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Models for quick evaluation of displaced right turn intersection performance

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ABSTRACT

Alternative intersection designs can provide cost-effective solutions to overcome the proven inadequacy of conventional approaches. Several studies have assessed the performance of alternative designs against a range of traffic volumes and geometric design aspects, each in isolation, but a model which can factor in multiple variables into the analysis is the identified research gap. The displaced left-turn – DLT intersection design was found to be the most versatile, efficient, and transferable to locations elsewhere in the world. In this paper, a *displaced right-turn intersection* – a variant of DLT, was modelled for a range of traffic flows and design conditions. Regression models were developed for Practical Reserve Capacity and Delay as dependent variables with traffic flow, proportion of right-turning traffic, signal cycle time and length of displaced turn as explanatory variables. These models can provide relatively quick preliminary estimates of the performance indicators before committing to resource-consuming junction remodelling works.

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Displaced right-turn; traffic simulation; regression model; practical reserve capacity; delay; junction modelling

1. Introduction

Vehicle traffic growth will have a significant effect on intersection capacities, as they are usually the bottlenecks in a road network. Delay time increases while the average speeds decrease with an increase in vehicle traffic leading to congestion (Hildebrand 2007), accompanied by higher emissions due to the stopping and moving nature of traffic. Given the evidence suggesting the ineffectiveness of investment in road expansions in reducing congestion (Transportation for America 2020) and the geographic limitations in urban areas, it is imperative to consider novel and effective engineering solutions to treat the existing junctions that are reaching their saturation levels.

Conventional approaches such as actuated signal systems, lane channelisation, and widening the right-of-way are routinely used to improve capacity (Goldblatt, Mier, and Friedman 1994) although they have diminishing returns for incremental capacity addition because of the transportation-land use interdependency (Hildebrand 2007).

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The addition of new vehicles to the roadway has resulted in an increase in delay time for through traffic because the traffic signal must remain green longer for the exclusive turn lanes. Grade-separated intersections are proposed when the conventional remedial methods are either exhausted or prove to be ineffective (Esawey and Sayed 2013). Careful thought must be given before resorting to grade separation as a solution, as substantial time and cost involved in construction and disruption to existing traffic are a few drawbacks among many others. Unconventional intersection designs potentially can provide an alternative at-grade solution for congested intersections which can enhance operational and safety performance (Esawey and Sayed 2013). Among several design types, the continuous flow/displaced left-turn is found to be the most flexible in terms of handling the through traffic and the varying proportions of turning volumes. Hence, this design is of particular interest in this study. Research into how multiple aspects of the design simultaneously affect the performance of the junction is the identified research gap.

The main aim of the study is to evaluate the performance of displaced right-turn intersection with a variation in the set of a wide range of independent variables which are identified to have a major influence. The main objective is to develop new tools to aid traffic engineers for quickly predicting the potential benefits of implementing unconventional designs required at pre-feasibility stages. The resultant mathematical models can provide quick preliminary estimates of performance indicators required at early stages at a fraction of cost which can render an effective tool to evaluate such designs without resorting to developing resource-consuming simulation models.

This paper is divided into five sections including this one. Section 2 describes the junction redesigning efforts around the world and the weaknesses identified post-implementation. Section 3 outlines the methodology used and discusses the model building and the scenarios utilised in the models. Section 4 describes the outcome of the study with the support of numerical outputs and an illustration of the utility of the generated mathematical models. Section 5 concludes the paper.

2. Review of junction improvement methods

The improvement of a congested junction is usually achieved through the adoption of special/optimised signal phasing, lane channelisation, widening the right-of-way and improving alternative routes (Goldblatt, Mier, and Friedman 1994). These measures are categorised as traditional/conventional approaches which also include other measures such as the use of protected turning phases, actuated signals and signal coordination (Esawey and Sayed 2013). Short-term immediate solutions are required in developed areas grappling with congestion issues and thus, conventional methods are adopted to provide immediate relief to congestion. They can provide marginal improvement to the capacities and the additional capacity thus created is often utilised soon by the induced traffic and saturated conditions return (Hildebrand 2007). On the other hand, measures such as the addition of extra lanes to road links can be infeasible owing to the restricted right-of-way or the high cost of doing so (Dhatrak, Edara, and Bared 2010). Although such shortcomings can be overcome by improvement, the evaluation exposes inherent limitations of the effectiveness of such measures.

Roundabouts have been widely utilised in the Americas, UK and Australia when an existing crossroad has to be upgraded to accommodate an increase in traffic and turning movements. Although roundabouts can handle high turning flows, they can create higher delays to minor roads when flow imbalance is encountered. Roundabouts are not always compatible with the local Urban Traffic Control (UTC) system and so they may not suit an urban environment (National Highways 2020). When the capacity of roundabouts is exceeded, some conventional techniques e.g. signalisation must be employed to enhance their capacities. Grade separation is considered an option when the traditional measures prove inadequate or infeasible and the traffic flows are beyond the capacities of a roundabout and signalised intersections. The consideration of grade separation has been criticised, since they are costly, time-consuming, disrupt existing traffic flow and is aesthetically unpleasant and affected by the induced traffic.

The limitations of signalised junctions, the cost and inconvenience of grade separation and the lack of fit of roundabouts in certain situations leave a range of unaddressed 'in-between' scenarios, captured graphically by Steyn et al. (2014) as shown in Figure 1. Alternative designs are considered as a solution by many studies in this area, the

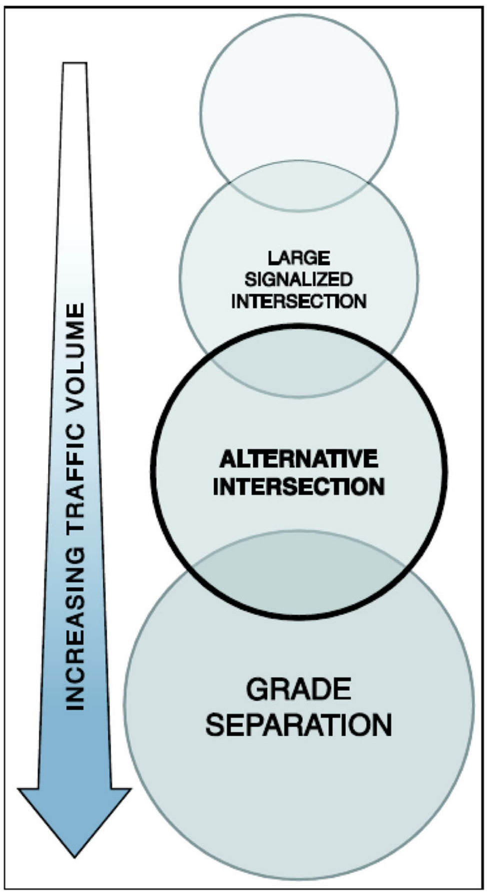

Figure 1. Relationship between traffic volume and intersection types (Source: Steyn et al. 2014).

works published by the Federal Highway Administration (USA) being the most prominent (Hughes et al. 2010).

The alternative intersections are considered non-conventional approaches by several authors who have explored these designs (Esawey and Sayed 2013; Hummer and Reid 2000). These designs have been developed and implemented in the USA and there have been a few adaptations by other countries. The two common principles based on which all unconventional designs work are: *(i) the reduction of delay to through traffic caused by opposing turning movements; and (ii) the reduction of conflict points by separating or relocating them in space.* The most often described advantage of these designs is the relative ease with which existing junctions can be transformed into unconventional design configurations through minor design changes such as lane marking, physical barriers and construction of additional movement bays, making them a cost-effective solution. Hughes et al. (2010) illustrates the most prominent designs of continuous flow intersections (Displaced Left-turn intersection), Median U-turn (MUT) intersections, Restricted crossing U-turn (RCUT) intersections, Quadrant Roadway (QR) intersections and Double Crossover Diamond (DCD) interchange. These designs are used when there are heavy left-turn movements (Right-turn in the case of the UK). Esawey and Sayed (2013) mention other designs such as the unconventional MUT, the Super Street Median (SSM), the Bowtie, Jughandle, Split intersection, Upstream Signalised Crossover (USC) and the Parallel Flow Intersection (PFI). Very recently, a new innovative design called Contraflow Left-turn Lane (CLL) has been introduced and implemented in over 50 locations in China, which relies on reversible lane design (Zhao et al. 2018).

