# Optimal Resource Allocation Recommendations for Safety Treatments at Perth Metropolitan High Risk Intersections

# C-MARC

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**Abstract**

As convergence points for drivers and other road users, intersections have higher crash risk than other parts of the road network. It is therefore important to identify high risk intersections so that they can be prioritised for infrastructure improvement. In this report we look at the potential countermeasures and their cost for each of the top 60 high risk intersections in the Perth metropolitan area, estimate the associated reduction in the KSI (killed and serious injury) metric and calculate the cost of reducing the KSI metric by one at each intersection. The report enables us to identify the cost-effectiveness of treatments for high risk intersections and thus to show where the least amount of money can be spent to save the most lives.



**Keywords**
Metropolitan intersection crashes, KSI crashes, risk factors, countermeasures, cost per unit reduction in KSI.

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### Introduction

The Government of Western Australia adopted the *Towards Zero* strategy (Office of Road Safety, 2009) which is based on the *Safe Systems* approach to road safety (Corben, Logan, Fanciulli, Farley, & Cameron, 2010; Langford, 2009). As part of the strategy, the *WA Safe System Matrix* was created to identify road safety initiatives in line with the *Safe Systems* paradigm. In metropolitan Perth, one of these initiatives was the "Safe System intersection transformation" (Langford, 2009). This initiative addresses the higher crash risk at metropolitan intersections, which represent convergence points for all road users.

This is the third report in the Metropolitan Intersection Safety project and builds on the first report *"Risk Factors for Killed and Seriously Injury Intersection Crashes in Metropolitan Perth: 2005-2015"*(Chow, Manners, & Meuleners, 2016) which identified risk factors for killed and seriously injured crashes at intersections and the second report *"Identification of High Risk Metropolitan Intersection Sites in Perth Metropolitan Area"* (Chow, Hobday & Meuleners, 2016) which outlined a method of identifying and ranking high risk intersections.

The third phase of the study aimed to assist Main Roads Western Australia in developing methodologies for prioritizing candidate intersections for road safety improvements by developing an optimization strategy that allows Main Roads to allocate resources to achieve the greatest improvement to road safety at metropolitan intersections.

The specific objectives of the project were to:

1. Identify appropriate countermeasures for the identified high risk intersections.
2. Calculate the cost of applying the countermeasures.
3. Estimate the reduction in the KSI metric if the countermeasures were applied.
4. Calculate the cost of reducing the KSI metric by 1 for each countermeasure at each intersection thus identifying which countermeasures are most cost-effective.

## Method

The top 60 high risk intersections in Perth Metropolitan Area were identified based on Road Trauma Risk Analysis, Comparative Safety Performance and the KSI metric. A detailed observational study of these intersections was undertaken to document their current characteristics and identify potential engineering improvements that may assist in reducing the number of fatal and serious injury crashes. Costs of applying the countermeasures and the estimated reduction in the KSI metric at each intersection as a result of the countermeasures were estimated from the Crash Risk Reduction Matrix. Cost per unit reduction in the KSI metric was then calculated.

## Results

A cost-effectiveness measure was developed for each intersection treatment option. This facilitates identification of where the least money can be spent to save the most lives. The cost per unit reduction in the KSI metric varied from $670 to $54M.

## Discussion and Recommendations

This report examined appropriate treatments and their associated costs for high risk intersections in metropolitan Perth. This has allowed us to produce a cost per unit reduction in the KSI metric, which enables us to identify the cost-effectiveness of treatments for the intersections and thus to show where the least amount of money can be spent to save the most lives. The method is flexible and can be suited to any budget.

## Recommendations

That Main Roads consider the cost-effectiveness estimates for the high risk intersection treatments when implementing their new program of work.

## ACKNOWLEDGEMENTS

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# 1. INTRODUCTION

The Government of Western Australia (WA) adopted the *Towards Zero* strategy in 2009 (Office of Road Safety, 2009), based on the *Safe Systems* approach to road safety, which combined aspects of Sweden's Vision Zero and the Netherlands' Sustainable Safety approaches (Corben et al., 2010; Langford, 2009). The four cornerstones of the Western Australian Safe Systems approach are i) *Safe roads and roadsides, ii) Safe speeds, iii) Safe vehicles* and *iv) Safe road users* (Langford, 2009).

As part of the strategy, the *WA Safe System Matrix* was created to identify road safety initiatives in line with the *Safe Systems* paradigm, targeting the three major geographic regions of WA: metropolitan Perth, regional WA and remote WA (Corben et al., 2010). In metropolitan Perth, the program associated with *Safe roads and roadsides* in the *Safe System Matrix* is "*Safe System intersection transformation*" (Langford, 2009) which involves the use of measures such as roundabouts, control of right-turns at signals and combination red light/speed cameras to improve the safety of intersections (Corben et al., 2010). A survey using a representative sample of the WA population demonstrated that 95% of respondents supported or strongly supported improving intersections (Corben et al., 2010).

Intersections represent convergence points for all road users (motorised vehicles, as well as vulnerable road users such as pedestrians and cyclists). Because road users' paths cross the road network at intersections, the risk of a crash is higher, despite road users spending a relatively short time travelling through them (Huiqin Chen, Cao, & Logan, 2012; NZTA, 2013). There are several reasons for this higher crash risk at intersections: i) vehicles and pedestrians travel on conflicting paths; ii) road users are required to make successful gap judgements about when it is safe to pull out into traffic; iii) intersections are located at points of traffic congestion and can cause congestion (Huiqin Chen et al., 2012).

Safety improvement measured at high-risk intersections need to focus on reducing the number of killed and serious injury crashes, concentrating on high risk movement types at intersections. Busy environments in urban areas place high demands on road users, particularly vulnerable road users such as pedestrians and cyclists (NZTA, 2013). In Perth metropolitan area, nearly 21% of serious injury crashes between 2005 and 2009 occurred

at intersections, while only 10% and 5% of serious injury crashes involved intersections in regional and remote Western Australia respectively (Palamara, Kaura, & Fraser, 2013).

This report forms part of the Metropolitan Intersection Safety project. The first report, "*Risk Factors for Killed and Serious Injury Intersection Crashes in Metropolitan Perth: 2006–2015"*(Chow, Manners, et al., 2016) identified risk factors for killed and serious injury (KSI) intersection crashes (compared to crashes involving medical treatment or property damage) in the Perth metropolitan area between 2006 and 2015. Risk factors identified with significant increased risk of a KSI intersection crash were i) temporal factors (crashes occurring at weekends and at night-time), ii) occurrence at non-level intersections, and iii) three-way, or four or more-way intersections (compared to roundabouts). The report recommended modification of high risk intersections to include appropriate countermeasures such as roundabouts or traffic lights where appropriate and that further investigations into the safety issues associated with intersections on roads that are not level be conducted.

The second report used a three-stage approach to identify and rank high risk intersections in the Perth metropolitan area. An assessment of intersection risk was undertaken using methodologies developed by Main Roads Western Australia: the Road Trauma Risk Analysis and the Comparative Safety Performance Analysis, which was followed by a ranking of the identified high risk intersections using a KSI metric. The results of the study identified the intersections that required the most urgent attention.

This third report identifies appropriate countermeasures for treatment of the high risk intersections and allocates a cost and estimated reduction in the KSI metric using the Main Roads Crash Reduction Matrix. The cost per unit reduction in the KSI metric is then calculated allowing identification of where the least money can be spent to save the most lives. The results of these reports will aid road safety authorities to make informed decisions about the management and investment of road safety resources.

## 1.1 Aims and objectives

This third phase of the study aims to develop a methodology for prioritizing candidate intersections for road safety improvements by developing an optimization strategy that allows Main Roads to allocate resources to achieve the greatest improvement to road safety at metropolitan intersections.

The specific objectives of the project were to:

- Identify appropriate countermeasures for the identified high risk intersections.
- Calculate the cost of applying the countermeasures.
- Estimate the reduction in the KSI metric that could be achieved if the countermeasures were applied.
- Calculate the cost of reducing the KSI metric by 1 for each countermeasure at each intersection thus identifying which countermeasures are most cost-effective.

## 1.2 Significance

The results of this report will provide Main Roads and other responsible agencies with reliable and objective information for future investments in developing road safety strategies.

# 2. METHODS

## 2.1 Study design

An observational study of high risk intersections in the Perth metropolitan area to document their current characteristics and identify potential engineering improvements that may assist in reducing the number of killed and serious injury crashes was undertaken.

## 2.2 Study environment

The study included all metropolitan intersections where at least one casualty crash occurred in the Perth metropolitan area during 2011-2015 (Table 12, Appendix). The Main Roads region code 7 was used to identify intersections located in the metropolitan area of Western Australia.

## 2.3 Databases

### 2.3.1 Integrated Road Information System (IRIS)

The Integrated Road Information System (IRIS) is a large dataset of reported crashes (Police and self-report) in Western Australia which is maintained by Main Roads. This includes fatal, hospitalisation and medical treatment crashes that occurred at intersections in the metropolitan area of Perth, WA.

