# ASSESSMENT OF DIFFERENT URBAN TRAFFIC CONTROL STRATEGY IMPACTS ON VEHICLE EMISSIONS

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## Abstract

This paper investigates the influence of traffic signal control strategy on vehicle emissions, vehicle journey time and total throughput flow within a single isolated four-armed junction. Two pre-timed signal plans are considered, one with two-stages involving permissive-only opposing turns and the other with four-stages which has no conflicting traffic. Additionally, the increase in efficiency by utilising actuated signal timing where green time is re-optimised as flow values vary is investigated. A microscopic traffic simulation model is used to model flows and AIRE (Analysis of Instantaneous Road Emissions) microscopic emissions model is utilised to output emission levels from the flow data. A simple junction model shows that the two-stage signal plan is more efficient in both emissions and journey time. However, as the level of opposed turning vehicles and conflicting movement increases, the two-stage model moves to being the inferior signal plan choice and the four-stage plan outputs fewer emissions than the two-stage plan. A real-world example of a four-armed junction has been used in this study and from the traffic survey data and existing junction layout; it is recommended that a two-stage plan is used as it produces lower amounts of emissions and shorter journey times compared to a four-stage plan. The results also show that nitrogen oxides ($NO_x$) are the most sensitive to changes in flow followed by carbon dioxide ($CO_2$), Black Carbon and then particulate matter ($PM_{10}$).

## 1. Introduction

In an urban environment, there tends to be more motorised vehicles than in rural areas. This can be understood to be an increase in the overall quality of life of the residents in the form of increased mobility and comfort (1). However, the emissions due to traffic greatly impact the overall air quality in the vicinity of the carriageway. These emissions can induce a wide range of health issues to humans, especially respiratory problems (2-3). Various improvements in vehicles design specifically target pollutant emissions from vehicles such as catalytic converters and particulate filters (4).

Thus, if pollutant emissions can be reduced even further, it would be beneficial to residents in urban environments. Numerous studies have been performed in terms of traffic management with the aim of reducing pollutant emissions as well as congestion and delay.

One commonly used method of traffic management at intersection is signalized junctions. Signal retiming can potentially reduce traffic delays, cut down fuel consumption and lower total pollutant emissions (5). On the other hand, safety and efficiency are both key objectives when it comes to signal timing (6).

However, while being able to provide orderly movement and safe manoeuvring, the presence of traffic signals at a junction with periods of low flow may not be efficient as drivers experience delay at the traffic lights. At busy junctions however, the usage of traffic signals are well-accepted as a form of traffic management (7).

This paper focuses on signal timing aspect of traffic management and its impact on vehicle emissions and delay for a single isolated junction. The objectives of this paper is to investigate the effect of opposing turns and assess the influence of optimisation of signal timing parameters for four-stage signal plan and the permissive only two-stage signal plan on vehicle pollutant emissions (carbon monoxide, nitrogen oxides and particulate matter), journey times and total throughput flow within a single isolated traffic junction. This paper utilises the state-of-the-art traffic microsimulation model (S-Paramics) and the emissions model (AIRE) to simulate traffic flow and emissions.

## 2. Literature Review

In order to minimise emissions, the main sources need to be identified. Pollutant emissions are known to be significant at traffic junctions. The accelerations and decelerations cause variable speeds which have a detrimental effect on the air (8).

Substantial previous research has addressed the signal timing and phasing of an isolated signalised junction with aims to minimise impacts such as delay and emissions. For a single junction in Nanjing City, a signal timing model was proposed to obtain an optimised solution for cycle length. This was performed with a performance index function, taking into account weighted factors of delay, fuel consumption and vehicle emissions. The hydrocarbon, carbon dioxide and nitrogen oxides emissions are expected to decrease by 2.69, 2.9 and 1.05% respectively (9). This paper only reviews the changes and impacts from varying cycle length. Additionally, for an isolated junction, Li et al. (10) utilised optimisation models to identify the relation between delay and the number of stops and vehicle emissions. It is found that the lower the number of stops, the carbon dioxide, hydrocarbon and nitrogen oxides emissions increase due to the increased delay. Using a simulation of an isolated signalised junction, the optimisation of the phase ordering of the traffic signals can result in up to a 40% reduction of stopped delay per car as well as savings of up to 100 gallons of fuel per signal in a

day (11). Barnes simulated a left-priority phase ordering with a straight-priority phase ordering and compared them. It should be noted that these values are dependent on the arrival rate and the amount of reduced delay and fuel savings will differ along with the flow. Instead of utilising signalised junctions, the implementation of roundabouts is an alternative and effective method to reduce emissions. With this change, it is possible to decrease pollutant emissions significantly, CO by 29% and $NO_x$ by 21% (12). This was done by utilising traffic counts and emulation vehicle driving behaviour in the Swedish town of Växjö. The main issue with roundabouts is that they are only applicable in low traffic flow densities (13).

In summary with regards to isolated junctions and traffic corridors, isolated junctions were investigated by Li et al. (9) to highlight the effects of cycle length, Li et al. (10) identified the relation between delay, number of stops and emissions and Barnes and Paruchuri (11) explored the impact of optimization of phase ordering. In terms of traffic corridors, Lv and Zhang (14) studied the effect of varying cycle lengths and offsets on emissions and delay, Zhang et al. (15) compared the emissions between two roads, one coordinated and the other not, De Coensel et al. (16) analysed the effect of implementing a green wave on emissions. However, there are limited studies on the efficiency of signal plans in terms of vehicle emissions and journey time given variations in flow. In a single day, the flow is not expected to stay constant throughout. For example, total flow and the turning ratio proportions could vary. This paper aims to investigate that by comparing two signal plans for an isolated four armed junction given variations in the percentage of right turning traffic as it would be the critical turning movement and variations in total flow as well as total flows deviating from the design flows.