Hughes et al. (2010), Hummer and Reid (2000) and Jagannathan and Bared (2004) have demonstrated that displaced left-turn intersection (DLT) outperforms other alternative designs, in terms of requirement of right-of-way and traffic handling capacity. The DLT/continuous flow intersection can handle a wide range of turning and through traffic volumes, and requires the least right of way, as the required space is confined to a rectangular intersection area 40’ by 300’ (Hummer and Reid 2000). The other designs require wider/lengthier right-of-way, which is hard to obtain in the case of an urban environment.

An adaptation of the DLT, which is the displaced right-turn (DRT), was demonstrated by Simmonite and Chick (2004) for the A4311 Motorola junction in England and concluded that it can be adapted to the UK road conditions. The design introduces a crossover node (minor intersection) placed at a certain distance upstream of the existing main signal block (main intersection) and a displaced lane across the opposing traffic lane. Right-turning vehicles enter the displaced lane placed to the right of the opposing lane at the crossover node. The displaced right-turning vehicles then proceed to make the right-turn at the main intersection simultaneously with the through traffic from the parent stream. Thus, the design eliminates the conflict between the right-turning and opposing through traffic at the main intersection. A three-stage design in a conventional T-intersection would be reduced to two stages and three/four stages in a conventional crossroads to two (Simmonite and Chick 2004). The conceptual layout of a four-arm configuration of the design with DRT (UK-style) is shown in Figure 2. Red arrow in Figure 2 indicates the right-turning traffic and the blue arrow indicates the through-traffic movement.

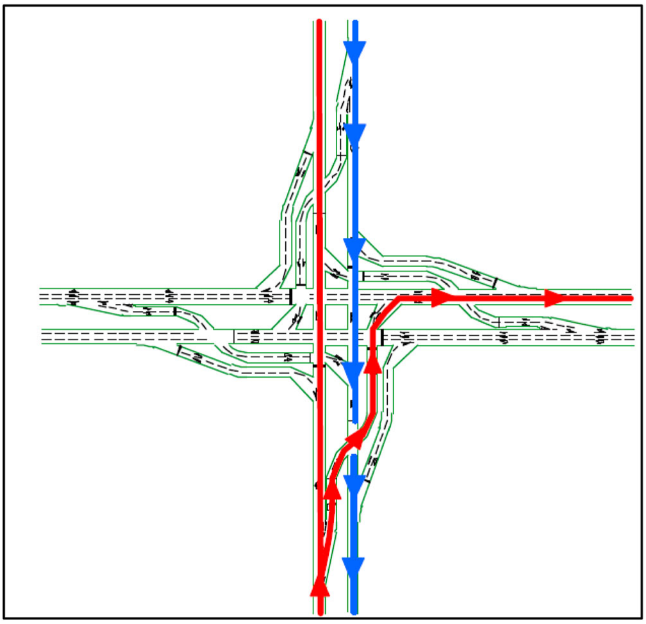

Figure 2. Movements in a full 4-arm DRT configuration (Source: Chick and Simmonite 2003).

Substantial qualitative research exists to prove that this design outperforms conventional intersections and a comparison against roundabouts has also been drawn by Chick and Simmonite (2003) to examine the potential improvement. Existing quantitative studies examine the operational performance by considering the impact of design variations in terms of right-of-way (ROW), the number of lanes, lane widths and length of storage bays (Esawey and Sayed 2013). Given the system of closely spaced intersections, spacing among the intersections to ensure coordination must be a key consideration (Chick and Simmonite 2003). Although the fact that the spacing should consider the trade-off between queue spillback from the main intersection and delays to traffic on displaced lanes has been acknowledged, guidelines to ascertain the distance are not well-developed yet.

A deterministic model showing the relationship between the length of displaced turn, green phase time and the travel time of vehicles through the intersection, developed by Carroll and Lahusen (2013) concluded that the traffic volume and the length of displaced turn together dictate the green times and offsets available for a particular movement. Once the geometry has been decided, cycle times must be adjusted to maintain coordination. Larger displaced length would be necessary in case of higher flows but beyond a certain limit, the operational efficiencies would be reduced (Pan et al. 2021). An argument that the capacity of displaced lane to hold the queue will vary depending on the signal timing offset and traffic demand compels us to consider the variation in length with an increase or decrease in traffic volume and the resulting signal optimisation to allow for the coordination. Pan et al. (2021) suggest that the right-turning proportion can be another variable in the analysis, as they have a significant effect on operational effectiveness. The increasing turning volume would eventually increase the utilisation of the displaced lane; hence it is meaningful to consider it in the mix. These conclusions open-up an opportunity for this study to explore the impact of variability in several design factors on operational performance and to develop tools to ascertain the possible combinations to aid the traffic engineers.

The evaluation of operational efficiency using measures of effectiveness is usually conducted at three levels, which are, 'Planning Analysis', 'Highway Capacity Manual Analysis' and 'Microsimulation Analysis' (Steyn et al. 2014). Microsimulation analysis has been the most used form of analysis. One of the notable studies by Jagannathan and Bared (2004) used micro-simulation analysis to develop a non-linear relationship between delay and queue length which depend on traffic flows. Jiang and Gao (2020); Wenrui et al.(2021) and Zhao et al.(2015) utilised different methods to develop optimisation models that calibrate the length of displaced turn with signal cycle time and offsets. However, these models consider very few variables, which seem inadequate considering the requirement of signal coordination, queuing and signal cycle time in the system of junctions in the design. It should be noted that the performance measures calculated may be exclusive to the design parameters and analysis network. Although microsimulation analysis is an effective tool, it would be a time-consuming and cost-intensive exercise to determine application feasibility. A quicker solution would be very helpful, especially in the pre-feasibility phase.

3. Methodology

LinSig software was used for junction modelling and simulation. LinSig is the UK industry-standard software for the design and assessment of traffic signal junctions, since 1985 (Moore 2010). For instance, Simmonite and Chick (2004) modelled the intersection located in Swindon on A4311 in England by utilising LinSig. The wider utilisation of LinSig in the UK indicates the practitioners' confidence in the underlying model and therefore, it can be used as a reliable predictor of measures of effectiveness which helps us to develop a statistical relationship. Simulation results were generated by feeding several combinations of signal cycle time, spacing of displaced turn and traffic flow to LinSig. The method used in this study differs from previous studies in a way that the simulation output is used to develop statistical relationships, by trusting the robustness of the underlying mathematical models, whereas studies conducted by Jiang and Gao (2020); Wenrui et al.(2021); Zhao et al.(2015) have either compared the results of their optimisation models to microsimulation outputs or mathematically developed relationships without the aid of microsimulation.

3.1 The framework of the study

Figure 3 depicts the steps involved in this study. An understanding of the displaced turn design in terms of available configuration was obtained through a literature review and a suitable one was adopted during the model building. The geometric features and signal design aspects were adopted from illustrations in previous works, as the signal phases and stages were designed to ensure coordination between the crossover nodes and the main intersection. The total traffic volume entering the junction, the directional split along arms and the proportion of left-