### 2.3.2 Traffic volume data

Data on traffic volumes (annual average daily traffic - AADT) at intersections were obtained for use in the analysis. AADT is the annual average daily traffic experienced by each leg of an intersection, and is recorded and maintained by Main Roads. If traffic data for 2015 was available, this was used for this project. If traffic data was only available from an earlier year, an annual growth rate of 2.18% was used to estimate the 2015 AADT. This is the most recent estimate of growth, using the Australian Bureau of Statistics estimates of Million Vehicle Kilometers Travelled - MVKT (ABS, 2015)

## 2.4 Operational definitions

The definition of a crash used throughout this report is the definition used in the annual publication *Reported Road Crashes in Western Australia 2014* (Road Safety Commission, 2016). That is, a crash is "*any unpremeditated incident where in the course*

*of the use of any vehicle on a road that was not temporarily closed off to the public, a person is injured or property is damaged. The crash must involve vehicle movement and does not include collisions that occur due to a medical condition, deliberate acts (e.g. suicide attempts) or police chases*".

The severity of a crash is derived from "*the most serious injury in a crash*". A fatal crash is *"a road crash in which at least one person was killed immediately or died within 30 days of the crash, as a result of the crash"*. A hospitalisation crash is a road crash that involved at least one admission to hospital but *"no fatalities within 30 days of the crash"*. A crash requiring medical treatment is *"a road crash in which the most serious injury resulted in a person requiring medical treatment, but without being admitted to hospital"*. A property damage only crash (PDO) involved no or unknown injuries.

For the purpose of this report, a killed or serious injury (KSI) crash was defined as a road crash that resulted in at least one person being either killed ("*killed immediately or died within 30 days of the day of the road crash as a result of the crash*") or seriously injured ("*admitted to hospital as a result of the road crash and who does not die from injuries sustained in the crash within 30 days of the crash*"). KSI crashes include all fatal crashes, and hospitalisation crashes. Non-KSI crashes included all crashes requiring medical treatment and PDO crashes. In WA, it is mandatory for the driver of a vehicle to report a traffic crash when the incident occurred on a road or any place commonly used by the public, e.g. carparks, and:

1. The incident resulted in bodily harm to any person; or
2. The total value of property damaged to all involved parties exceeds $3000; or
3. The owner or representative of any damaged property is not present.

### 2.4.1 The KSI Metric

The KSI metric is an adjusted total of KSI crashes if a proportion of each medical treatment crash was added toward the KSI total. This is based on the consideration that there is always a component of randomness in crashes at any given location, and that a medical treatment crash always had the potential to have been more severe by chance (Chow, Hobday, & Meuleners, 2016), The equation for the KSI metric is given below.

**Equation 1: KSI metric**

$$KSI\ Metric_{(of\ an\ intersection\ of\ type\ xy)} = \sum_z \left[No.of\ KSI\ Crashes_{(of\ crash\ type\ z\ at\ the\ intersection)} + Severity\ Index_{xyz} \times No.of\ Medical\ Crashes_{(of\ crash\ type\ z\ at\ the\ intersection)}\right]$$

*where*

*x= speed environment, y= intersection control, z=crash type and*

$$Severity\ Index_{xyz} = \frac{Number\ of\ KSI\ Crashes_{xyz}}{Number\ of\ Casualty\ Crashes_{xyz}}$$

## 2.5 Criteria for ascertainment of an intersection crash

All metropolitan intersections with at least one casualty crash (fatal, hospitalisation, or crash requiring medical treatment) from 2011 to 2015 were investigated, resulting in a total of 996 intersections. These included state road/state road intersections and state road/local road intersections but excluded local road/local road intersections (Main Roads, 2016). The full list of intersections used in this report is contained in Table 6 in the Appendix.

Intersections were categorised based on:

1. Speed Environment (highest approach speed):
    a. Built-up: all legs of the intersection were less than 80km/hr and at least one greater than 50km/hr
    b. Open: at least one leg of the intersection was 80km/hr or more
    c. Low-speed: all legs of the intersection were 50km/hr or less

2. Intersection Control:
    a. Traffic Signals (i.e. has traffic control lights)
    b. Roundabout
    c. No traffic signals (i.e. has no traffic control lights)

This created nine possible intersection types:

1. Built-up speed environment with traffic signals
2. Built-up speed environment with roundabout
3. Built-up speed environment with no traffic signals
4. Open speed environment with traffic signals

5. Open speed environment with roundabout
6. Open speed environment with no traffic signals
7. Low-speed environment with traffic signals
8. Low-speed environment with roundabout
9. Low-speed environment with no traffic signals

## 2.6 Analysis of crashes

The safety of each of the nine types of intersections was first assessed using Road Trauma Risk Analysis (Section 2.6.1). High risk intersections were then identified and assessed using the Comparative Safety Performance Analysis methodology (Section 2.6.2). Finally, high risk intersections were ranked by the KSI metric (Section 2.6.3).

### 2.6.1 Road Trauma Risk Analysis

The Road Trauma Risk Analysis was used to assess Road Trauma Risk (RTR) and to allocate each intersection into one of four quadrants of the RTR tool: black, red, orange and green – Figure 1 (Main Roads, 2016). The measure of the horizontal axis of the tool is crash density (the KSI metric) while the measure of the vertical axis is crash rate (the KSI metric divided by the level of exposure to traffic – product of flow). The equations for crash rate and product of flow are given below.

**Equation 2: Crash rate**

$$Crash\ Rate\ (\ intersection) = \frac{KSI\ Metric\ \times\ 10^8}{PoF\ \times\ 5\ \times\ 365\ \times\ 1.7}$$

*where PoF = product of flow*

**Equation 3: Product of flow**

$$Product\ of\ Flow$$
$$= \{Average\ (AADT\ for\ major\ road\ before\ \&\ after\ intersection)$$
$$\times\ Average\ (AADT\ for\ minor\ road\ before\ \&\ after\ intersection)\}^{0.4}$$

*where AADT = annual average daily traffic(Main Roads, 2016)*

For each intersection, both crash density and crash rate were rated from low to high (Table 1), and then the intersection was allocated to the correct quadrant according to the ratings

demonstrated in the horizontal axis (crash density) and vertical axis (crash rate) in Figure 1.

**Figure 1: Road Trauma Risk Analysis tool**

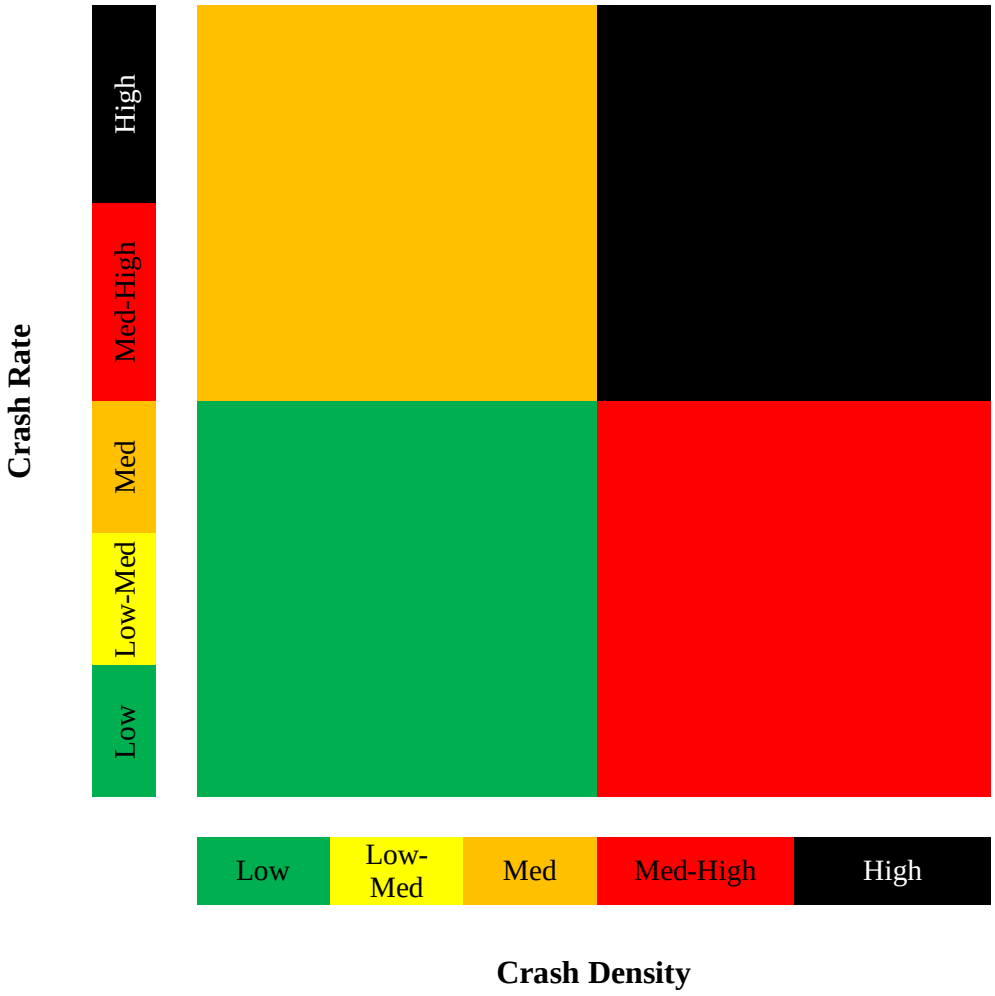



**Table 1: Thresholds for categories of crash density and crash rate[1]**

| | Density | Rate |
|---|---|---|
| **High** | Greater than 2.786 | Greater than 106.339 |
| **Med-High** | 1.366 to 2.7867 | 51.826 to 106.339 |
| **Med** | 1.000 to 1.366 | 29.450 to 51.826 |
| **Low-Med** | 1.366 to 0.371 | 11.443 to 29.450 |
| **Low** | Less than 0.371 | Less than 11.443 |

[1] Thresholds are percentile cut-offs provided by Main Roads Western Australia, based on their list of high risk intersections in 2013 calculated from 2009-2013 crash data.