# 3. Modelling tools

## 3.1 Microsimulation Model

To model the traffic flows through the junction, this paper utilises a microscopic simulation approach via S-Paramics. Microscopic simulations are able to output detailed information about vehicles including the influence of driving behaviour such as accelerations and idling. Thus, a better resolution solution can be formed to measure the impacts on driving behaviour and consequently, more realistic results from signal timing changes (17).

Only by analysing individual vehicles can the effect of congestion and driver behaviour can be properly simulated (18). This can be prevalent in terms of emissions as levels of carbon monoxide and nitrogen oxides can be significantly higher during acceleration compared to emissions during cruising and idling (15). Fleet composition is also taken into account due to the presence of heavy goods vehicles, trucks and buses which have higher emission rates.

## 3.2 Emission Estimation Model

In order to calculate the emissions output from the traffic in the model, the AIRE (Analysis of Instantaneous Road Emissions) model is chosen. AIRE utilises Instantaneous Emissions Modelling (IEM) tables derived from Passenger car and Heavy Duty Emissions Model (PHEM) to estimate emissions from simulated vehicles.

AIRE is able to interface natively with Paramics and takes into account traffic composition and vehicle data. At every time step of the simulation, AIRE uses dynamic data for each individual vehicle within the network and outputs the amount of nitrogen oxide, particulate matter and total carbon. Compared to traditional average-speed based methods, AIRE is able to output more detailed estimates (17).

# 4. Methodology

## 4.1 Construction of Hypothetical Junction

Firstly, an isolated junction with four arms is modelled with S-Paramics. In order to represent a common junction, each arm consists of two entry and two exit lanes as shown in Figure 1. In UK, the left-hand driving rule is applied. The opposing turns at the junction are generally the right turns.
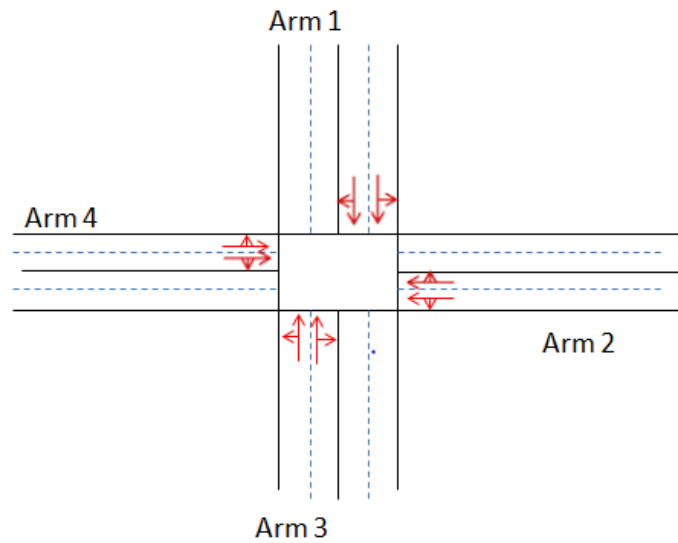
**FIGURE 1: Simple Isolated Four-Arm Intersection**
**Showing Allowed Turns**

Each lane is 3.65 meters wide and each arm is modelled to be straight and 500 meters in length. The road gradient of all links is assumed to be zero. The traffic fleet composition is also assumed to consist completely of cars representing one passenger car unit (PCU) each although an assessment on the effects of HGVs on emissions is also conducted. Loop detectors are placed at the end of the exit lanes to detect the flow leaving the junction. The model of the junction is designed to be generic and could be applied to a variety of cases.

Figure 2 shows the movements for each stage for the four-stage and two-stage plan. Each plan also includes an additional pedestrian stage where all lanes are met with a red signal, allowing pedestrians to cross without worry. The four-stage plan allows all movements (left turns, straight ahead and right turns) to move unopposed during the green period. The two-stage plan is a permissive only case where the drivers wishing to make a right turn are opposed by the conflicting traffic by the straight ahead traffic from the opposite arm.

The right turners are of a lower priority and must give way to the conflicting movements. Right turning movements are only directly conflicting with the straight through movements of the opposing arm as opposing right turning vehicles may pass each other offside to offside and opposing left turning vehicles may turn into the left exit lane while the right turning vehicles may turn into the right exit lane.
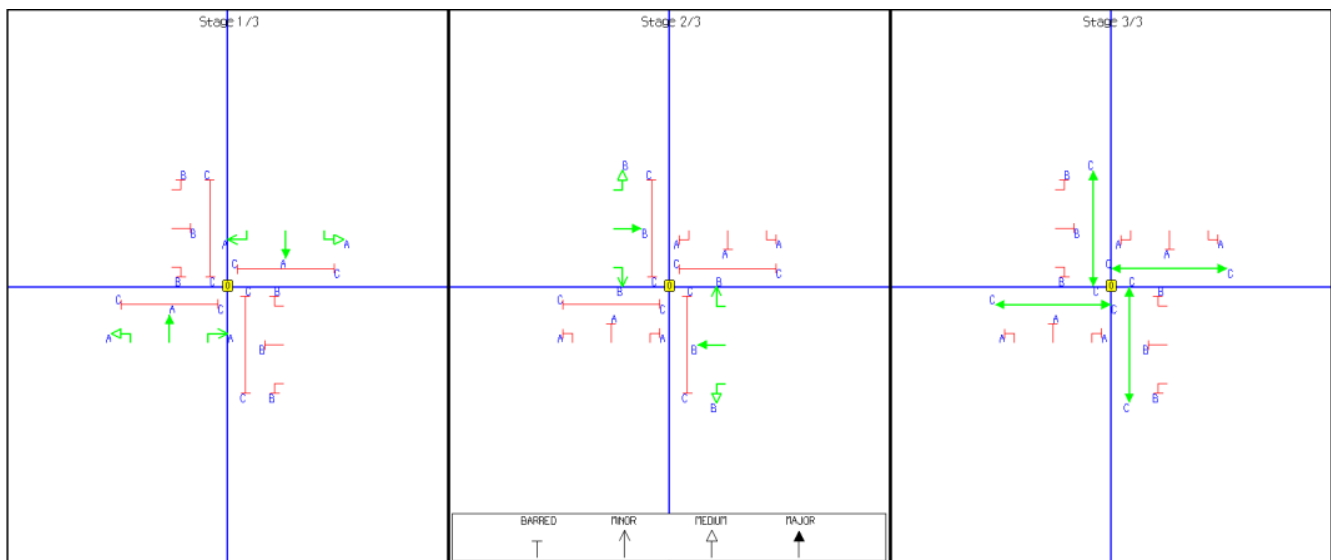