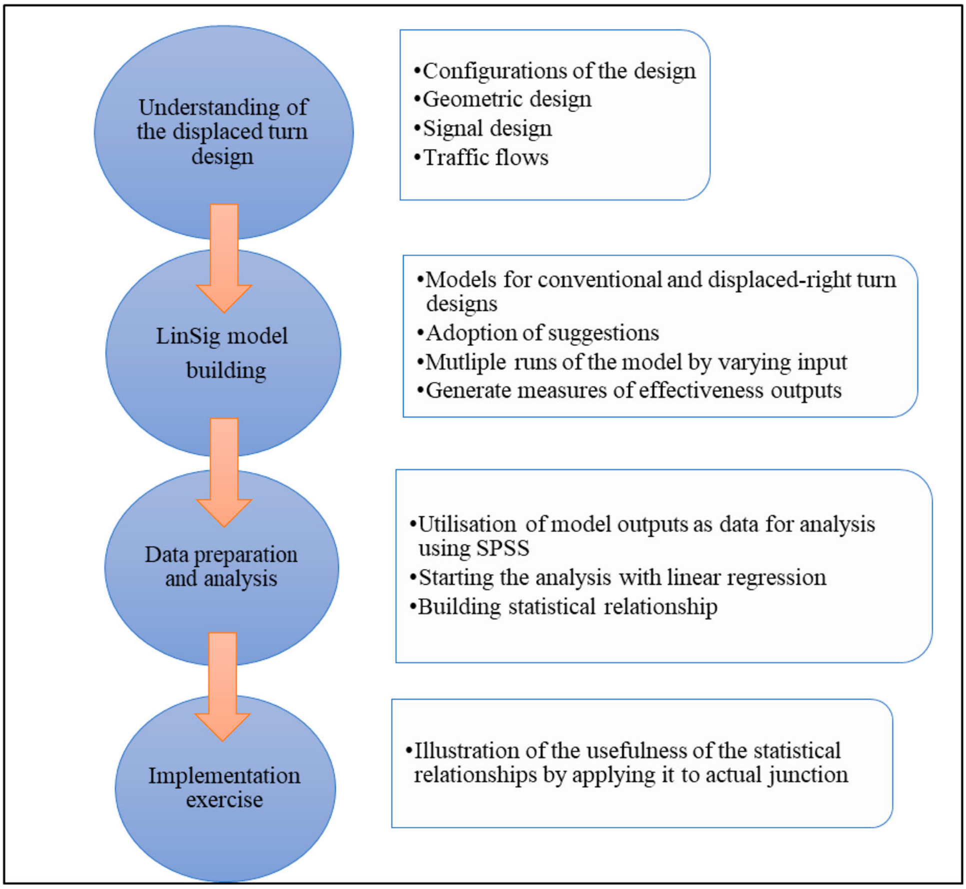

Figure 3. Structure of the study.

turning vehicles were inspired by the works of Jagannathan and Bared (2004); Dhatrak, Edara, and Bared (2010); Olarte and Kaisar (2011); Steyn et al. (2014); Wenrui et al. (2021). Three separate models were developed, one for a conventional 4-arm design and two models for two combinations of the DRT design. The conventional 4-arm design was modelled to enable comparison of results and identification of the benefit of DRT over a conventional design. Several combinations of the variables were incorporated into the DRT model and simulations were run. The resulting output in terms of performance measures was recorded for further analysis and structured into a format that can be used for statistical analysis in SPSS. The general linear regression model is considered a starting point to explain the relationship of performance measures with independent variables, although the relationship might not be linear indeed. Explanation of variables in question with statistical significance and to a good degree of fitness, measured by Coefficient of Determination (R^2) is the desired outcome. Furthermore, an illustration of the utility of these models was undertaken by applying them to an actual junction in the UK which is operating in congested conditions.

3.2 Junction modelling

A ‘Four-legged DRT intersection with major street displaced right and channelised left-turns on the major street’ with ‘channelised left-turn on minor roads’ was the chosen configuration among several available types. This type closely represents the common situation intended to be addressed by this design, where two major ‘A’ roads or a major ‘A’ road meets a minor road. Secondly, the channelised left-turn on minor roads can provide additional capacity in case the traffic increases on the minor road. Carroll and Lahusen (2013) support the utilisation of partial DLT (See the example in Figure 4) by arguing that this configuration is the most prominent, and more complex than a full DLT and so the results from this design are reliable. Therefore, a displaced right-turn adaptation of partial DLT was developed in this study.

The design was envisaged to address two types of possible combinations. Firstly, a 3-lane dual carriageway (D3AP) meets a 2-lane dual carriageway (D2AP). The displaced turns are placed on the 3-lane approach which carries the major traffic. Secondly, two 2-lane dual carriageways meet each other. In this case, the displaced turns are placed on the approach with higher traffic flow. A possible combination of two 3-lane dual carriageways was not considered based on the rationale that the existing practice which advocates a grade separation in such conditions, given that the flow would almost reach a level comparable to that of a motorway. In case this design has to be considered, the displaced turns have to be provided on both approaches, which will increase the land requirement. Anything beyond 3 lanes will be in the realm of motorways in the U.K, which cannot have at-grade junctions due to the function of high operational speeds.

An adaptation of the geometric dimensions from the work of Hughes et al. (2010) was used in model building, described in Table 1. The suggested distance (325’/99m) between the crossover node and the main intersection was not adopted as it is not feasible to keep this length always around 100m (Pan et al. 2021). Instead, this distance was considered as a variable with a range of values from 30 to 150m, with a 10m increment. It is important

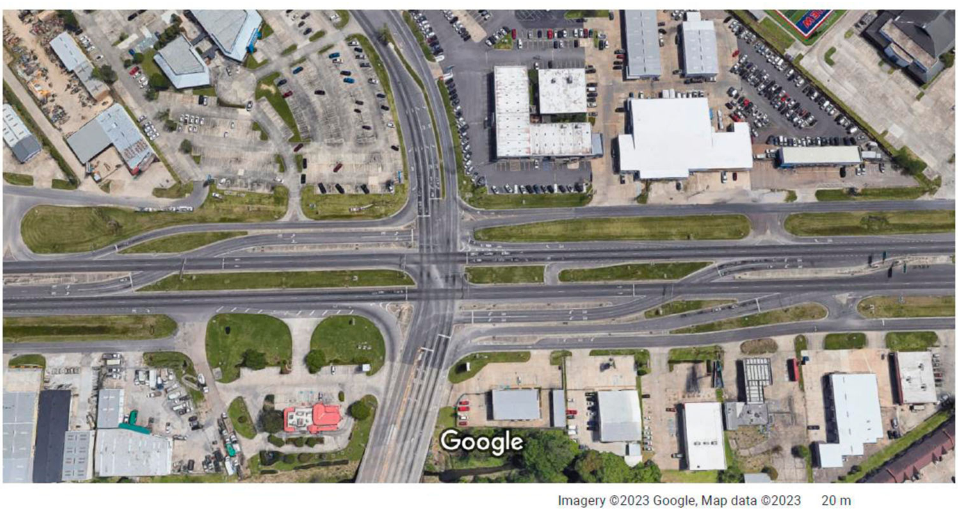

Figure 4. Partial four-legged DLT intersection in Baton Rouge, Los Angeles.

Table 1. Geometric dimensions.

Geometric feature	D3AP – D2AP intersection		D2AP – D2AP intersection	
	Length (metres)	Number of lanes	Length (metres)	Number of lanes
Major road	***3-lane dual carriageway***		***2-lane dual carriageway***	
Approach roads	500	3	500	2
Right-turn diverging section towards crossover	107	2	107	1
Channelised left-turns	66	1	50	1
Displaced right-turn – Variable	50–150	2	30–100	1
Minor road	***2-lane dual carriageway***		***2-lane dual carriageway***	
Approach roads	345	2	345	2
Left-turn bypass/Channelised left-turns	315	1	315	1

to note that this distance dictates the length of the displaced turn. The uniformity in the number of lanes before and after crossover increases the number of vehicles that can move across the junction in each green time (Jiang and Gao 2020) and so it is meaningful to use the same number of lanes on the displaced turn as the right-turn diverging section.

Any queue spillback from the displaced right-turn towards the crossover can block the opposing traffic in the next phase, hence, to ensure this, the maximum allowable queue on the two roads between the crossover node and the main intersection was set to a value of 75% of lane capacity. This is equivalent to a Queue Length Ratio of 0.75 as defined by Xianfeng et al. (2013) which was also recommended by Moore (2010). A saturation flow of 1800 Pcu/Hr has been utilised for the lanes entering a junction directly. For the other lanes, the saturation flow was unconstrained. The vehicles were coded in pcu (1 pcu = 5.75m). The mean cruise speed on the lane connectors was set at 35 km/hr.

The pedestrians cross the major road in two stages, by using the central refuge. The crossing across the minor road happens in a single movement, as the minor road width would be lesser. The crossing distance across the carriageways was calculated by adding the road widths (3.5 and 3.6 m widths used) and the time required by pedestrians to cross was calculated by considering an average speed of 1.2 m/s according to Traffic Signs manual Chapter-6 (Department for Transport 2019).