Intersections falling in the black quadrant were characterised by both high crash density (a high number of KSI crashes at the intersection) and crash rate. Intersections in the red quadrant had high crash density but lower crash rate (higher number of KSI crashes at intersections which may also have high traffic volumes). Intersections in the orange quadrant had lower crash density but high crash rate (lower KSI crash numbers per intersection). Intersections in the green quadrant have both low crash density and low crash rate.

For intersections with a Road Trauma Risk (RTR) in the black quadrant but with less than 3 observed KSI crashes, the following exceptions applied:

1. If the intersection was on a main or major road (road ID beginning with "M"), the RTR quadrant was downgraded to orange.
2. If the intersection was on a highway or freeway (road ID beginning with "H"), the RTR quadrant was downgraded to red.

### 2.6.2 Comparative Safety Performance Analysis

High risk intersections identified by the Road Trauma Risk Analysis were compared by KSI metric at different product of flow levels, and each intersection was assigned a percentile score according to the intersection's safety record relative to other intersections of the same type. The percentile cut-offs of all intersection control/speed environment combinations were provided by Main Roads. This enabled the definition of each intersection into one of five Comparative Safety Performance (CSP) categories (Table 2). Percentile cut-offs by intersection type are indicated in the Appendix (Table 5). The CSP Analysis highlights which intersections are performing worse in terms of the KSI metric for their traffic control type, speed environment and product of flow.

**Table 2: Comparative Safety Performance percentile scores and definitions**

| Comparative Safety Performance | | Percentile band | Definition |
|---|---|---|---|
| **V** | **Extremely poor** | 90 to 100th | Crash rate in the worst 10% band. Higher than expected in 90% of intersections of similar speed environment and signal type. |
| **IV** | **Very poor** | 70 to 90th | Crash rate in the worst 10% to 30% band. Higer than expected of 70% of similar intersections but better than the worst 10% |
| **III** | **Poor** | 50 to 70th | Crash rate in the worst 30% to 50% band. Higher than expected of 50% of similar intersections but better than the worst 10% |
| **II** | **Adequate** | 30 to 50th | Crash rate lower than the worst 50%, but higher than the safest 30% of intersections. |
| **I** | **Good** | 0 to 30th | Crash rate in the best 30% band. Lower than expected of 70% of intersections of similar speed environment and signal type. |

### 2.6.3 Ranking of high risk intersections

1. All intersections falling in the black quadrant were ranked above those in the red quadrant.
2. All high risk intersections in the same quadrant were then ranked by CSP, with those with a CSP of V being ranked above those with a CSP of IV, and so on.
3. Finally, all intersections were further ranked from the highest KSI metric to the lowest.

### 2.6.4 Top 60 high risk intersections

This phase of the project concentrated on the top 60 high risk intersections. The top 60 high risk intersections were selected based on RTR, CSP and KSI metric. High risk intersections included all intersections in the RTR Black category with CSP V or a CSP IV and a KSI metric of 5.2 or more.

## 2.7 Detailed inspection of intersections

Detailed inspections of all 60 high risk intersections were carried out using aerial imagery from google maps and the online software Nearmap (Nearmap Ltd., 2016). The information recorded from the site inspections included;

- The number of lanes on each road entering the intersection, presence of turning lanes and the direction of traffic flow.
- Presence of bus and bike lanes.
- Presence or absence of a median strip, whether the median strip was raised or painted and the width of the median strip.
- Presence of traffic signals and right and left turning arrows.
- Speed limit of lanes entering the intersection.

## 2.8 Changes to intersections from the start of the study period

The online software Nearmap was used to check each high risk intersection for any painting, road safety treatments or structural changes to the intersection from the start of the study period, 1 January 2011 to the end of the data analysis period at 30 July 2017. This involved using the geographic co-ordinates to locate each intersection, and then visually comparing the aerial views of the intersection immediately prior to the start date, 1 January 2011 and close to the end date, 1 December 2016. Although many of the high risk intersections were altered during the course of the study, in most cases the countermeasures applied to these intersections were costed and included in the study.

## 2.9 Main Roads Workshop

A workshop was held with Main Roads Project Engineers to examine appropriate countermeasures for a selection of the 60 high risk intersections. These high risk intersections were compared with control sites which had similar characteristics but a lower KSI metric. The Project Engineers explained the process of selecting countermeasures and described the factors that need to be taken into consideration. This information was then applied by C-MARC staff in selecting appropriate countermeasures for other high risk intersections.

## 2.10 Selection and costing of countermeasures

A crash reduction matrix was obtained from Main Roads' Crash Analysis Reporting System (CARS). This included a list of countermeasures that can be implemented at intersections, together with the project life and the cost of implementing the measure in terms of infrastructure cost, ancillary works cost, operating cost and the estimated reduction on crashes by road user movement (RUM) code. Appropriate countermeasures

were selected from the crash reduction matrix for each high risk intersection. If appropriate, more than one countermeasure was selected for a site and costs were prepared for alternative scenarios. The costs for countermeasures were calculated based on a five year time frame and included the infrastructure cost, ancillary works cost and operating cost where relevant. The costs provided were for the year 2000. These were inflated to 2016 costs using the BITRE Road Construction and Maintenance Price (RCMP) index. Costs for the addition of speed cameras came from a report by Chen et al (H. Chen, Meuleners, & Hendrie, 2012).

## 2.11 Calculation of reduction in the KSI metric

The reduction in the KSI metric was also calculated using the crash reduction matrix and the Chen et al report regarding speed cameras which reported KSI reduction by nature of crash, i.e. right turn through or side swipe. (H. Chen et al., 2012). The "road user movement" (RUM) codes for all crashes at each high risk intersection during the period 2011-2015 were extracted from the IRIS database. The reduction in the KSI metric by RUM code for each countermeasure was obtained from the crash reduction matrix. If a countermeasure affected more than one RUM code at an intersection, all proportions were added together after having applied a proportionate reduction. Calculation of cost per unit reduction in the KSI metric was obtained by dividing the total cost for each countermeasure or group of countermeasures by the total reduction in the KSI metric expected to be achieved by the countermeasure(s). The cost of a unit reduction in the KSI metric having applied different countermeasures was then compared.

## 2.12 Ethics approval

The project was approved by Curtin Human Research Ethics committee in April 2016 (approval number HRE 2016-0071).

# 3. RESULTS

## 3.1 Top 60 high risk intersections

The top 60 high risk intersections and their characteristics such as Road Trauma Risk level, Comparative Safety Performance and KSI metric are shown in Appendix Table 6. Aerial photographs of each intersection are also included at the end of the appendix (page 45). These intersections include the following: 32 built-up signal, 11 open signal, 9 built-up non-signal, 7 open non-signal and 1 low speed signal. The complete list of recommended treatments and the estimated cost of applying these treatments are shown in Appendix Table 7, together with the cost for reducing the KSI metric by 1. As mentioned in the methods, some of the top 60 high risk intersections were treated, or treatment commenced during the study period. These are still included for comparative purposes unless the countermeasure included multiple treatments that were too complex to be included in this report or were aimed at reducing congestion rather than improving road safety (a total of 8 intersections). A further 11 intersections had works completed or commenced by August 2017. These are included in the tables but not in the figures.

## 3.2 Cost of treating high risk intersections

Table 3 shows the treatment and cost information for the top 12 high risk intersections. This shows that the cost per KSI metric reduced ranged from $670 to nearly $54M. The most cost-effective options are for altering traffic light phasing and specifically the removal of right turn filters. The least cost-effective options are those requiring grade separation or widening of bridges to accommodate additional right turning lanes. Table 4 provides simplified summary information regarding the most cost-effective means of reducing the KSI metric depending on the appropriate countermeasure. The costs per unit reduction in the KSI metric in this table assume that only one crash of each type is prevented whereas in reality there could be multiple crashes of a particular type. The RUM codes shown in this table are the most common crash types at the high risk intersections, accounting for nearly 80% of crashes. The data demonstrate that costs can potentially range from as little as $1500 to around $18M for reducing the KSI metric by one. This is very similar to the data provided in Table 3 and also reflects that the most cost-effective countermeasures were modifying traffic signals to prevent a right turn filter, banning a right hand turn, and extending the median through an intersection. For between $10,000 and $100,000, further countermeasures to reduce the KSI metric by one

include adding a seagull in the median strip, street closure, adding a protected right hand turn lane, improving sight lines and adding traffic median islands (Table 4). A further range of countermeasures are available in the $100,000 - $600,000 category including more extensive signal modification, extending right and left turn pockets and adding a roundabout. The most expensive countermeasure is grade separation with estimates varying from $3.75M-$54M per unit reduction in the KSI metric depending on the site and location specific factors.