**(a): Two Stage Plan**
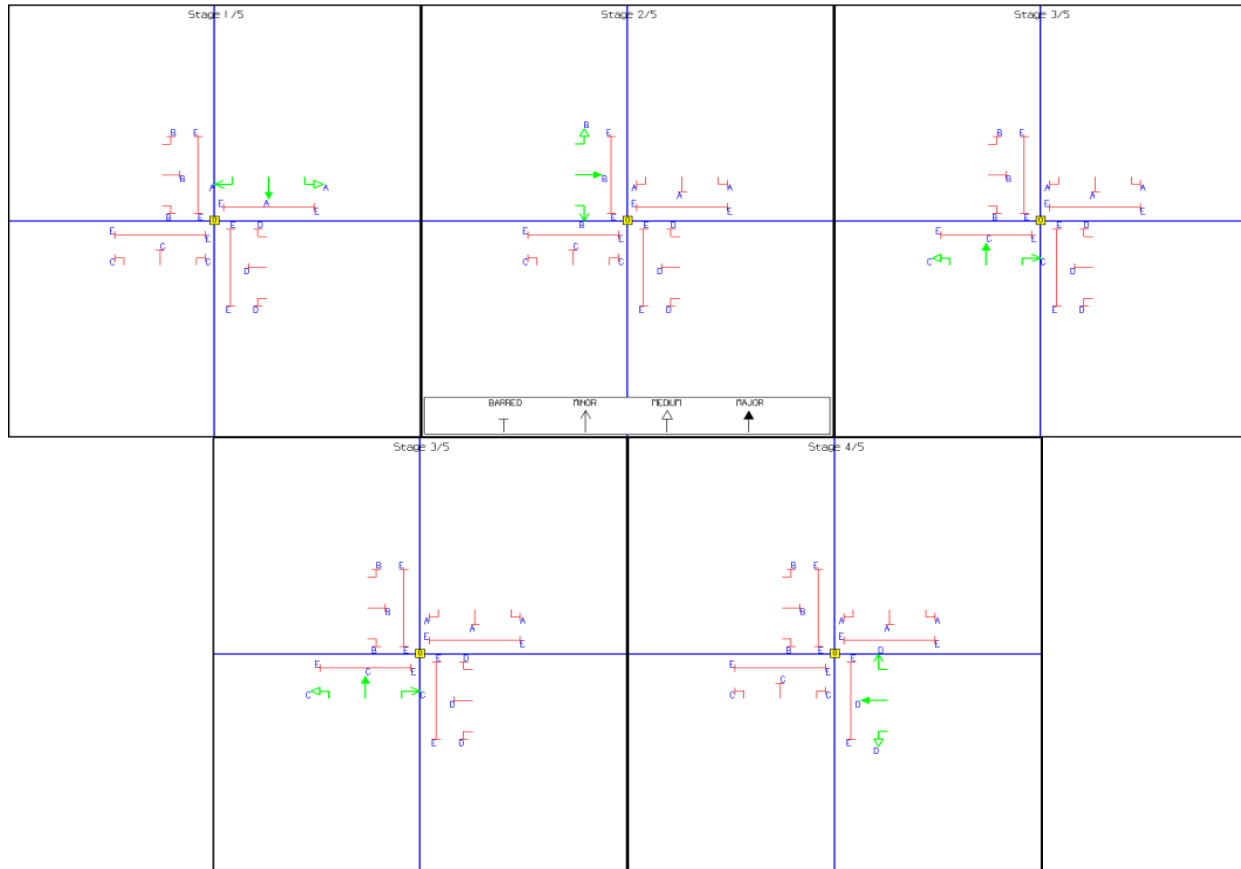
**(b) Four Stage Plan**
**FIGURE 2: Stages and Movements**

## Symbols and Notations

A list of symbols and notations that is used in this paper is provided below:

$N$ = Number of runs required
$t_{\alpha/2}$ = Critical value of the $t$-distribution for confidence interval $1-\alpha$
$\delta$ = Standard deviation of already conducted simulation runs
$\mu$ = Mean of already conducted simulation runs
$\varepsilon$ = Allowable error as a fraction of the mean
$c$ = Cycle Time (s)
$L$ = Lost Time (s)
$Y$ = Sum of critical flow to saturation flow ratios for all stages
$g_i$ = Green time for Stage i (s)
$y_i$ = Critical Flow to Saturation Flow ratio for stage $i$
$S_1$ = Saturation flow for unopposed movements (veh/hr)
$S_2$ = Saturation flow for opposed movements (veh/hr)
$d_n$ = Dummy variable (1 for nearside, 0 for offside)
$d_g$ = Dummy variable (1 for uphill, 0 for downhill)
$G$ = Percentage gradient of lane
$w$ = Width of lane (m)
$f$ = Proportion of turning vehicles
$r$ = Radius of curvature of turn
$T$ = Through car unit of a turning vehicle in a mixed traffic lane
$X_0$ = Traffic intensity in opposing direction
$N$ = Number of storage space for right turners
$C$ = Cycle time (s)
$U$ = Effective green to cycle time ratio
$P$ = Conversion factor
$NO_x$ = Nitrogen Oxides
$PM_{10}$ = Particulate matter of diameters 10 micrometres or less
$CO_2$ = Carbon Dioxide

