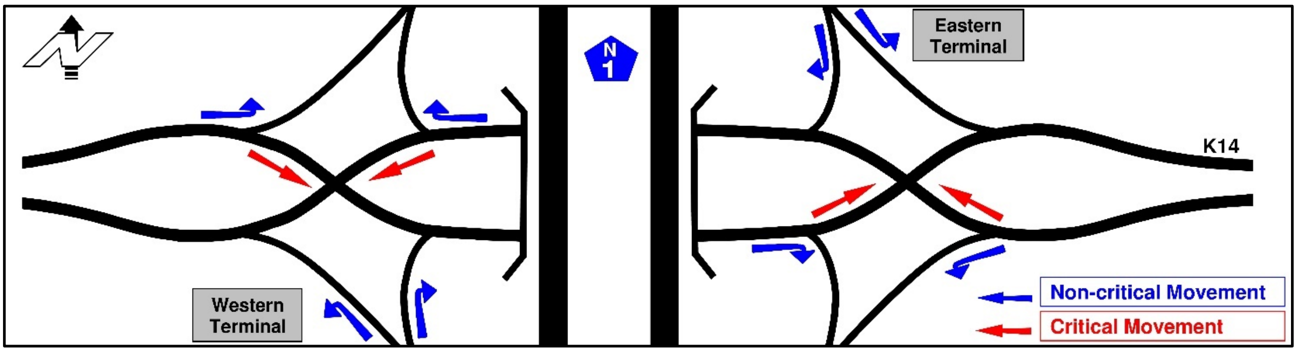


Figure 8: Critical Movements at Diverging Diamond Interchange

2.4 Challenges from an Operational Point of View

Although the operational complexities – especially in terms of non-motorised and public transport – are generally perceived as obstacles, the investigations and actual practical experience in the USA prove otherwise (*Jackson, K, 2014*).

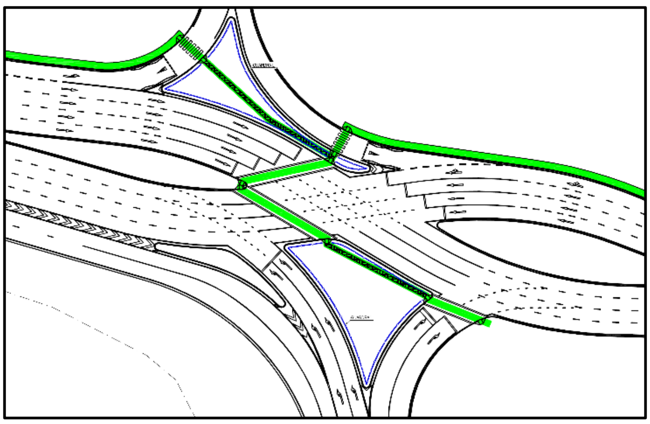
A bird's eye view of a DDI – refer to Figure 6 – creates the impression that motorists can easily become confused and disorientated with hazardous consequences. This assumption was proven to be incorrect. The switchover occurred as smoothly as can be expected. Information flyers and pamphlets were distributed to motorists at adjacent intersections prior to the opening, and the media centre of BAKWENA liaised with the local media & radio stations as well as on social media prior to the opening.

Opening of the new interchange was accomplished by closing all entry points to the interchange from all four directions before the morning peak hour (05:00) – to clear the interchange – after which motorists were directed to the new lanes by points-men / flag men. No accidents occurred during the construction period followed by only a few small unrelated accidents during the past one year of operations.

No taxi and bus facilities were considered at the terminals of the interchange to discourage pedestrian movements between the N1 freeway and the street network.

The design of pedestrian crossings and pedestrian phases required special mentioning. Pedestrian crossings can only be provided on one side of each terminal since pedestrians are expecting traffic from the right. Only one pedestrian sidewalk was provided along the cross-road; i.e. Sefako Makgahto Drive (K14), on the northern side of this road. This encourages pedestrians to cross the lower volume movements on the northern side instead of crossing the large uninterrupted turning movements from south-to-west at the western terminal and from west-to-south at the eastern terminal. Refer to Figure 9 and Figure 10.

Signage on overhead gantries were essential on the main approaches and the use of S4 signal heads (green disc with directional arrow) to control the main through movements, instead of S1 signal heads (green disc), reduced the signage requirement significantly.



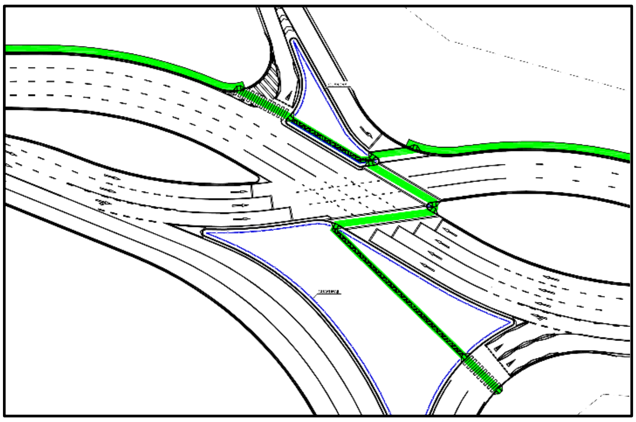


Fig 9: Pedestrian Paths at Western Terminal
Fig 10: Pedestrian Paths at Eastern Terminal

3. IMPLEMENTATION

The DDI was designed by V&V Consulting Engineers and constructed by G4Civils. The existing DI at the N1 / Sefako Makgatho Drive crossing was replaced with a DDI during a total construction period of 10 months (new road works was open to traffic after 8 months) at a total cost of R 27.81 million. A total of ±38,500 m^2 of asphalt surfacing was done that comprised of 40% new road surface and 60% overlay of existing surface.

Apart from the layer works and road surfacing, other major cost items were new gantries for signage (±R 1.185m) and accommodation of traffic (±R 2.076m). Only small amendments to the existing road reserves were necessary as shown in Figure 6.

The increase in capacity-to-capital cost ratio of the new DDI compared to the old DI is between R9,000 and R14,000 per peak hour trip. It is interesting that this compares well with current bulk engineering contributions for roads and storm water in Gauteng which amounts to approximately the same rates.

The comparison between the old DI and the DDI may appear illogical given that the two configurations did not have the same number of critical lanes. The upgrading of the old DI would however only have resulted in wasted expenditure (road works that cannot be used) given the introduction of road curvature to accomplish the cross-overs.

4. CONCLUSIONS

It is concluded that the implementation of alternative intersections is potentially very cost-effective with an "*increase in capacity-to-capital cost ratio*" of between R9,000 and R14,000 per peak hour trip.

The capacity benefits of the DDI are most notable if the critical terminal of the DI is compared with the corresponding terminal of the DDI, i.e. an increase of 44% at the eastern terminal during the weekday morning peak hour and an increase of 46% at the western terminal during the weekday afternoon peak hour. The relatively smaller or no gains of the non-critical terminals of the DDI compared with the DI during the weekday morning and afternoon peak hours respectively illustrate that a DDI is not effective under all circumstances but only when large in- and out-flows occur via the ramps of the interchange with relatively lower straight through movements on the cross-road.

The detailed traffic counts available at the ramp toll plazas show only moderate increases in peak 5-minute flows through the plazas given that other bottlenecks remain upstream and downstream of the toll plazas (Sefako Makghato Dr West and N1 South).

The operational complexities and non-motorised transport challenges were furthermore found not to be conundrums but factors that can be managed successfully.

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