**Table 3: Treatments and Cost per unit reduction in the KSI metric for the top 12 high risk intersections**

| Intersection Description | treatments | Road infrastructure, ancillary works and operating cost $ α | Estimated reduction in the KSI metric | Cost per unit reduction in the KSI metric |
|---|---|---|---|---|
| REID HWY & BEECHBORO RD NORTH | Grade separation | $15,003,750 | 4 | $3,750,938 |
| ARMADALE RD & NICHOLSON RD (a) | Repaint lines on road (use K11 for RUM codes, K17 cost) | $23,250 | 0 | - |
| ARMADALE RD & NICHOLSON RD (b) | Modify signals - reconstruct intersection (with right turn arrows without filter) Armadale road; add a right turn lane on both approaches to the intersection from Armadale Road | $363,750 | 2.9 | $125,431 |
| ARMADALE RD & NICHOLSON RD (b) | Install roundabout | $1,507,500 | 1.6 | $942,188 |
| SOUTHPORT ST & CAMBRIDGE ST | Modify signals - new right turn arrows (without filter); Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $387,000 | 1.8 | $215,000 |
| FRANCISCO ST & ORRONG RD & FRANCISCO PL (a) | Add mast arm Orrong Rd | $75,000 | 1.4 | $53,571 |

| | | | | |
|---|---|---|---|---|
| FRANCISCO ST & ORRONG RD & FRANCISCO PL (b) | Protected right turn lane (indented right turn island); Land acquisition; Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $1,952,250 | 2.92 | $668,579 |
| FRANCISCO ST & ORRONG RD & FRANCISCO PL © | Both options together | $2,027,250 | 3.1 | $653,952 |
| REID HWY & REID HWY - MITCHELL FWY STH ON & H016 STH BOUND - REID HWY OFF & BALC | Upgraded last quarter 2015 - more lanes added going straight ahead | - | - | - |
| ALBANY HWY (END DUAL) & DUNCAN ST | 2 x extend right turn pocket; widen Duncan St south; Indented left turn slip (give way, stop or signal control); Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $659,250 | 2.7 | $230,278 |
| HUTTON ST ON - H016 STH BOUND & HUTTON ST & H016 STH BOUND - HUTTON ST OFF (a) | Extend left turn pocket to mitigate rear end crashes in through lane | $271,500 | 0.4 | $678,750 |
| HUTTON ST ON - H016 STH BOUND & HUTTON ST & H016 STH BOUND - HUTTON ST OFF (b) | Bridge widening (cost as for 0.5 grade sep); Protected right turn lane (indented right turn island) | $7,728,750 | 1.44 | $5,367,188 |
| H016 NTH BND - WHITFORDS AV OFF & WHITFORDS AV & | Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $2,250 | 3 | $750 |

| | | | | |
|---|---|---|---|---|
| WHITFORDS AV OFF - H016 NTH BND (a) | | | | |
| H016 NTH BND - WHITFORDS AV OFF & WHITFORDS AV & WHITFORDS AV OFF - H016 NTH BND (b) | Bridge widening (use 0.5 grade sep); Protected right turn lane (indented right turn island) | $7,727,250 | 0.8 | $9,659,063 |
| ALBANY HWY & BURSLEM DR | Protected right turn lane (indented right turn island); Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $227,250 | 2.88 | $78,906 |
| MCDOWELL ST & ORRONG RD | Protected right turn lane (indented right turn island) | $227,250 | 1.2 | $187,500 |
| NICHOLSON RD & THOMAS RD | Install roundabout | $757,500 | 2.3 | $329,348 |
| CANNING HWY & EAST ST (a) | Extend median through intersection to allow only left in left out movements | $4,500 | 4.5 | $667 |
| CANNING HWY & EAST ST (b) | Improve sight lines for right approach (eg clear verge) | $11,250 | 0.9 | $6,667 |
| CANNING HWY & EAST ST (c) | Add wider median to protect right turners | $15,000 | 0.4 | $25,000 |

α Cost does not include traffic surveys and modelling or traffic management.

**Table 4: Cost range by treatment category**

| Treatment | Road User Movement Code for Crash type | | | | Average reduction in KSI metric | 5 year cost of treatment | Cost per unit reduction in the KSI metric |
|---|---|---|---|---|---|---|---|
| | 11-Adjacent approach | 14-Adjacent approach | 22-Opposing turns | 31-Rear End | | | |
| Ban right turns | | 0.5 | 0.5 | 0.5 | 0.50 | $750 | $1,500.00 |
| Modify signals - prevent right turn filter (for existing right turn arrows with filter) | | | 0.6 | | 0.60 | $2,250 | $3,750.00 |
| Extend median through intersection | 1 | 1 | 1 | | 1.00 | $4,500 | $4,500.00 |
| Seagull in median (select terminating leg of Tee) not recommended for median widths < 10m. | 0.5 | | 0.4 | | 0.45 | $7,500 | $16,666.67 |
| Street closure [close stem of Tee] | 1 | 1 | 1 | 0.5 | 0.88 | $15,000 | $17,142.86 |
| Improve sight lines for right approach (eg clear verge) | 0.3 | 0.3 | | | 0.30 | $6,750 | $22,500.00 |
| Protected right turn lane (indented right turn island) | | | 0.3 | 0.4 | 0.35 | $22,500 | $64,285.71 |
| Traffic median islands on approaches | | | 0.2 | 0.2 | 0.20 | $15,000 | $75,000.00 |
| Painted right turn lane | | | 0.2 | 0.2 | 0.20 | $23,250 | $116,250.00 |
| Traffic signal: Overhead mast arms | 0.3 | 0.3 | 0.3 | 0.2 | 0.28 | $75,000 | $272,727.27 |
| Modify signals - new right turn arrows (without filter) | | | 0.6 | | 0.60 | $206,250 | $343,750.00 |
| Modify signals - reconstruct intersection (with right turn arrows without filter) | 0.5 | 0.5 | 0.6 | | 0.53 | $206,250 | $386,718.75 |
| Extend right turn pocket to mitigate rear end crashes in through lane | | | | 0.4 | 0.40 | $196,500 | $491,250.00 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Extend left turn pocket to mitigate rear end crashes in through lane | | | | 0.4 | 0.40 | $196,500 | $491,250.00 |
| Indented left turn slip (give way, stop or signal control) | 0.3 | | | 0.5 | 0.40 | $226,500 | $566,250.00 |
| Roundabout | 0.7 | 0.7 | 0.4 | -0.2 | 0.40 | $277,500 | $693,750.00 |
| New traffic signal [no turn arrow] | 0.7 | 0.7 | -0.9 | | 0.17 | $322,500 | $1,935,000.00 |
| Grade separation | 1 | 1 | 0.5 | | 0.83 | $15,003,750 | $18,004,500.00 |

### 3.3 Treatments ordered by cost-effectiveness

The cost per unit reduction in the KSI metric, the total cost of implementing a treatment at a specified intersection and the cumulative cost of treating all of the intersections are shown in Figures 2 (costs less than 900K) and 3 (costs greater than 900K). For this part of the analysis, a preferred treatment has been selected for each intersection. This has been based on cost-effectiveness of the treatment while taking into consideration that some treatments such as blocking off roads may appear effective, but may result in crashes being relocated to the next available intersection. Where the cost per unit reduction in the KSI metric is greater than the total cost for the intersection, this indicates that the treatment is estimated to reduce the KSI metric by less than 1. Alternatively, where total cost is greater than the cost per unit reduction in the KSI metric, the treatment is estimated to reduce the KSI metric by more than 1. The total cost of applying all the treatments (where treatment has not yet commenced) was estimated to be around $80 million. However, the cut-off point can be chosen anywhere along the line based on the available budget. In Figures 2-4 intersections have been placed in order of cost-effectiveness, but they may also be placed in order of their high risk rank and a cut-off point determined based on this order.

Figure 4 shows the estimated reduction in the KSI metric for each intersection and the estimated cumulative reduction in the KSI metric if all intersections were treated. Treatment of all high risk intersections, excluding those where treatment has begun, is estimated to prevent approximately 66 serious or fatal injuries.

**Figure 2: Cost per unit reduction in the KSI metric and total cost at each high risk intersection (total costs < $900,000)**