**4.2 Effect of opposing Turns on Junction Performance for Two Stage and Four Stage Plans**

To properly conduct a fair comparison between these two signal plans, both sets of timings must be the optimum case for a given amount of flow. This is necessary as both approaches are inherently different and require different timings for cycle time and green time given similar traffic conditions.

$$c = \frac{1.5L+5}{1-Y} \tag{1}$$

Equation [1] is used to calculate the optimum cycle time. Webster (20) proposed this method which aims to minimize vehicle delay, taking into account lost time and critical flow ratios. This provides a good starting point, allowing the two cases to be fairly compared. Cycle time is an important parameter to be calculated as a short cycle time may result in lower delay to users as the time taken for the cycle to end and a stage to repeat is reduced (21). However, a cycle time which is too short leads to an increase in the number of phase changes within a certain period of time. These phase changes result in higher amount of lost time which reduced the effectiveness of the signalized junction.

$$g_i = \frac{y_i(c-L)}{Y} \tag{2}$$

Equation [2] is utilised to appropriately allocate green time to the stages (22). This method can prevent queues and congestion by providing more green time for stages which are more saturated than others.

The saturation flows are calculated using a formula outlined in TRL Research Report 67. This method uses geometric data such as turning radii, gradient and lane widths to provide an estimation of the saturation flow (23).

$$S_1 = \frac{2080-140d_n-42d_gG+(w-3.25)}{1+1.5\frac{f}{r}} \tag{3}$$

$$S_2 = S_g + S_c \tag{4}$$

$$S_g = \frac{2080-42d_gG+(w-3.25)-230}{1+f(T-1)} \tag{5}$$

$$S_c = P(1+N_s)(fX_0)^{0.2}\frac{3600}{uC} \tag{6}$$

$$T = 1+\frac{1.5}{r}+\frac{t_1}{t_2} \tag{7}$$

$$t_1 = \frac{12X_0^2}{(1+0.6(1-f)N_s)} \tag{8}$$

$$t_2 = 1-(fX_0)^2 \tag{9}$$

Equation [3] is used for lanes with unopposed movements and Equations [4]-[9] are used for lanes with opposed conflicting movements (24). For saturation flow calculations for lanes containing movements with conflicting traffic, a few iterations were performed until the results converge.

To investigate the impact of opposing turns, the turning ratio of the flow on Arm 1 of the junction from Figure 1 is varied from 0% opposing turns to 100% opposing turns. However, the impact of opposing turns for a permissive-only situation as with the two-stage signal plan is dependent upon the flow of conflicting movements. It should be noted that for this model, right turning cars from opposing arms turn offside to offside. Additionally, a right-turning car from one arm may move concurrently with a left-turning car from the opposing arm as there are two exit lanes on all arms. Thus, the main conflict for right-turning traffic is the straight through movement from opposing arms causing right-turners to stop and give way.

Four cases are considered for the two-stage plan: The conflicting movement flow (Arm 3) at 33.3%, 50%, 70% and 100% of the total flow into the arm. The four-stage signal plan has no conflicting movements and an increase in the proportion of straight flows would simply be divided between the two lanes so only the case of flow being split equally among the movements is considered. Although the turning ratios of the lane are altered, the total flow into each arm is kept constant at 450 vehicles per hour.

Measures of effectiveness used in this paper are the average journey time (s), total number of vehicles exiting the model (veh/hr), nitrogen oxide ($NO_x$), particulate matter ($PM_{10}$) and carbon dioxide ($CO_2$) emissions. Comparisons can then be sensibly made against the four-stage and two-stage model using the parameters measured per vehicle per kilometre.

As these tests are made using a hypothetical model, a model of a real junction is also considered. The real junction modelled is based upon the junction of Byres Road and University Avenue in Glasgow, Scotland. Some simplifications are made in this model such as the assumption that there are no other signalized junctions present. The gradient and geometry of the roads are taken into account. Arms 1 – 4 are 413.5m, 276.5m, 434.5m and 436.5m respectively in length. Two key differences in this model and the hypothetical model is the number of exit lanes and allowed turns. On Arm 4, there is only 1 exit lane. This prevents right turning traffic from Arm 1 to move concurrently with left turning traffic on Arm 3 in the two-stage plan because the left turning vehicles have higher priority. In the Byres Road junction, it is modelled such that the right lane is or right turning vehicles only.
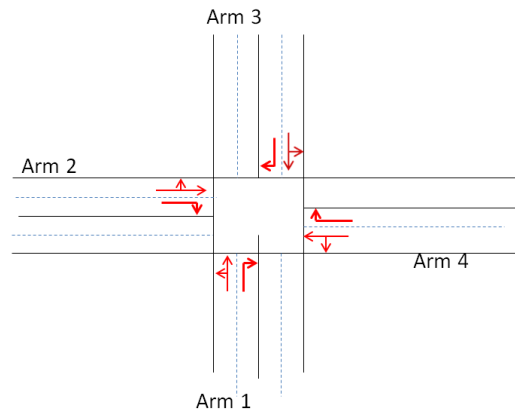


**FIGURE 3: Isolated Four-Arm Junction Showing Allowed Turns for Byres Road Junction**

The same signal plans as the hypothetical junction are used and design flows for 33.3% and 70% straight flows are utilised to compare the two. As the percentage of straight flows increase, the four-stage model is expected to change given the turns allowed for each lane. So, the four-stage model is investigated for a 70% as well.