The developed DRT junction network for the D3AP – D2AP and D2AP-D2AP intersections are shown in the Appendix. The roads from the east and west are the major roads with displaced right-turns and channelised left-turns. The roads from the north and the south are minor roads with left-turn bypasses.

3.3 Development of scenarios for simulation

Total traffic flow entering the junction arbitrarily ranged from 5000 pcu/Hr up to 7000 pcu/Hr with an increment of 500 pcu/hr, for the D3AP-D2AP intersection. Based on the summary of typical values of the volume splits (V_{Major}/V_{Minor}), Directional Distributions (DD) and turning proportions used in similar studies by Esawey and Sayed (2013), the most commonly used values were generated, and the traffic flow was further structured for use. The total traffic volume was split with two different ratios (60/40 and 70/30), hence giving two values at a particular flow level. The DD within the major road/ minor road is usually split equally. That is, the major road volume is equally distributed between the two approaches and similarly for the minor road. The proportion of right-turning volumes increased with an increase in volume, based on the expectation of an increase in delay with the increase in turning volumes regardless of the intersection type (Abdelrahman et al. 2020). Unbalanced conditions were created by using two different turning proportions for the major and minor roads. The unbalanced conditions can test the DRT design for its capacity to handle variations in traffic demand. Based on these flows, flow groups were developed for input into the model. For the D2AP – D2AP intersection, variation in the lower flow range of 3000–4500 pcu/Hr was introduced, anticipating that this intersection would be suitable for a lower traffic volume range and flows beyond 5000 pcu/Hr will not be suitable.

The DRT design requires three sets of signals to be coordinated for the major road, i.e. two at the crossover nodes and one at the main intersection. The signals at crossovers operate over two phases and the signal at the main intersection can have a different number of phases based on the design. In this study, three phases were used. The phase and stage sequence was developed using the principles followed in practice and are shown in Figure 5. The intergreen times were calculated according to Traffic Signs Manual (Department for Transport 2019). After these signal settings, the model was ready for simulation and optimisation.

The two performance indicators used in this study are the Practical Reserve Capacity (PRC) in % and Overall Delay in PcuHr. PRC is a measure of how much more traffic could pass through a junction whilst maintaining a maximum degree of saturation of 90% on all links. Negative PRC indicates that the junction is oversaturated and queues will form. Overall Delay is the total aggregate delay experienced in the modelled junction by all traffic expressed in PcuHr. Since the DRT design requires signals at the crossover node to be coordinated with the signal at the main intersection, varying the signal cycle times for different flow groups will generate different values of PRC and Delay. Hence, the cycle time was considered a variable and a range starting from 60s up to 120s was used. Simulation runs were set up with possible discrete combinations of 22 flow groups, 13 displaced lengths (30–150 m with 10m increment) and seven cycle times (60–120 s with 10s increment).

As delay minimisation and coordination is the key requirement of the design for reducing the number of stops, *green splits and offsets were optimised* for Delay. A simple model representing a traditional signalised intersection was also developed for a D3AP

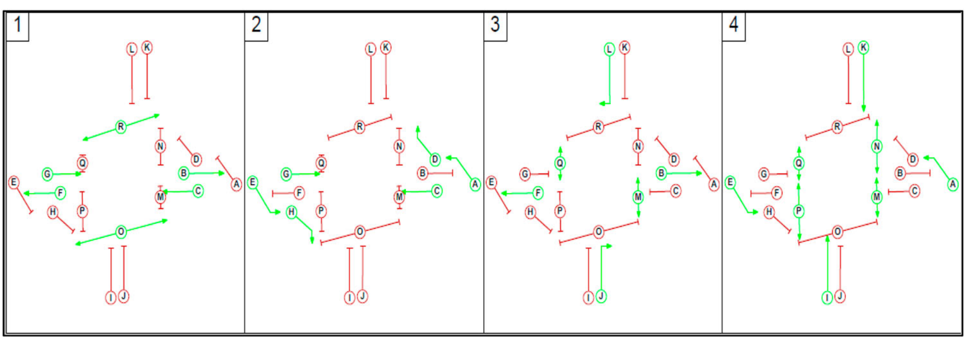

Figure 5. Stage diagram for DRT.

road meeting a D2AP road. Each run provided a value for PRC and Delay and the obtained values from both models were recorded for further analysis.

3.4 Statistical modelling

Building regression models will help us in establishing a mathematical relationship, which can explain the behaviour of performance indicators with variations in the discussed geometric, traffic and signal parameters. Here, the performance indicators (PRC and Delay) are the dependent variables. The major and minor road flows are the first two independent variables derived based on volume split ratios. The variation in the proportion of right-turning volume from the major road was introduced to study the response of PRC/Delay to the increasing number of vehicles that would use the displaced right-turn, which will be the third independent variable. The variation in cycle time and displaced turn length makes them the fourth and fifth independent variables.

A general linear regression model has the form shown below, and the study aims to build the least squares multiple linear regression of this form.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon$$

where,

y is the dependent variable,

β_0 is the intercept,

β_1–β_k are the partial regression coefficients for 'k' number of independent variables and x_1, x_2, … x_k are the independent variables.

The variable x may have a linear relationship with the dependent variable, or it can be mathematically transformed to allow the general linear form of analysis. The analysis starts with the assumption that the relationship between the dependent variable and the independent variables is linear, any non-linearity being identified subsequently by either lack of goodness of linear fit, shape of the residuals or shape of the scatter plot between the dependent and each independent variable taken separately (Black 2010). The regression analysis results were examined for significant 't' values of the partial regression coefficients and the overall significance of the model, observed through significant 'F' values. Homoscedasticity, normality of the residuals and multicollinearity were examined to check for any violations. Jagannathan and Bared (2004) used an exponential relationship between Delay and traffic flows. This observation can help us while considering the relationship of Delay between the major road and minor road flows. A logarithmic transformation of left-turning volume coded within the general linear model with Delay as the dependent variable was statistically significant with an R^2 of 0.58 (Abdelrahman et al. 2020). Based on these studies a non-linear relationship can be expected for the overall Delay. The stepwise method was employed for model building.

4. Numerical results

4.1 Performance of DRT vs conventional intersection

For comparing the performance of conventional intersection and the DRT model (D3AP-D2AP intersection), a traffic volume ranging from 2000 to 5000 pcu/Hr was used, with an increment of 500 pcu/Hr. The purpose of this comparison is to assess the range of flow levels which a conventional intersection can handle beyond which the DRT may prove advantageous. To compare both the designs, 80s cycle time was selected, as substantiated by a similar finding by Jagannathan and Bared (2004), which was 82 s. The values of PRC and Delay over the traffic volume range of 2000–5000 pcu/Hr were obtained from the simulation and plotted as shown in Figure 6 and Figure 7.

At lower traffic, both DRT and conventional designs perform well in terms of PRC and Delay. A very high PRC for DRT design (176%) at 2000 pcu/Hr indicates that it would be unnecessary at low traffic volumes. The actual need of DRT seems to be arising from a flow level of 3500 pcu/Hr, where the conventional design starts getting highly congested (Negative PRC and increasing Delay). As the junction reaches a high degree of saturation, the ability to move the traffic smoothly across the junction reduces. The ability of the DRT to maintain higher PRC is due to the capacity of displaced-turn to hold the turning traffic and eliminate the conflict at the main junction. At 5000 pcu/Hr, clearly DRT outperforms the conventional design, as the latter deteriorates to negative PRC and the Delay is almost 10 times that of DRT. A similar result was obtained from the comparison made by Jagannathan and Bared (2004), which revealed that the delay in conventional intersections start increasing rapidly from 3200 vehicles/Hr. The delay rapidly escalates in conventional design because there is a continuing presence of a queue at the junction and the vehicles joining the queue may not be cleared in a single cycle, which compounds the delays due to oversaturation. The advantage of this design is most pronounced when traffic demand approaches or exceeds the capacity of conventional designs and when heavy right-turn movements require protected phases (Goldblatt, Mier, and Friedman 1994). The DRT starts to shine from 5000 pcu/Hr, which retrospectively supports the decision to start traffic flows in DRT model runs from that level.