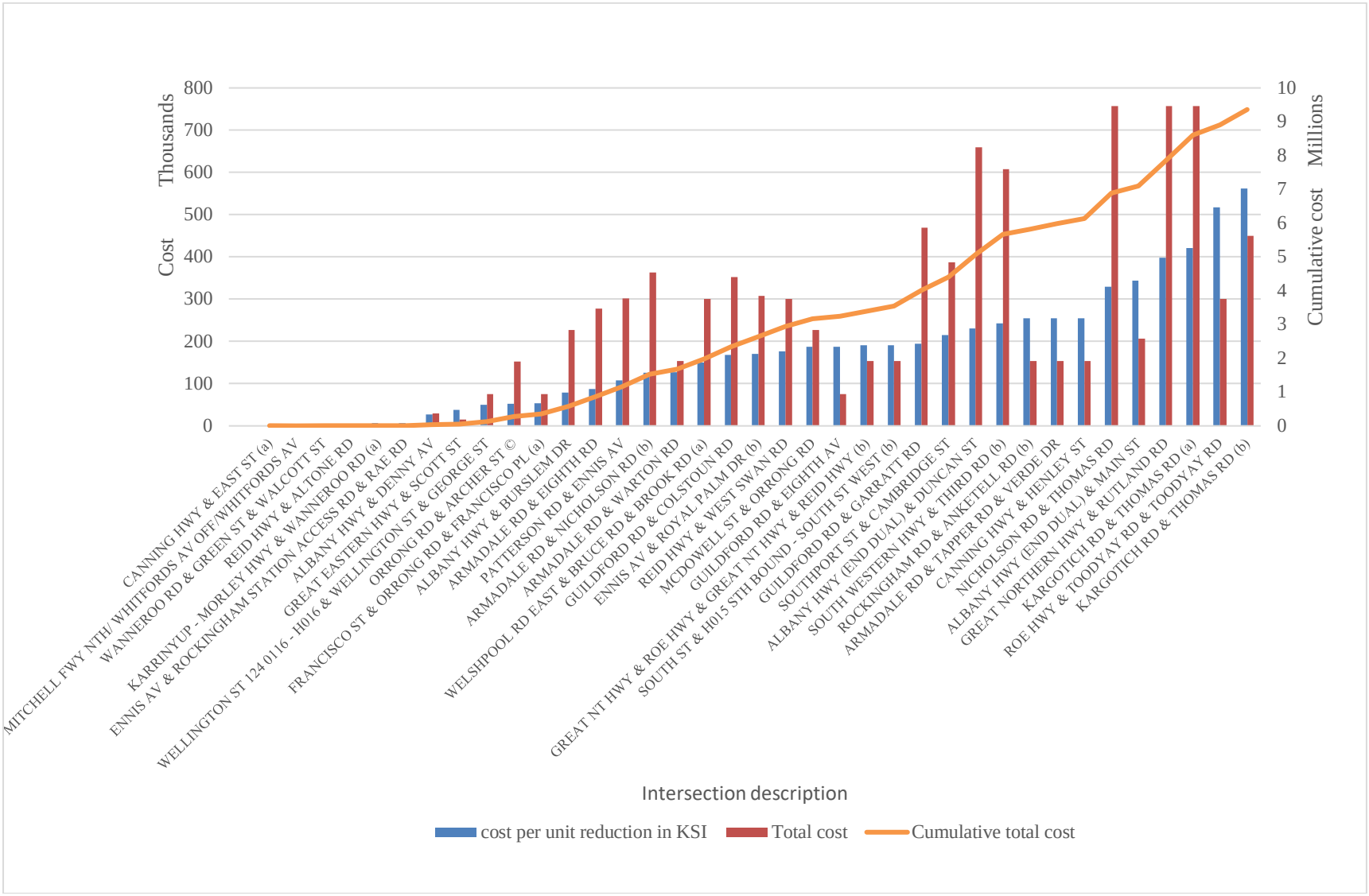


**Figure 3 Cost per unit reduction in the KSI metric and total cost at each high risk intersection (total costs > $900,000)**

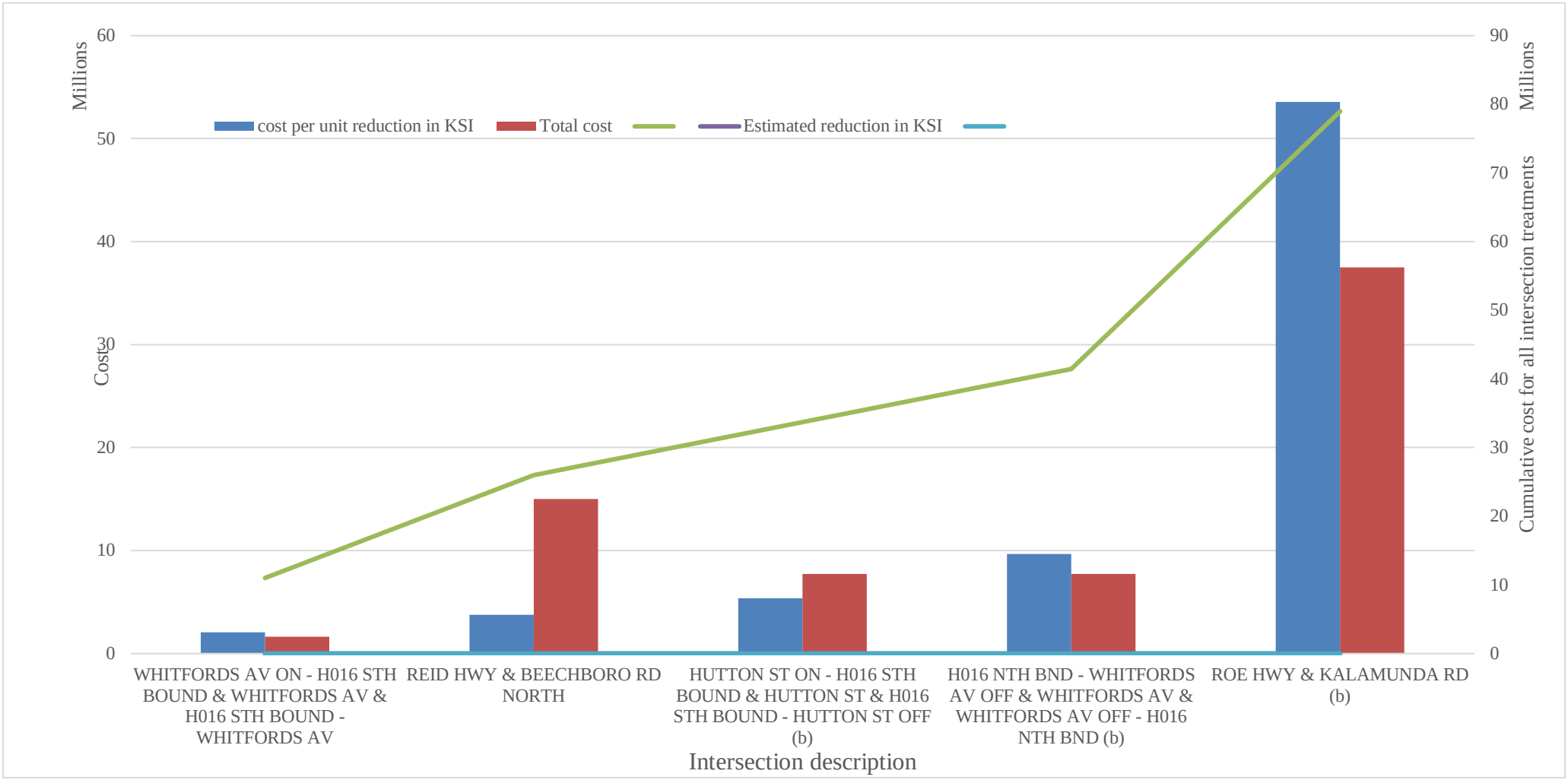
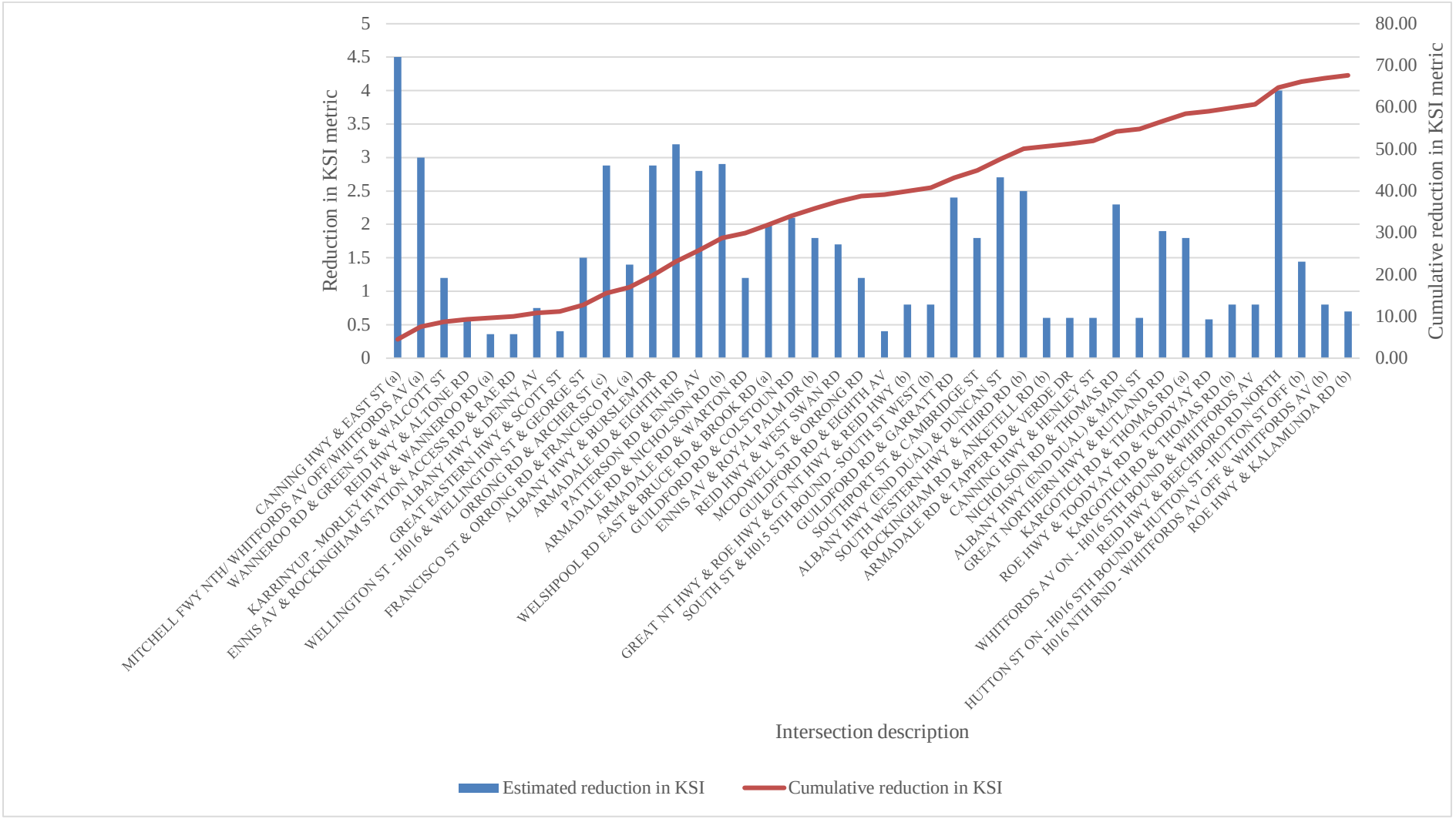