# 5. Results

To compare the two-stage and the four-stage signal plans, the same traffic conditions must be used. Thus, each arm is assumed to have a flow of 450 vehicles per hour for both cases. The flow is also assumed to be equally distributed between all movements. From Equations [2] – [10] with a lost time of 5 seconds per stage, the saturation flows and subsequently the cycle time and green split is calculated.

For example, in the case of the four-stage plan, the critical saturation flow for each lane obtained is 1697.1 vehicles per hour from Equation [4] where $dn = 1$, $G = 0$, $r = 6$ and $f = 0.667$. The total lost time is assumed to be 39 seconds and flow is assumed to be distributed equally on both lanes. Then, using Equation [2], the cycle time is calculated as 135.19 seconds. The saturation flow calculation for the two-stage plan involves several iterations due to the presence of conflicting traffic.

$$Cycle\ Time = \frac{1.5 * (39) + 5}{1 - 0.53} = 135.19s$$

The following assumption have been made in the calculation: the equation for cycle time used is only accurate for unsaturated lanes. The equations utilised are for minimizing junction delay when arrivals are random. Another assumption is that the junction is isolated, ignoring other signalized junctions. These equations also only take into account the constraints of lost time and saturation flow as well as prioritizing vehicular delay. The optimal signal plans for the assumed case of a flow of 450 vehicles per hour for each arm are shown in Table 1.

**Table 1 : Optimal signal plans**

|  | Cycle Time (s) | Stage 1 (s) | Stage 2 (s) | Stage 3 (s) | Stage 4 (s) | Pedestrian (s) |
|---|---|---|---|---|---|---|
| **2 Stage** | 65 | 23 | 23 | - | - | 19 |
| **4 Stage** | 135 | 29 | 29 | 29 | 29 | 19 |

Simulations are run with S-Paramics to obtain vehicle data which then input into AIRE to output emissions data. Like Paramics, AIRE is not a deterministic model and does not converge onto a single solution. Random numbers are used for behaviour and vehicles. Thus, multiple simulation runs should be undertaken to ensure a minimum degree of uncertainty for the results obtained. A student $t$-distribution is used as the population mean and variance is unknown.

$$N = (t_{\frac{\alpha}{2}} * \frac{\delta}{\mu\varepsilon})^2$$

[10]

An initial 10 runs are simulated and the results are recorded. Then, Equation [1] is used to assess whether the number of runs are sufficient. For example, in the case of nitrogen oxides in the four-stage plan with 60% of right turning vehicles, the standard deviation of the sample is 19948, the mean is 431842, an allowable error of 0.025 and for confidence interval of 95%, the number of runs required is 12.066. This is higher than 10 so 5 additional runs are simulated and Equation [1] is used again to output 14.175 runs. Thus, all models are run 15 times to ensure statistical significance.

With the signal plans as shown in Table 2, the impact of the of opposed turning traffic onto emissions, journey time and total exiting flow are recorded as follows in Table 3. The results for a 100% right turns with 100% opposing conflicting movements are not recorded as the model is severely congested with vehicles queuing outside of the model. This would provide inaccurate results due to limitations of the model.

The four-stage model is observed to be less sensitive to right turns as the percentage increase of emissions, journey time and exiting flows are lower than the two-stage model for all cases of conflicting movements. The trends of the two-stage model change as the proportion of conflicting movements on the opposing arm increase. As the amount of conflicting movements increase, the point at which the gradient increases significantly occurs with a lower proportion of right turning traffic. Thus, the two-stage plan is more sensitive to right turns as well as conflicting traffic on the opposing arms. From Figures 4 to 7, it is observed that at certain proportions of right turning traffic, the two-stage plan performs less efficiently. The two-stage plan is always outputs lower emissions than the 4 stage plan at low proportions of right turns. However, with higher proportions of right turns and conflicting movements, the 4 stage model performs more efficiently. All pollutants including black carbon show an increasing trend as the amount of right turning vehicles increase. This trend is present in both the four-stage plan and two-stage plan.