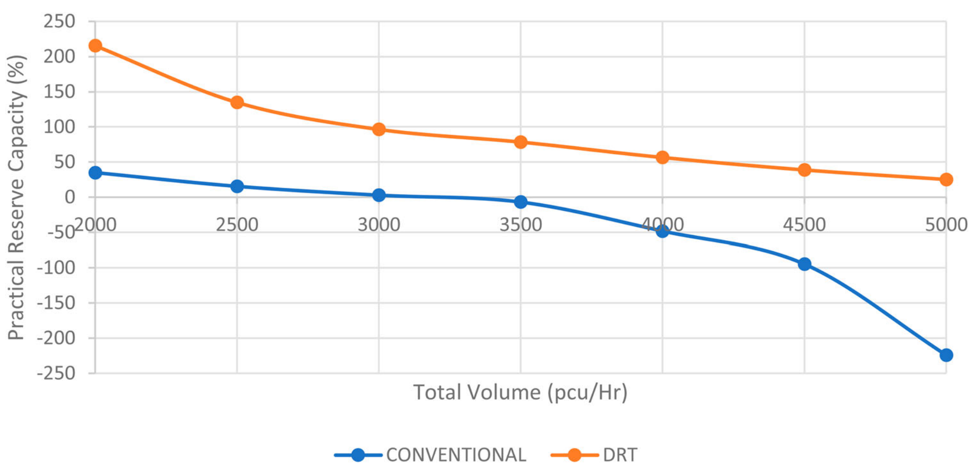

Figure 6. Practical Reserve Capacity in DRT and conventional designs.

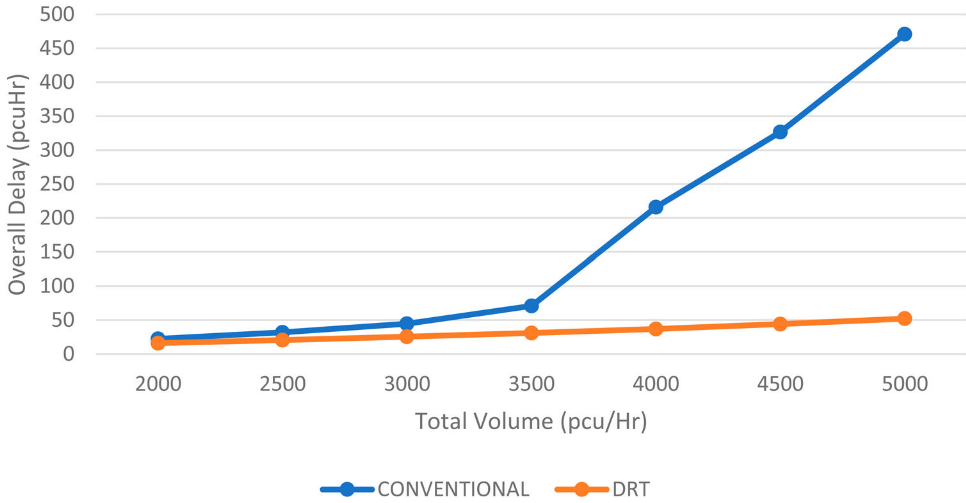

Figure 7. Delay in DRT and conventional designs.

4.2 Statistical models for estimating PRC and delay of DRT designs

The purpose of simulation is to generate a set of responses as measured by PRC and the Delay for a range of input flow levels combined with various displaced turn lengths and signal cycle times as described in Section 3.3 earlier. A few inferences could be made from the initial review of the output. The D2AP-D2AP intersection was highly congested at 4500 pcu/Hr. Across all traffic flow levels, both configurations could not work with 60s cycle time but improved from 70s, as noted by consistent negative PRC and high delay values were observed. Hence the corresponding PRC and Delay data points were excluded from analysis by deeming the 60s cycle time as unworkable. At a traffic volume of 7000 pcu/Hr, the 70s cycle time also produced a systematically high level of congestion, which was also excluded from the analysis. These exclusions were necessary for refining the datasets as these data points could become outliers and can negatively influence the regression analysis, which is sensitive to outliers. For low traffic volumes, shorter displaced-turn lengths were sufficient to produce positive PRC. As the traffic flow increases, the performance of a design increases with an increase in the length of the displaced turn. At a high flow value of 7000 pcu/Hr, a minimum length of 120m is required along with higher cycle times (100s, 110s or 120s) to provide positive PRC and low delays. These observations were consistent with Jiang and Gao (2020); Pan et al. (2021), who found that with increasing lane length, the capacity of the junction and the number of vehicles entering the displaced lane increase. However, a marginal performance improvement is expected after a certain length thus indicating that the length should only be increased up to a point where satisfactory performance is achieved. For the D2AP-D2AP intersection, any change in displaced length beyond 100m produced no improvement. We can conclude that the D2AP – D2AP intersection works for low volume range with shorter displaced lanes compared to the D3AP – D2AP intersection.

The structured dataset was carried into SPSS for regression analysis. The purpose of the analysis is to develop tools which can help traffic engineers to be able to predict the performance of DRT without needing them to setup and run resource-intensive simulation models. A least-squares multiple linear regression analysis was carried out with *PRC* as the dependent variable and five independent variables, which were *major road flow (pcu/Hr), minor road flow (pcu/Hr), the proportion of traffic turning right from the major road (%), cycle time (seconds) and the length of displaced turn (metres).* In the case of D3AP – D2AP intersection, although the first model had a high adjusted R^2 and was statistically significant, it had high multicollinearity among the independent variables verified by the variation-inflation factor (VIF). A multiplicative term of major road flow and minor road flow was introduced, as high VIF was observed in these terms. The next iteration of regression reduced the VIF to below 10, thereby suppressing the multicollinearity and retaining the normality of the residuals. The normality P–P plot and histogram of residuals are shown in Figure 8 and histogram of residuals is shown Figure 9.

As the presence of heteroscedasticity was observed in the residuals scatter plot, stepwise weighted least squares regression was used as a remedial measure, as suggested by Su, Yan, and Tsai (2012). A new model was generated and the ANOVA table for the four steps in the model-building is shown in Table 2. The final model had all five independent variables as predictors. The overall model is statistically significant, as indicated by the *F*-value of 1730.005 at $\alpha = 0.01$. The adjusted R^2 was very high with a value of 0.916. The details of the coefficients from the stepwise model-building process are shown in Table 3. In the fourth and final model, the t-values of the constant and the partial coefficients of regression were statistically significant at $\alpha = 0.01$.

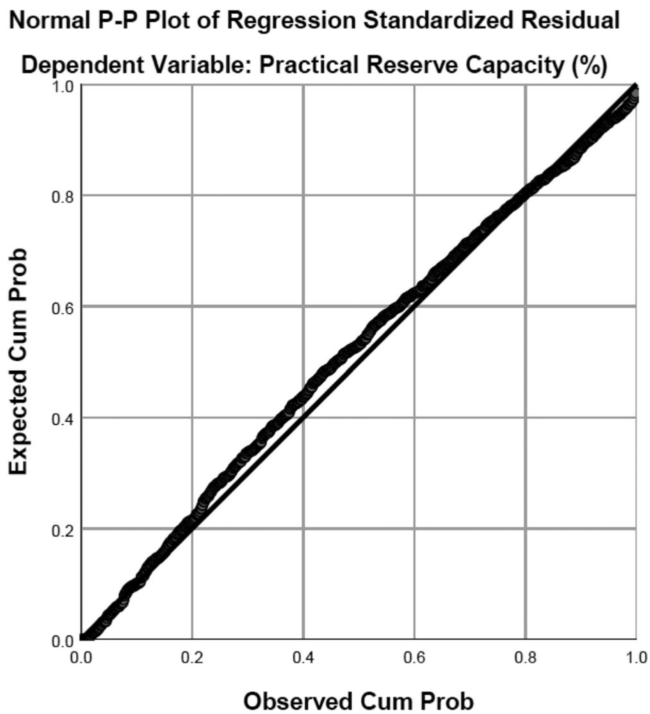

Figure 8. Normality P–P plot and histogram of residuals.