**Figure 4 Estimated individual and cumulative reduction in the KSI metric following intersection treatment ordered by cost-effectiveness**



# 4. DISCUSSION

This report examined appropriate treatments for high risk intersections in metropolitan Perth and their associated costs. This has allowed production of a cost per unit reduction in the KSI metric, which enables identification of the cost-effectiveness of treatments for the intersections and thus to show where the least amount of money can be spent to save the most lives. The method is flexible and can be suited to any budget.

Costs of treatments to reduce the KSI metric by one are shown to vary from less than $1000 to millions of dollars in cases where construction of bridges or grade separation is required. In many cases road safety measures must be accompanied by measures to deal with traffic congestion which then requires road construction projects and leads to escalating cost. In some cases more expensive intersection treatment is not undertaken because road construction projects are already planned that will include removal or rebuilding of the intersection.

The most common type of treatments recommended in this study were "*protected right turn lanes*" followed by "*roundabouts*", *red light cameras* and *signal modification*. The use of *protected right turn lanes*, *signal modification* and *red light cameras* reflects the fact the most of our high risk intersections were already signalized intersections. Roundabouts are currently thought to be the safest type of intersection for motor vehicles (Road and Traffic Engineering Branch, 2015) and these would provide suitable treatments for a number of high risk intersections currently without traffic signals.

These results have largely focused on providing "*safe roads*" to prevent crashes resulting in fatal and serious injuries at intersections. In some signalized intersections which already appear to have necessary countermeasures in place, it is likely necessary to address "*safe speed*". One proven method of reducing speed at signalized intersections is the deployment of red light cameras and this option has been considered at some sites. Reduction of the speed limit may be another option.

There are limitations of this project which should be noted. From 2014 onward, underreporting of hospitalisation crashes was observed. It was suggested that administrative changes introduced around this period caused a decrease in crashes being reported from one government agency to another. Government agencies are currently

working to rectify this problem. This is likely to result in an underestimate of cost-effectiveness estimates in this report and may be proportionally larger for intersections having the greatest number of hospitalisation crashes.

High level estimate of generic countermeasure costs were provided by Main Roads, but the precise cost is site specific and will depend on the nature and size of the construction project required. In some cases, the treatment would also require land acquisition and again the necessity for this and its cost not been estimated in detail. While these costs may not be completely accurate, the relative costs for intersections should still be reasonably accurate. It is recommended that once costs are firmed up that the locations continue to be re ranked to account for actual anticipated project costs.

Estimates of reduction in the KSI metric were taken from the Main Roads Crash Reduction Matrix. The accuracy of our estimates are dependent on the validity of this matrix. Main Roads advised that this matrix and the reductions contained within are due for a review.

This is the only study of this nature that we are aware of, largely as it is specific to named intersections in the Perth metropolitan area. However, there are a number of generalizable conclusions regarding the most cost-effectiveness of intersection treatments and we have presented a method that allows prioritization of intersection treatments based on their cost-effectiveness and which can be suited to any budget.

# 5. RECOMMENDATIONS

## 5.1 Recommendations for intersection safety improvements

That Main Roads consider the cost-effectiveness estimates when implementing their new program of work

## 5.2 Recommendations for future work

That the evidence base on which reductions in crashes are based continues to be improved.

That Main Roads continue to collect more detailed data on costs where possible.

## 5.3 Conclusion

Our approach of estimating cost per unit reduction in the KSI metric allows identification of where the road safety budget can be spent to enable the greatest reduction in crashes causing serious injury or death. However, this does not negate the requirement for the more expensive construction projects such as grade separation which are focussed on improving traffic flow and preventing congestion but also result in safer intersections.

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## APPENDIX A – Additional tables

### Table 5: Thresholds for categories of crash density and crash rate by intersection type[2]

| Comparative Performance | | Percentile Band | Speed Environment | Traffic Signals | Roundabout | No Traffic Signals |
|---|---|---|---|---|---|---|
| V | Extremely poor | 90 to 100th | Built-Up Speed Environment | Greater than 103.11 | Greater than 137.28 | Greater than 116.4 |
| IV | Very poor | 70 to 90th | | 62.00 to 103.11 | 49.96 to 137.28 | 46.94 to 116.4 |
| III | Poor | 50 to 70th | | 41.63 to 62.00 | 33.34 to 49.96 | 24.99 to 46.94 |
| II | Adequate | 30 to 50th | | 26.98 to 41.63 | 12.70 to 33.34 | 10.28 to 24.99 |
| I | Good | 0 to 30th | | Less than 26.98 | Less than 12.70 | Less than 10.28 |

| Comparative Performance | | Percentile Band | Speed Environment | Traffic Signals | Roundabout | No Traffic Signals |
|---|---|---|---|---|---|---|
| V | Extremely poor | 90 to 100th | Open Speed Environment | Greater than 155.45 | Greater than 97.34 | Greater than 361.38 |
| IV | Very poor | 70 to 90th | | 99.92 to 155.45 | 31.59 to 97.34 | 146.41 to 361.38 |
| III | Poor | 50 to 70th | | 61.48 to 99.92 | 28.25 to 31.59 | 74.31 to 146.41 |
| II | Adequate | 30 to 50th | | 36.00 to 61.48 | 21.75 to 28.25 | 37.68 to 74.31 |
| I | Good | 0 to 30th | | Less than 36.00 | Less than 21.75 | Less than 37.68 |

| Comparative Performance | | Percentile Band | Speed Environment | Traffic Signals | Roundabout | No Traffic Signals |
|---|---|---|---|---|---|---|
| V | Extremely poor | 90 to 100th | Low-Speed Environment | Greater than 252.46 | No cut-offs provided by Main Roads Western Australia due to low number of such intersections | Greater than 289.36 |
| IV | Very poor | 70 to 90th | | 104.00 to 252.46 | | 63.11 to 289.36 |
| III | Poor | 50 to 70th | | 68.87 to 104.00 | | 23.45 to 63.11 |
| II | Adequate | 30 to 50th | | 45.70 to 68.87 | | 5.95 to 23.45 |
| I | Good | 0 to 30th | | Less than 45.70 | | Less than 5.95 |