**Table 2: Emissions, Journey Time and Exiting Flow Per Vehicle**
**Per Kilometer**

| | Right Turn Percentage | NOx (mg/veh/km) | PM10 (mg/veh/km) | CO2 (g/veh/km) | Black Carbon (mg/veh/km) | Average Journey Time (s) | Exiting Vehicles per Arriving Vehicles |
|---|---|---|---|---|---|---|---|
| 2 Stage | 0% | 222.31 | 8.956 | 214.728 | 5.187 | 93.705 | 0.973 |
| 33% Opposing | 20% | 221.954 | 8.98 | 213.87 | 5.411 | 93.879 | 0.973 |
| Straight Flow | 40% | 223.508 | 9.013 | 214.541 | 5.284 | 94.267 | 0.972 |
| | 60% | 226.164 | 9.108 | 216.696 | 5.241 | 96.614 | 0.971 |
| | 80% | 247.834 | 9.331 | 241.415 | 5.458 | 127.133 | 0.959 |
| | 100% | 260.036 | 9.482 | 251.656 | 5.645 | 141.439 | 0.955 |
| 2 Stage | 0% | 221.948 | 8.961 | 213.377 | 5.224 | 92.698 | 0.973 |
| 50% Opposing | 20% | 221.973 | 8.951 | 214.718 | 5.249 | 93.298 | 0.973 |
| Straight Flow | 40% | 224.838 | 9.018 | 215.533 | 5.273 | 96.18 | 0.971 |
| | 60% | 241.076 | 9.287 | 234.266 | 5.448 | 120.645 | 0.959 |
| | 80% | 259.996 | 9.443 | 252.557 | 5.558 | 143.799 | 0.952 |
| | 100% | 266.279 | 9.544 | 262.99 | 5.417 | 153.819 | 0.936 |
| 2 Stage | 0% | 220.826 | 9.007 | 212.257 | 5.316 | 92.355 | 0.972 |
| 70% Opposing | 20% | 221.669 | 8.972 | 214.072 | 5.165 | 93.892 | 0.974 |
| Straight Flow | 40% | 229.295 | 9.088 | 223.774 | #DIV/0! | 112.075 | 0.967 |
| | 60% | 253.702 | 9.413 | 249.159 | 5.284 | 140.253 | 0.954 |
| | 80% | 267.384 | 9.539 | 264.33 | 5.435 | 153.339 | 0.936 |
| | 100% | 278.162 | 9.627 | 284.844 | 5.536 | 165.48 | 0.901 |
| 2 Stage | 0% | 220.298 | 8.992 | 211.181 | 5.32 | 91.453 | 0.975 |
| 100% Opposing | 20% | 221.324 | 8.96 | 214.882 | 5.216 | 97.102 | 0.971 |
| Straight Flow | 40% | 242.994 | 9.291 | 240.367 | 5.405 | 130.711 | 0.952 |
| | 60% | 267.478 | 9.479 | 275.649 | 5.429 | 170.096 | 0.909 |
| | 80% | 278.456 | 9.585 | 294.269 | 5.402 | 181.923 | 0.891 |
| | 100% | - | - | - | - | - | - |
| 4 stage | 0% | 234.747 | 9.091 | 228.636 | 5.348 | 122.147 | 0.969 |
| | 20% | 232.701 | 9.059 | 228.885 | 5.234 | 121.283 | 0.97 |
| | 40% | 234.314 | 9.108 | 228.742 | 5.297 | 121.412 | 0.969 |
| | 60% | 236.172 | 9.218 | 229.034 | 5.4 | 121.689 | 0.969 |
| | 80% | 243.249 | 9.285 | 235.566 | 5.342 | 131.963 | 0.965 |
| | 100% | 256.986 | 9.463 | 255.13 | 5.53 | 156.481 | 0.957 |
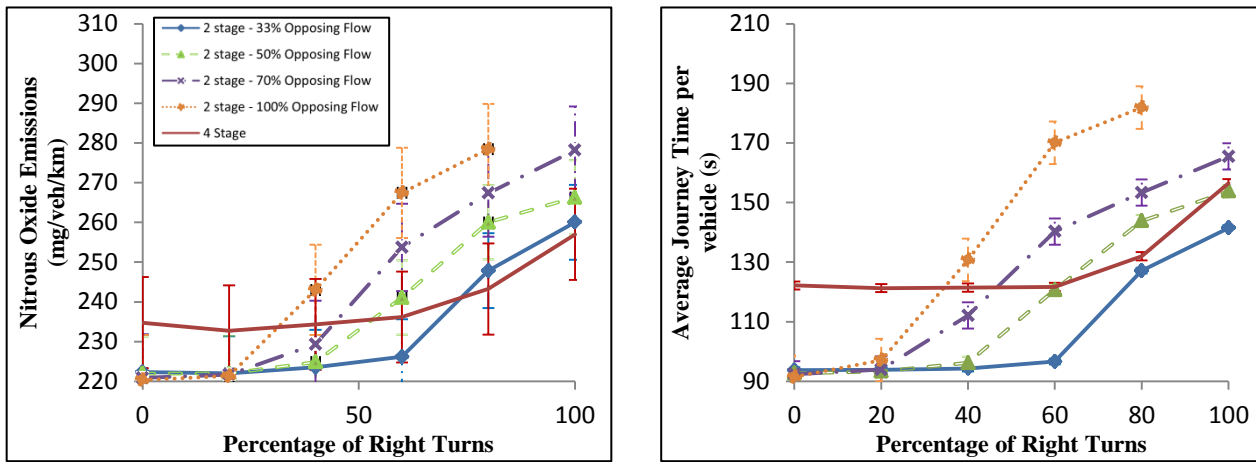
**FIGURE 4(a): Impact of Opposing Turns on Nitrogen oxide; 4(b) Impact of Opposing Turns on Average Journey Time**

The exact point at which the 4 stage model becomes the better signal plan is dependent upon the proportions of right turns and conflicting traffic. In the case with a 33.33% proportion of conflicting movements, the point at which the two-stage plan causes more emissions lies within the region where the proportion of right turns increases from 60% to 80%. The point lies within the region of 40-60% for 50% and 70% proportions of conflicting movements while it is within 20-40% given the opposing traffic consists of 100% conflicting movements.