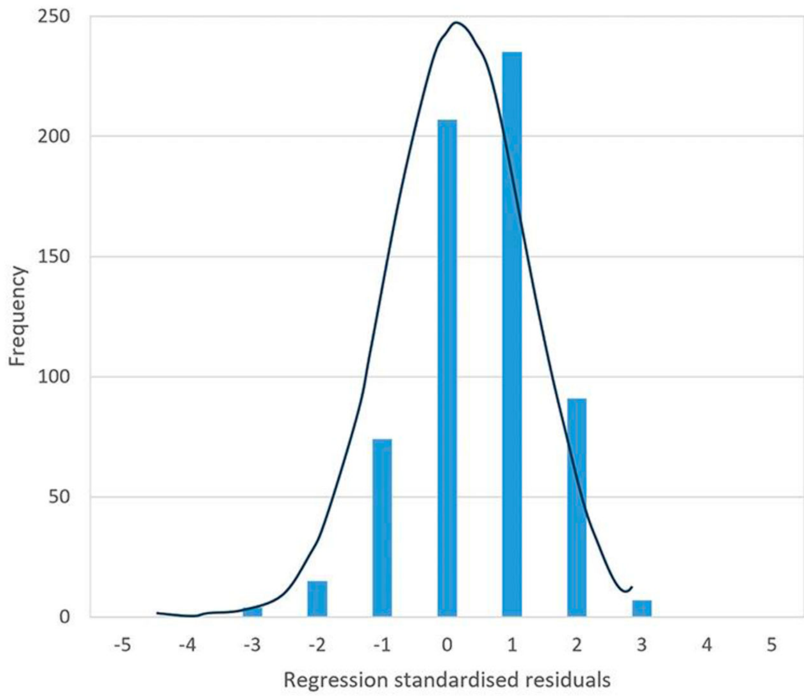

Figure 9. Histogram of residuals.

The resulting regression model with PRC as the dependent variable and five independent variables is expressed by the equation below, for the D3AP-D2AP intersection.

$$PRC = 105.359 - (3.88 \times 10^{-6} * MaRF * MiRF) - (246.395 * PRT) + (0.258 * CT) + (0.108 * DL) \quad (1)$$

where, PRC is the Practical Reserve Capacity, $MaRF$ is the Major Road traffic flow, $MiRF$ is the Minor Road traffic flow, PRT is the proportion of major road traffic turning right, CT is the signal cycle time, DL is the Length of the displaced turn.

Table 2. ANOVA of weighted regression for PRC.

Model Iteration	Predictor variables	*F*-value	Significance (α=0.01)
	D3AP – D2AP intersection		
1	Major x Minor road flow	2012.538	0.000
2	Major x Minor road flow, Cycle time	1613.7	0.000
3	Major x Minor road flow, Cycle time, Length of displaced lanes	1490.4	0.000
4	Major x Minor road flow, Cycle time, Length of displaced lanes, Proportion of turning volume	1730.005	0.000
	D2AP – D2AP intersection		
1	Major x Minor road flow	450.437	0.000
2	Major x Minor road flow, Cycle time	458.601	0.000
3	Major x Minor road flow, Cycle time, Length of displaced lanes	712.982	0.000
4	Major x Minor road flow, Cycle time, Length of displaced lanes, Proportion of turning volume	608.992	0.000

Table 3. Partial regression coefficients of weighted regression for PRC.

Predictors	Unstandardised coefficients B	Standard error	*t*-value	Significance (α=0.01)
D3AP – D2AP intersection				
Constant	105.359	4.33	24.334	0.000
Major × Minor road flow	−3.882E-06	0.00	−19.027	0.000
Cycle time	0.258	0.11	23.252	0.000
Length of displaced lanes	0.108	0.006	17.504	0.000
Proportion of right-turning volume	−246.395	14.148	−17.416	0.000
D2AP – D2AP intersection				
Constant	63.465	8.484	7.48	0.000
Major × Minor road flow	−1.978E-05	0.000	−38.272	0.000
Cycle time	0.458	0.021	22.043	0.000
Length of displaced lanes	0.323	0.015	20.857	0.000
Proportion of right-turning volume	−154.132	21.72	−7.096	0.000

A similar process was followed for the D2AP-D2AP intersection model. There were no multicollinearity and heteroscedasticity issues. The resulting regression model with adjusted R^2 of 0.849 is as shown below:

$$PRC = 63.465 - (1.978 \times 10^{-5} * MaRF * MiRF) - (154.132 * PRT) + (0.458 * CT) + (0.323 * DL) \quad (2)$$

The PRC decreases as the traffic flow increases, which is evident in the model. As more traffic enters the junction, the capacity of the junction to handle reduces, which is very much the case in conventional designs also. The proportion of the right-turning volume from the major road negatively affects PRC. As the right-turning proportion increases, the volume entering the displaced turn increases. The green time for the displaced turn can only accommodate a certain volume without affecting the next stage. As a result, a few vehicles which have crossed over to the displaced turn, fail to make it through the green available at the main intersection and must wait for the next cycle. The positive effect of the increase in cycle time on PRC was revealed earlier while studying the cycle time optimisation for the DRT design, which is reflected in this model as well. However, careful attention must be given to the delay which increases with cycle time. The length of the displaced turn also has a positive effect on PRC. This pattern was earlier understood from the works of Jiang and Gao (2020); Pan et al. (2021). As the length of the displaced turn increases, more vehicles can be accommodated within the intersection. At higher flows, higher lengths are required to have positive PRC.

A least-squares multiple linear regression was developed for Delay as the dependent variable and the five independent variables mentioned as earlier. Although the overall model and the coefficients were statistically significant, the residuals were not normally distributed and showed the presence of heteroscedasticity, which violates the assumption of linear regression rendering the model invalid. The scatter plot showed a large deviation from the expected pattern of equal variance, indicating the probability of a non-linearity of the relationship. Hence, non-linear relationships were explored further for Delay using the curve-estimation function. The best fit for the delay with major road flow, minor road flow and the proportion of right-turning volume was an exponential relationship. The cycle time and the length of displaced turn variables could be fitted with both linear and exponential relationships, but the exponential relationship was chosen to maintain uniformity. The major and minor road flow variables showed the best exponential fit among all the five variables. When the two variables were combined multiplicatively, the resulting exponential fit had a much higher value of R^2. The resulting model are described below:

For the D3AP-D2AP intersection:

$$Delay = 28.157 + exp^{[(6.906 \times 10^{-3} * MaRF * MiRF) + (8.379 * PRT) - (0.002 * CT) - (0.003 * DL)]} \quad (3)$$

For the D2AP-D2AP intersection:

$$Delay = 31.093 + exp^{[(1.253 \times 10^{-6} * MaRF * MiRF) + (4.467 * PRT) - (0.24 * CT) - (0.007 * DL)]} \quad (4)$$

Equations (3) and (4) had an R^2 value of 0.897 and 0.847 respectively, providing a good explanation for variance in the dependent variable. The application of R^2 is mainly to linear regression, however with very few outliers, the pseudo-R^2 can be applied to non-linear regression as well (Kvalseth 1985, cited in Jagannathan and Bared 2004, 6). To check the ability of the model to predict the delay values, the recorded values from LinSig were plotted against the predicted values from the model (Figure 10). The scatter-plot shows that the recorded and predicted values cluster together at the lower to mid-range of delay. But they begin to scatter at higher values of delay beyond 110 pcuHr. The higher values of delay are apparent at higher total traffic volumes of 6500 and 7000 pcu/Hr. Therefore, this model can be used with confidence up to 6500 pcu/Hr and caution must be exercised when applying this model for traffic volumes beyond.