[2] Thresholds are percentile cut-offs provided by Main Roads Western Australia

**Table 6: Ranking of high risk intersections**

| Inter-section Number | Intersection Description | Product of Flow | Crash Rate | Crash Rate Category | Crash Density Category | RTR[1] Quadrant | CSP[2] Category | KSI Metric | Inter-section rank |
|---|---|---|---|---|---|---|---|---|---|
| 14275 | GUILDFORD RD & H017 STH BOUND ON & OFF RAMPS | 3,425.13 | 155.74 | High | High | Black | V | 16.55 | 1 |
| 14261 | REID HWY & BEECHBORO RD NORTH | 2,314.13 | 180.89 | High | High | Black | V | 12.99 | 2 |
| 4061 | ARMADALE RD & NICHOLSON RD | 1,940.28 | 211.94 | High | High | Black | V | 12.76 | 3 |
| 50781 | SOUTHPORT ST & CAMBRIDGE ST | 3,524.70 | 113.63 | High | High | Black | V | 12.43 | 4 |
| 39039 | FRANCISCO ST & ORRONG RD & FRANCISCO PL | 3,329.14 | 104.13 | Med-High | High | Black | V | 10.76 | 5 |
| 3642 | REID HWY & REID HWY - MITCHELL FWY STH ON & H016 STH BOUND - REID HWY OFF & BALC | 2,904.69 | 116.73 | High | High | Black | V | 10.52 | 6 |
| 14185 | ALBANY HWY (END DUAL) & DUNCAN ST | 847.88 | 393.72 | High | High | Black | V | 10.36 | 7 |
| 4347 | HUTTON ST ON - H016 STH BOUND & HUTTON ST & H016 STH BOUND - HUTTON ST OFF | 1,764.45 | 151.58 | High | High | Black | V | 8.30 | 8 |
| 13882 | H016 NTH BND - WHITFORDS AV OFF & WHITFORDS AV & WHITFORDS AV OFF - H016 NTH BND | 1,746.19 | 152.63 | High | High | Black | V | 8.27 | 9 |
| 14753 | ALBANY HWY & BURSLEM DR | 2,030.19 | 126.27 | High | High | Black | V | 7.95 | 10 |
| 81636 | MCDOWELL ST & ORRONG RD | 1,382.65 | 179.01 | High | High | Black | V | 7.68 | 11 |
| 54230 | NICHOLSON RD & THOMAS RD | 1,353.33 | 169.91 | High | High | Black | V | 7.13 | 12 |
| 42886 | CANNING HWY & EAST ST | 1,252.39 | 182.49 | High | High | Black | V | 7.09 | 13 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 14184 | ARMADALE RD & WARTON RD | 790.82 | 252.34 | High | High | Black | V | 6.19 | 14 |
| 141661 | TONKIN HWY & CHAMPION DR | 668.56 | 298.38 | High | High | Black | V | 6.19 | 15 |
| 14902 | ROE HWY & MORRISON RD & MORRISON RD | 1,141.09 | 170.47 | High | High | Black | V | 6.03 | 16 |
| 14192 | ALBANY HWY & GRESHAM ST | 1,496.35 | 117.13 | High | High | Black | V | 5.44 | 17 |
| 45285 | WELSHPOOL RD EAST & BRUCE RD & BROOK RD | 850.04 | 203.48 | High | High | Black | V | 5.37 | 18 |
| 168405 | H016 NTH BND END & BURNS BEACH RD | 984.04 | 175.76 | High | High | Black | V | 5.37 | 19 |
| 14879 | SOUTH WESTERN HWY & THIRD RD | 719.71 | 223.61 | High | High | Black | V | 4.99 | 20 |
| 14845 | ALBANY HWY & DENNY AV | 1,075.08 | 145.65 | High | High | Black | V | 4.86 | 21 |
| 14295 | GUILDFORD RD & COLSTOUN RD | 878.20 | 176.73 | High | High | Black | V | 4.82 | 22 |
| 82815 | ALBANY HWY (END DUAL) & MAIN ST | 706.74 | 212.69 | High | High | Black | V | 4.66 | 23 |
| 47051 | SOUTH ST & WHEATLEY DR | 1,198.25 | 122.32 | High | High | Black | V | 4.55 | 24 |
| 14786 | ROE HWY & BERKSHIRE RD | 1,084.13 | 133.33 | High | High | Black | V | 4.48 | 25 |
| 12315 | ARMADALE RD & TAPPER RD & VERDE DR | 1,297.60 | 110.84 | High | High | Black | V | 4.46 | 26 |
| 119141 | REID HWY & OKELY RD (NORTH) | 1,334.46 | 103.86 | Med-High | High | Black | V | 4.30 | 27 |
| 119092 | KWINANA FWY NTH - RUSSELL RD & RUSSELL RD & RUSSELL RD - KWINANA FWY NTH | 513.20 | 250.24 | High | High | Black | V | 3.98 | 28 |
| 14121 | CANNING HWY & HENLEY ST | 1,160.57 | 110.41 | High | High | Black | V | 3.98 | 29 |
| 4414 | ALBANY HWY & GOSNELLS RD WEST | 706.25 | 176.09 | High | High | Black | V | 3.86 | 30 |
| 50639 | EAST PDE - LORD ST & LORD ST & NEWCASTLE ST | 1,168.34 | 105.11 | Med-High | High | Black | V | 3.81 | 31 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 138328 | ENNIS AV (NTH BND) & PORT KENNEDY DR | 1,538.38 | 305.05 | High | High | Black | IV | 14.56 | 32 |
| 4549 | TONKIN HWY & GOSNELLS RD WEST | 1,700.49 | 237.80 | High | High | Black | IV | 12.55 | 33 |
| 14241 | TONKIN HWY & BENARA RD | 2,522.55 | 153.09 | High | High | Black | IV | 11.98 | 34 |
| 4543 | TONKIN HWY & HORRIE MILLER DR & KEWDALE RD | 3,185.22 | 106.62 | High | High | Black | IV | 10.54 | 35 |
| 77668 | REID HWY & WEST SWAN RD | 3,109.87 | 99.56 | Med-High | High | Black | IV | 9.61 | 36 |
| 4552 | ROE HWY & KALAMUNDA RD | 2,622.48 | 117.37 | High | High | Black | IV | 9.55 | 37 |
| 4147 | GREAT NORTHERN HWY & ROE HWY & GREAT NORTHERN HWY & REID HWY | 3,165.27 | 93.42 | Med-High | High | Black | IV | 9.17 | 38 |
| 4143 | PATTERSON RD & ENNIS AV | 2,361.60 | 119.53 | High | High | Black | IV | 8.76 | 39 |
| 4336 | WANNEROO RD & NEWCASTLE ST & CHARLES ST ON - H016 STH BOUND & H016 NTH BOUND - C | 2,666.58 | 95.56 | Med-High | High | Black | IV | 7.91 | 40 |
| 55048 | KARRINYUP - MORLEY HWY & WANNEROO RD | 3,085.44 | 80.76 | Med-High | High | Black | IV | 7.73 | 41 |
| 77885 | REID HWY & ALTONE RD | 1,694.96 | 145.01 | High | High | Black | IV | 7.63 | 42 |
| 1544 | ENNIS AV & ROCKINGHAM STATION ACCESS RD & RAE RD | 2,362.26 | 100.92 | Med-High | High | Black | IV | 7.40 | 43 |
| 55516 | KARRINYUP - MORLEY HWY & FLINDERS ST | 2,996.15 | 78.79 | Med-High | High | Black | IV | 7.32 | 44 |
| 36346 | ARMADALE RD & EIGHTH RD | 1,470.23 | 160.56 | High | High | Black | IV | 7.32 | 45 |
| 38822 | ORRONG RD & ARCHER ST | 2,731.93 | 85.31 | Med-High | High | Black | IV | 7.23 | 46 |
| 50690 | WANNEROO RD & GREEN ST & WALCOTT ST | 2,874.66 | 79.39 | Med-High | High | Black | IV | 7.08 | 47 |
| 50569 | WELLINGTON ST 124 0116 - H016 & WELLINGTON ST & GEORGE ST | 1,137.22 | 198.78 | High | High | Black | IV | 7.01 | 48 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 4160 | GUILDFORD RD & GARRATT RD | 3,119.15 | 72.45 | Med-High | High | Black | IV | 7.01 | 49 |
| 75571 | ENNIS AV & WILLMOTT DR | 967.98 | 226.54 | High | High | Black | IV | 6.80 | 50 |
| 4018 | GREAT NORTHERN HWY & RUTLAND RD | 789.65 | 272.74 | High | High | Black | IV | 6.68 | 51 |
| 14106 | SOUTH ST & H015 STH BOUND - SOUTH ST WEST | 2,577.70 | 81.10 | Med-High | High | Black | IV | 6.49 | 52 |
| 10142 | ROCKINGHAM RD & ANKETELL RD | 1,804.63 | 108.22 | High | High | Black | IV | 6.06 | 53 |
| 54070 | KARGOTICH RD & THOMAS RD | 579.39 | 336.45 | High | High | Black | IV | 6.05 | 54 |
| 14898 | ROE HWY & TOODYAY RD & TOODYAY RD | 2,878.37 | 62.87 | Med-High | High | Black | IV | 5.61 | 55 |
| 14172 | GUILDFORD RD & EIGHTH AV | 1,933.93 | 89.15 | Med-High | High | Black | IV | 5.35 | 56 |
| 80578 | ENNIS AV & ROYAL PALM DR | 842.57 | 203.26 | High | High | Black | IV | 5.31 | 57 |
| 4432 | GREAT EASTERN HWY & SCOTT ST | 1,750.35 | 97.81 | Med-High | High | Black | IV | 5.31 | 58 |
| 14713 | GREAT EASTERN HWY & FAUNTLEROY AV | 2,432.35 | 69.48 | Med-High | High | Black | IV | 5.24 | 59 |
| 13900 | WHITFORDS AV ON - H016 STH BOUND & WHITFORDS AV & H016 STH BOUND - WHITFORDS AV | 1,987.46 | 84.10 | Med-High | High | Black | IV | 5.19 | 60 |

[1]RTR: Road Trauma Risk [2]CSP: Comparative Safety Performance
*Modification date