**Table 3: Emissions, Journey Time and Exiting Flow Per Vehicle Per Kilometer for Real World Case**

|  | Right Turn Percentage | NOx (mg/veh/km) | PM10 (mg/veh/km) | CO2 (g/veh/km) | Journey Time per veh (s) |
|---|---|---|---|---|---|
| 2 Stage 33.3% Opposing Straight Flow | 0% | 286.154 | 10.306 | 262.055 | 102.635 |
|  | 20% | 286.954 | 10.364 | 262.183 | 102.709 |
|  | 40% | 305.514 | 10.684 | 280.381 | 124.901 |
|  | 50% | 317.603 | 10.83 | 296.884 | 145.283 |
| 4 stage 33.3% Opposing Straight Flow | 0% | 309.02 | 10.865 | 290.596 | 141.454 |
|  | 20% | 301.915 | 10.732 | 280.675 | 127.251 |
|  | 40% | 298.013 | 10.623 | 274.52 | 119.947 |
|  | 60% | 297.282 | 10.654 | 275.719 | 119.904 |
|  | 80% | 303.158 | 10.703 | 285.932 | 131.624 |
| 2 Stage 70% Opposing Straight Flow | 0% | 287.035 | 10.285 | 260.293 | 92.355 |
|  | 20% | 291.184 | 10.419 | 262.735 | 93.892 |
|  | 30% | 297.42 | 10.559 | 272.461 | 112.075 |
|  | 40% | 310.566 | 10.737 | 298.821 | 140.253 |
| 4 stage 70% Opposing Straight Flow | 0% | 321.132 | 10.953 | 307.431 | 92.698 |
|  | 20% | 309.845 | 10.753 | 291.94 | 93.298 |
|  | 30% | 307.52 | 10.721 | 284.771 | 96.18 |
|  | 40% | 305.57 | 10.656 | 282.724 | 120.645 |
|  | 60% | 309.75 | 10.755 | 284.709 | 143.799 |
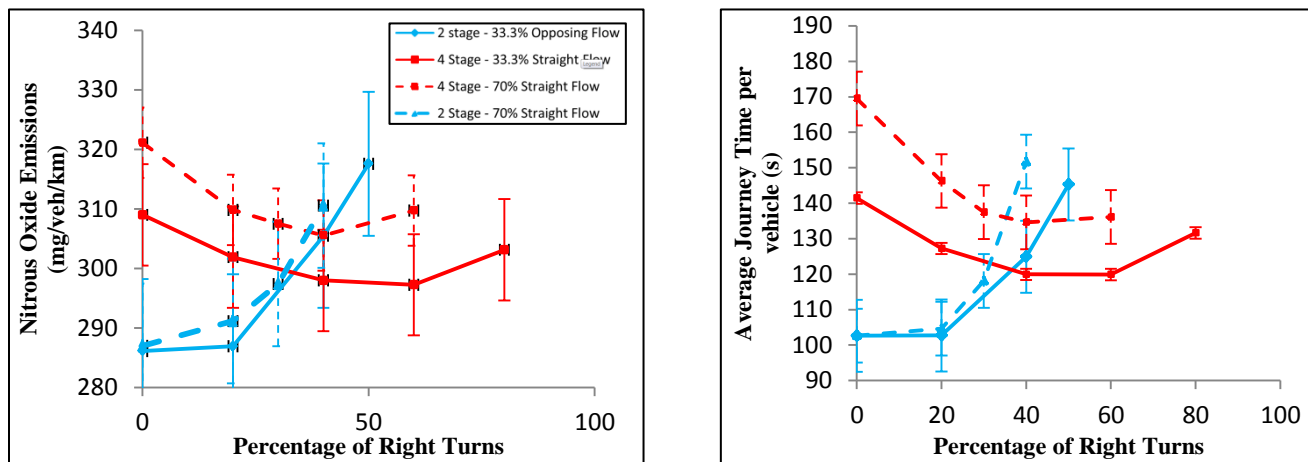
**FIGURE 5(a): Impact of Opposing Turns on Nitrogen Oxides;     5(b) Impact of Opposing Turns on Journey Time**

The Byres Road Junction Model shows a similar trend where the two-stage plan results in less emissions and shorter journey times at a low percentage of right turns but as the number of right turns increases, it becomes more inefficient. In both cases (33.3% and 70% of opposing traffic is straight ahead movements), the two-stage plan becomes the worse option between the region of 30% to 40% of right turns. This is a noticeably lower percentage when compared to the generic model. Another difference that is observed is that the four-stage Byres Road model results in high emissions and journey times at low percentages of right turns. The two-stage model results are only recorded up to 40% and 50% percentage of right turning traffic for 33.3% opposing straight flow and 70% opposing straight flow. Further increments of right turns cause the simulation model to congest severely with vehicles queuing outside the model. This in turn would end in inaccurate results so the results are not considered.

## 6. Discussion

From Equations [2] to [10], the cycle time obtained for the two-stage and four-stage plan is 65 seconds and 135 seconds respectively. The two-stage plan has a noticeably shorter cycle timer due to its lower lost time. Total lost time is the sum of the clearance times, start-up times and full pedestrian stages (20). Thus, the more stages in the signal plan, more delay is expected.

From Table 2, the four-stage plan is less sensitive to the proportion of right turns given a fixed total flow. Varying the percentage of right turns from 0% to 100%, the percentage increase of emissions, journey time and exiting flow per vehicle per kilometre is lower than the increase of that of all the two-stage plans considered. This is due to the fact that the movements on the four-stage plan are all unopposed. For any stage, there are no conflicting movements. Thus, the only significance that an increase in right turning traffic has on the four-stage plan is a shift of flow from being equally distributed on both lanes to being more heavily concentrated on the right lane.

Queues form on the right lane as right turning traffic increases and demand exceeds the capacity of the lane. These queues cause an increase in journey time and the longer the vehicles stay within the model, the more emissions are released. This is especially due to a larger amount of stops. Stops cause vehicles to decelerate and accelerate which leads to increased emission (15).

The two-stage plans are much more sensitive to right turns as the right turning traffic does not move unopposed during green. The right turning vehicles have to give way to the straight ahead vehicles on the opposing arm and wait for a sufficiently sized headway to complete their movement (7). As such, the two-stage plan is not only dependent on the proportion of right turns but the proportion of conflicting traffic on the opposing arm. As right turning vehicles are forced to wait and give way due to conflicting traffic, queues start to form. The right lane of the two-stage plan is more prone to congestion, having a lower saturation flow due to having to move past conflicting traffic.