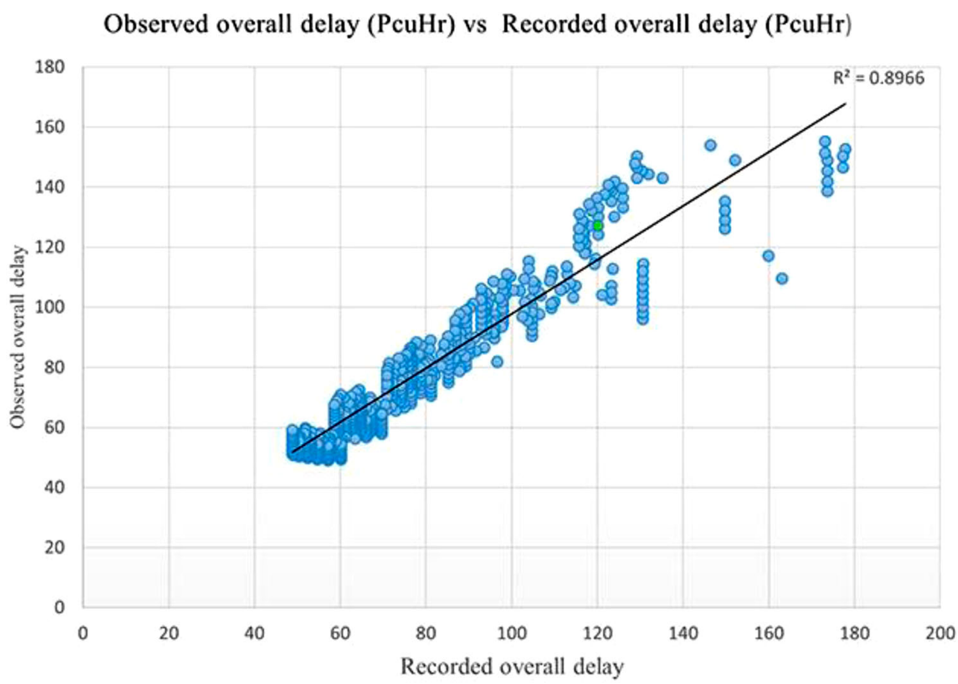

Figure 10. Scatterplot of recorded delay values vs. predicted values.

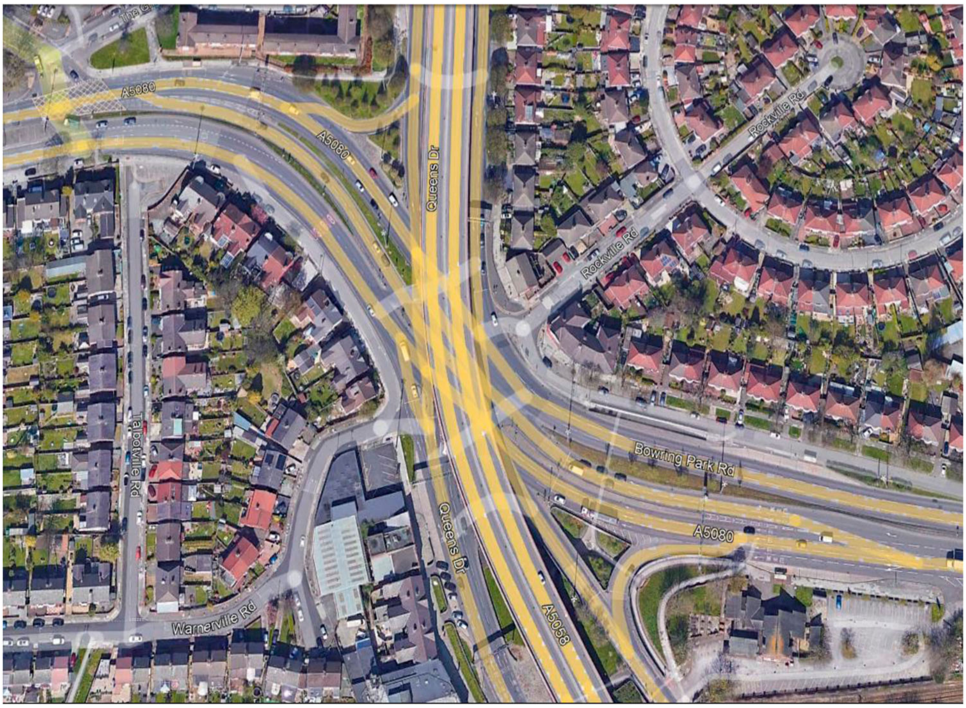

Figure 11. Google earth image of the A5080 and A5038 junction, Liverpool, UK.

4.3 Utility of the models

To illustrate the use of the models developed for a practical application, junction A5080 W (J4) at A5058 Broad Green (Figure 11) in Liverpool, UK was considered, which is a four-arm junction experiencing severe congestion (Inrix 2014).

Over 100,000 vehicles a day use this junction with many of them accessing the Motorway M62 (Highways England 2019). A traffic signal-controlled gyratory along with a new dual-lane tunnel was proposed as part of a major junction redesign at an estimated cost of £120m. Perhaps, a displaced right-turn design can help reduce the congestion at a much lower cost. A5080 was considered the major road and the A5058 the minor road, based

Table 4. Peak hour traffic on A5080 and A5058.

	Peak hour traffic (pcu/Hr)						
Road description	Pedal cycles	Two wheeled motor vehicles	Cars and taxis	Buses and coaches	Light goods vehicles	Heavy goods vehicles	Total
Major road – A5080 – Westbound	0.6	1.3	1182.2	4.9	276.6	178.7	1644
Major road – A5080 – Eastbound	0.6	1.1	925.7	10.6	245.0	90.2	1273
Minor road – A5058 – Northbound	0.6	1.5	887.7	11.1	199.5	78.9	1179
Minor road – A5058 – Southbound	0.6	1.5	899.9	11.9	192.8	82.9	1190
Total volume							**5286**

Source: DfT 2021.

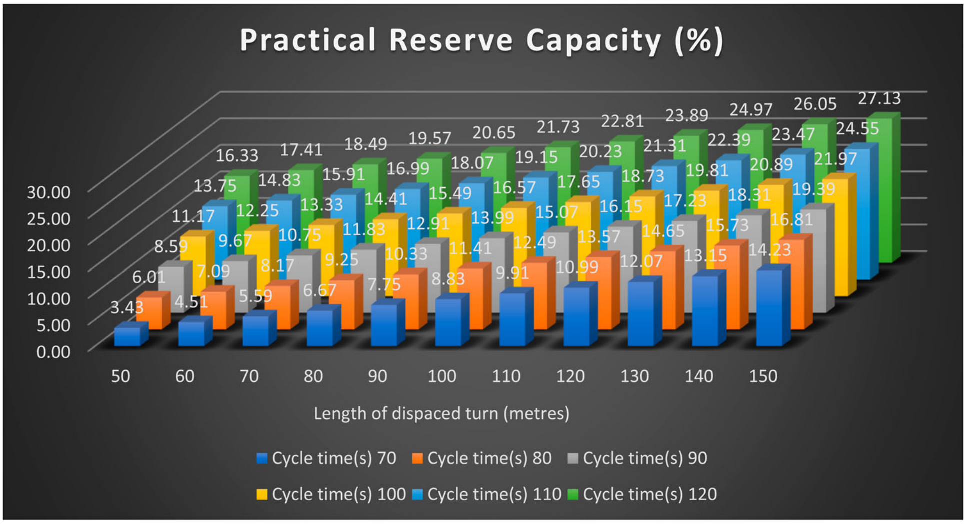

Figure 12. PRC for variable cycle time and displaced lane length.

on the annual average traffic counts obtained from the road traffic estimates (DfT 2021). Table 4 shows the peak hour traffic on A5080 and A5058, obtained by converting the AADF to peak hour traffic by applying a factor of 7% and converting them to pcu units considering HGVs and other vehicle types (Transport for London 2021).