Given low proportions of right turning traffic and conflicting traffic, the two-stage model performs better in terms of emissions (nitrogen oxide, particulate matter and carbon dioxide), journey times and total exiting flow. However, as the proportions increase, the four-stage plan outperforms the two-stage plan as seen in Figures 4 and 5. As the proportion of conflicting movements increase, the two-stage plan starts to yield inferior results with lower proportions of right turning traffic due to the vehicles not being able to complete their movement.

Thus, the four-stage signal plan should be used when the proportion of right turning vehicles is low. However, the amount of conflicting traffic needs to be taken in consideration as well. With a 33.3% of conflicting traffic on the opposing arm, the two-stage plan still functions better even with 60% of the flow being right turning traffic. If there is a 50%, 70% and 100% proportion of conflicting traffic on the opposing arm, the two-stage plan only performs better with up to 40%, 40% and 20% proportion of right turns respectively.

More simulations could be run to obtain more data points to obtain a smoother curve and increase the resolution to be able to estimate with more confidence at what point does the four-stage plan outperform the two-stage plan. Additionally, the proportion of right turns on only one arm is considered in this experiment. If the proportion of right turns increase on an adjacent arm increases as well, the two-stage plan would become less efficient with a lower proportion of right turns as its effect on emissions and delay is increased. However, if both opposing arms have high proportions of right turns, the two-stage plan would still be efficient as opposing right turning vehicles are able to turn offside to offside. Proper visibility must be ensured for these turns to happen but if so, the right turning vehicles are able to complete their movement which leads to fewer queues and less emissions.

As these tests were conducted upon a hypothetical four armed junction, the impact of opposed turning vehicles on a two-stage and a four-stage plan is also tested on a junction modelled upon the junction of Byres Road and University Avenue in Glasgow. Given the same arrival flows and signal plans, it is observed that the two-stage plan becomes the inefficient choice compared to the four-stage plan with a lower percentage of right turns. This is due to the fact that in Arm 4, there is only one exit lane. As such, the right turning vehicles are opposed by not only the straight ahead flows on the opposing arm but also the left turning vehicles. Thus there is a higher level of conflicting movements with the Byres Road junction. Additionally, the four-stage plans are observed to produce higher amounts of emissions and longer journey times compared to the hypothetical model at low percentages of right turns. This is due to the fact that all right lanes are limited to right turning traffic. So at low percentages of right turning traffic, all the flow runs through the left lane, congesting it and causing queues and delay.

Traffic survey data from performed via manual counts is also analysed. For a weekday from 8am – 9am, it is observed that the total flow into the North, East, South and West arms is 406, 342, 310 and 548 vehicles per hour. The data most resembles the experiment with 70% conflicting traffic with the North, East, South and West arms having 335, 290, 225 and 474 vehicles per hour which are conflicting which is most similar to the experimental case with 315 vehicles per hour.

**Table 4: Number of Turning Vehicles In Byres Road From 8-9am**

| Arm | Left Turn | Straight | Right Turn |
|---|---|---|---|
| North | 106 | 229 | 71 |
| East | 96 | 194 | 52 |
| South | 35 | 190 | 85 |
| West | 91 | 383 | 74 |

The South arm only has 85 right turning vehicles per hour whereas the point at which the four-stage model produces less emissions is between 135 and 180 Right turning vehicles per hour. Thus, it is more beneficial to utilize a two-stage model as the number of right turns during the peak period has not exceeded the capacity of the lane.

It is due to the signal timing that causes the presence of congestion. Although the two-stage model seems to accumulate queues faster than the four-stage plan due to its lower saturation flow, the two-stage model has a higher effective green time to cycle time ratio as there are only two-stages with the addition of a pedestrian stage.

The reason the two-stage plan can handle a higher amount of flow is because it has a greater capacity. Although having a lower total saturation flow, the two-stage plan has a much higher effective green to cycle time ratio. Appropriate signal timing can create more capacity within the junction. In regions in figures 4 to 7 where the gradient of emission levels rise significantly, queues form and cause congestion which leads to more emissions and longer journey times.

$$C_i = s_i \frac{g_i}{c} \qquad\qquad [11]$$

$C_i$ – Capacity for lane $i$

$g_i$ – Green Time for lane $i$

$s_i$ – Saturation flow for lane $i$

$c$ – Cycle Time

At this point, demand starts to exceed capacity. Queues form and cause vehicles to emit more emissions per km as well as lengthen journey time (22). The congestion that forms also decreases the amount of vehicles able to leave the junction in an hour. With the appropriate signal plan, the capacity of the lanes increases. Thus, with a higher capacity, the lane is able to handle higher amounts of flow without congestion occurring.

## 7. Conclusion

In conclusion, the level of emissions, throughput flow and journey times are closely related to the type of signal plan and the arrival flows for a four armed junction. Furthermore, upon deciding on the choice of signal plan, the estimates of flow through the junction should be studied and the degree of traffic intensity in flow should be projected as accurately as possible. Large proportions of right turns and conflicting traffic deem the two-stage permissive only signal plan inefficient compared to a four-stage signal plan in terms of both emissions and journey times. As observed in the junction of Byres Road and University Avenue in Glasgow, the permitted turns

and number of lanes need to be considered as well as having only one exit lane causes more conflicting movements for right turning traffic in two-stage plans. Additionally, based on the traffic survey data at the Byres Road Junction, it is most beneficial to utilize a two-stage plan instead of a four-stage plan to maximize efficiency and lower emissions.

## 8. Acknowledgements

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