The total traffic volume is beyond the 5000 pcu/Hr mark that the DRT aims to handle. The proportion of right-turn from the major road was assumed at 35%, as there was no data available. The cycle times varied from 70s to 120s and the length of the displaced turn varied from 50m to 150m. These values were input into the PRC and Delay models for D3AP-D2AP design to generate the likely outcomes (Figure 12 and Figure

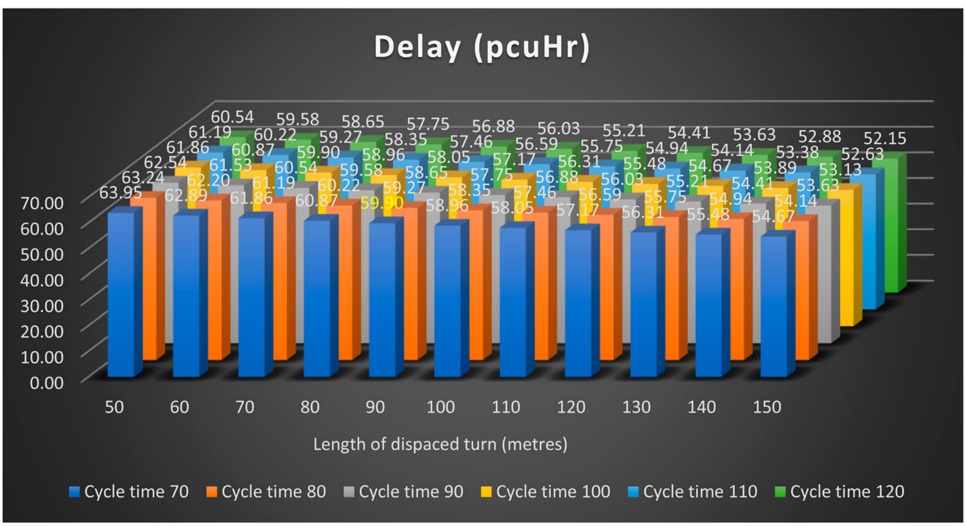

Figure 13. Delays for variable cycle time and displaced lane length.

13). Considering the existing right-turn auxiliary lanes and the distance of the stop line at the junction, a maximum of 90m length of displaced turn can be accommodated in the design. There are existing channelised left-turns on A5080, which reduce the amount of land take-up and the displaced turn can be introduced within the existing right-of-way. For a 90m displaced turn length and a cycle length of 70s, a PRC of 7.75% and a Delay of 59.9 pcuHr can be achieved. These models can predict possible improvements for different combinations of variables and can be compared with the values from the existing congested conditions to judge the feasibility of implementing the design, without building resource-consuming simulation models.

5. Concluding remarks

Conventional junction improvement approaches have been found to be ineffective often and the cost-intensive grade separation solutions would be the last resort. Alternative/unconventional design can provide cost-effective and timely solutions to cater for the growing vehicle traffic. The study aimed to develop statistical models to predict the performance measures (PRC and Delay) for an unconventional DRT design as it was found to be versatile in practice.

Models have been developed for PRC and Delay for two intersections with different lane combinations, viz., D3AP meeting a D2AP, and D2AP meeting another D2AP by simulating the DRT with a wide range of input situations with varying flow, cycle time and length of the displaced turn. A weighted-linear regression model was developed for PRC (adjusted R^2 of 0.916 and 0.849, respectively) with four independent variables viz., a multiplicative term combining major and minor road flows, proportion of right-turns, cycle time and the length of the displaced turn. Considering the normality of residuals, a non-linear regression model with exponential relationship was developed for the Delay, which produced a pseudo R^2 of 0.897 and 0.847 for the two intersection combinations respectively.

The main conclusions from this work are as below. Conventional designs for D3AP-D2AP perform well at flow values such as 2000 pcu/Hr and up to about 3500 pcu/Hr they can produce positive PRC values indicating that they are not over saturated. Thereafter, the performance of conventional designs deteriorates rapidly making it necessary to consider alternative designs. The DRT design was found to be essential from a total traffic flow of 5000 pcu/Hr (D3AP-D2AP intersection), as the conventional design fails absolutely at this stage. On the other hand, conventional designs for D2AP-D2AP intersection would work well for low volumes of traffic and at flow levels of over 3000 pcu/Hr the junctions will be highly oversaturated needing an unconventional design to generate the additional capacity required.

The models developed were found to be robust and could reproduce the simulated results for a range of flow values such as 5000 pcu/Hr and up to 6500 pcu/Hr beyond which they need to be used with caution. The regression models developed in this paper can be used by practitioners to analyse the feasibility of DRT design and compare the performance with other solutions. A detailed micro-simulation study or model development can be avoided, as these regression models can provide reliable values of PRC and Delay, hence the decision-making process timely and cost-effective.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix: LinSig models of D3AP-D2AP and D2AP-D2AP intersections

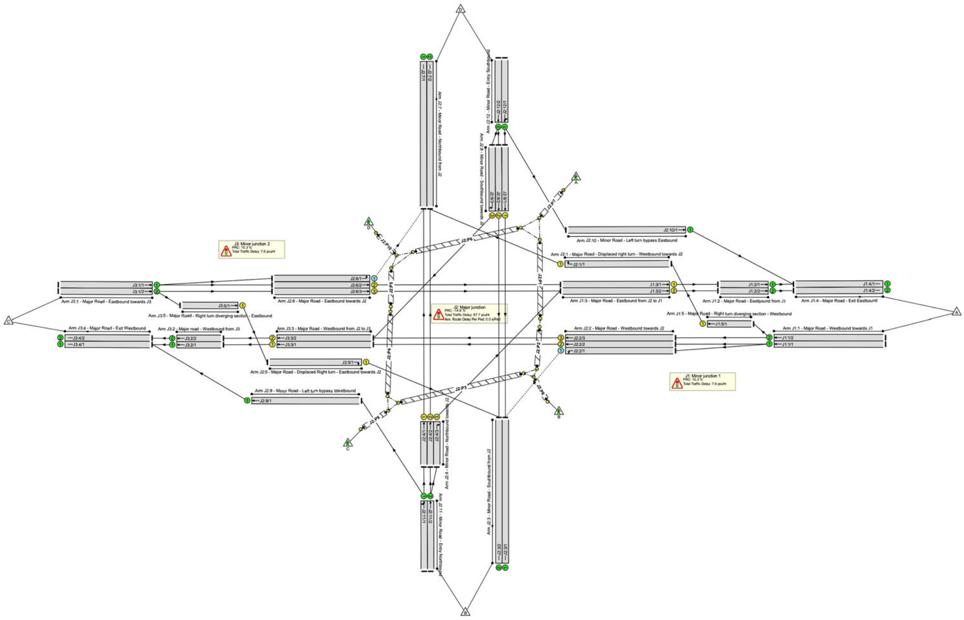

Figure A1. LinSig model of D2AP meeting D2AP.

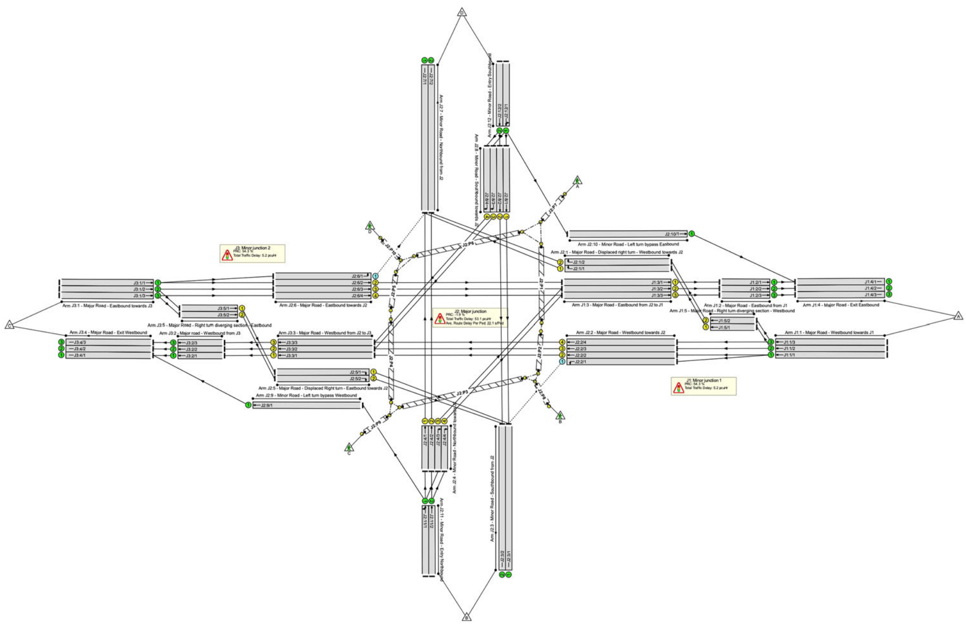

Figure A2. LinSig model of D3AP meeting D2AP.