**Table 7: Treatments, cost and cost per unit reduction in KSI metric for the Top 60 intersections ordered by cost-effectiveness***

| Intersection Description | Treatments | Road infrastructure, ancillary works and operating cost $ α | Estimated reduction in the KSI metric | Cost per unit reduction in the KSI metric, $ | Intersection alterations |
|---|---|---|---|---|---|
| CANNING HWY & EAST ST (a) | Extend median through intersection to allow only left in left out movements | $4,500 | 4.5 | $667 | |
| CANNING HWY & EAST ST (b) | Improve sight lines for right approach (eg clear verge) | $11,250 | 0.9 | $6,667 | |
| CANNING HWY & EAST ST (c) | Add wider median to protect right turners | $15,000 | 0.4 | $25,000 | |
| KARRINYUP - MORLEY HWY & FLINDERS ST (a) | Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $2,250 | 3 | $750 | Remove filter, extend right turn pockets July 2016 |
| KARRINYUP - MORLEY HWY & FLINDERS ST (b) | Extend right turn pocket to mitigate rear end crashes in through lane | $241,500 | 0.4 | $603,750 | Remove filter, extend right turn pockets July 2016 |
| H016 NTH BND - WHITFORDS AV OFF & WHITFORDS AV & WHITFORDS AV OFF - H016 NTH BND (a) | Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $2,250 | 3 | $750 | |

| | | | | | |
|---|---|---|---|---|---|
| H016 NTH BND - WHITFORDS AV OFF & WHITFORDS AV & WHITFORDS AV OFF - H016 NTH BND (b) | Bridge widening (use 0.5 grade sep); Protected right turn lane (indented right turn island) | $7,727,250 | 0.8 | $9,659,063 | |
| WANNEROO RD & GREEN ST & WALCOTT ST | Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $2,250 | 1.2 | $1,875 | |
| REID HWY & ALTONE RD | Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $2,250 | 0.6 | $2,500 | |
| REID HWY & OKELY RD (NORTH) - altered Jan 2016 | Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $2,250 | 0.6 | $3,750 | January 2016, extra lane added to Reid Hwy in both directions, Remove right filter |
| ENNIS AV & ROYAL PALM DR (a) | Street closure [close stem of Tee] | $15,000 | 3 | $5,000 | |
| ENNIS AV & ROYAL PALM DR (b) | Roundabout | $307,500 | 1.8 | $170,833 | |
| KARRINYUP - MORLEY HWY & WANNEROO RD (a) | Traffic light phasing | $2,250 | 0.36 | $6,250 | |

| | | | | | |
|---|---|---|---|---|---|
| KARRINYUP - MORLEY HWY & WANNEROO RD (b) | Protected right turn lane (indented right turn island) | $600,000 | 0.58 | $1,034,483 | |
| ENNIS AV & ROCKINGHAM STATION ACCESS RD & RAE RD | Traffic light phasing | $2,250 | 0.36 | $6,250 | |
| GREAT NORTHERN HWY & ROE HWY & GREAT NORTHERN HWY & REID HWY (a) | Traffic light phasing; | $4,500 | 0.6 | $7,500 | |
| GREAT NORTHERN HWY & ROE HWY & GREAT NORTHERN HWY & REID HWY (b) | Red light camera | $153,000 | 0.8 | $191,250 | |
| SOUTH ST & WHEATLEY DR | Seagull in median (select terminating leg of Tee) not recommended for median widths < 10m. | $7,500 | 0.8 | $9,375 | Seagull added to South street median strip July 2014⁑ |
| SOUTH ST & H015 STH BOUND - SOUTH ST WEST (a) | Traffic light phasing; red light camera | $2,250 | 0.2 | $11,250 | |

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|---|---|---|---|---|---|
| SOUTH ST & H015 STH BOUND - SOUTH ST WEST (b) | Red light camera | $153,000 | 0.8 | $191,250 | |
| ROCKINGHAM RD & ANKETELL RD (a) | Traffic light phasing; red light camera | $2,250 | 0.2 | $11,250 | |
| ROCKINGHAM RD & ANKETELL RD (b) | Red light camera | $153,000 | 0.6 | $255,000 | |
| ALBANY HWY & DENNY AV | Street closure | $30,000 | 0.75 | $26,667 | |
| GREAT EASTERN HWY & SCOTT ST | Seagull in median (select terminating leg of Tee) not recommended for median widths < 10m. | $15,000 | 0.4 | $37,500 | |
| TONKIN HWY & GOSNELLS RD WEST | New signal with right turn arrows (without filter) | $277,500 | 5.6 | $49,554 | Traffic lights added August 2016 |
| WELLINGTON ST 124 0116 - H016 & WELLINGTON ST & GEORGE ST | Mast arm | $75,000 | 1.5 | $50,000 | |
| ORRONG RD & ARCHER ST | Modify signals - prevent right turn filter (for existing right turn arrows with filter); Protected right turn lane (indented right turn island) | $152,250 | 2.88 | $52,865 | |

| | | | | | |
|---|---|---|---|---|---|
| FRANCISCO ST & ORRONG RD & FRANCISCO PL (a) | Add mast arm Orrong Rd | $75,000 | 1.4 | $53,571 | |
| FRANCISCO ST & ORRONG RD & FRANCISCO PL (b) | Protected right turn lane (indented right turn island); Land acquisition; Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $1,952,250 | 2.92 | $668,579 | |
| FRANCISCO ST & ORRONG RD & FRANCISCO PL (c) | Both options together | $2,027,250 | 3.1 | $653,952 | |
| ENNIS AV (NTH BND) & PORT KENNEDY DR | New traffic signal [no turn arrow] | $517,500 | 7.7 | $67,208 | traffic lights added May 2015⁑ |
| ALBANY HWY & GRESHAM ST | Ban right turns; widen Gresham street on both sides | $38,250 | 1 | $75,750 | June 2017 under construction. |
| ALBANY HWY & BURSLEM DR | Protected right turn lane (indented right turn island); Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $227,250 | 2.88 | $78,906 | |
| ARMADALE RD & EIGHTH RD | Roundabout | $277,500 | 3.2 | $86,719 | |
| ARMADALE RD & EIGHTH RD | Traffic lights | $352,500 | 3.5 | $100,714 | |
| ENNIS AV & WILLMOTT DR | New signal with right turn arrows (without filter) | $352,500 | 3.5 | $100,714 | traffic lights added Dec 2014⁑ |

| | | | | | |
|---|---|---|---|---|---|
| PATTERSON RD & ENNIS AV | Indented left turn slip (give way, stop or signal control) | $301,500 | 2.8 | $107,679 | |
| ARMADALE RD & NICHOLSON RD (a) | Repaint lines on road | $23,250 | 0 | - | |
| ARMADALE RD & NICHOLSON RD (b) | Modify signals - reconstruct intersection (with right turn arrows without filter) Armadale road; add 2*RT lanes Armadale Road | $363,750 | 2.9 | $125,431 | |
| ARMADALE RD & NICHOLSON RD (b) | Roundabout | $1,507,500 | 1.6 | $942,188 | |
| ARMADALE RD & WARTON RD | Modify phasing/red light camera | $153,000 | 1.2 | $127,500 | |
| WELSHPOOL RD EAST & BRUCE RD & BROOK RD (a) | Ban right turns; facilitate u-turns | $300,750 | 2 | $150,375 | |
| WELSHPOOL RD EAST & BRUCE RD & BROOK RD (b) | Roundabout | $1,207,500 | 3.2 | $377,344 | |
| GUILDFORD RD & COLSTOUN RD | New signal with right turn arrows (without filter) | $352,500 | 2.1 | $167,857 | |
| REID HWY & WEST SWAN RD | Protected right turn lane (indented right turn island) | $300,000 | 1.7 | $176,471 | |

| | | | | | |
|---|---|---|---|---|---|
| ROE HWY & KALAMUNDA RD (a) | Add extra lanes | $600,000 | 3.3 | $181,818 | |
| ROE HWY & KALAMUNDA RD (b) | Grade separation | $37,503,750 | 0.7 | $53,576,786 | |
| MCDOWELL ST & ORRONG RD | Protected right turn lane (indented right turn island) | $227,250 | 1.2 | $187,500 | |
| GUILDFORD RD & EIGHTH AV | Traffic signal: Overhead mast arms | $75,000 | 0.4 | $187,500 | |
| GUILDFORD RD & GARRATT RD | Extend right turn pocket to mitigate rear end crashes in through lane; Extend left turn pocket to mitigate rear end crashes in through lane; Modify signals - prevent right turn filter (for existing right turn arrows with filter); mast arm | $468,750 | 2.404 | $194,988 | |
| SOUTHPORT ST & CAMBRIDGE ST | Modify signals - new right turn arrows (without filter); Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $387,000 | 1.8 | $215,000 | |
| ALBANY HWY (END DUAL) & DUNCAN ST | 2 * Extend right turn pocket; widen Duncan St south; Indented left turn slip (give way, stop or signal control); Modify signals - prevent right turn filter (for existing right turn arrows with filter) | $659,250 | 2.7 | $230,278 | |

| | | | | | |
|---|---|---|---|---|---|
| SOUTH WESTERN HWY & THIRD RD (b) | Roundabout | $607,500 | 2.5 | $243,000 | |
| SOUTH WESTERN HWY & THIRD RD (a) | Traffic median islands on approaches; Protected right turn lane (indented right turn island) | $337,500 | 0.47 | $718,085 | |
| ALBANY HWY & GOSNELLS RD WEST | New signal with right turn arrows (without filter) | $352,500 | 1.4 | $251,786 | Traffic lights Feb 2013⁑ |
| ARMADALE RD & TAPPER RD & VERDE DR | Modify phasing/red light camera | $153,000 | 0.6 | $255,000 | |
| CANNING HWY & HENLEY ST | Modify phasing/red light camera | $153,000 | 0.6 | $255,000 | |
| GUILDFORD RD & H017 STH BOUND ON & OFF RAMPS | Protected right turn lane (indented right turn island); extend right turn pocket; extend left turn pocket | $618,000 | 2.4 | $257,500 | |
| NICHOLSON RD & THOMAS RD | Roundabout | $757,500 | 2.3 | $329,348 | |
| ALBANY HWY (END DUAL) & MAIN ST | Modify signals - new right turn arrows (without filter) | $206,250 | 0.6 | $343,750 | |

| | | | | | |
|---|---|---|---|---|---|
| EAST PDE - LORD ST & LORD ST & NEWCASTLE ST | Protected right turn lane (indented right turn island) | $150,000 | 0.4 | $375,000 | RT lane added East Parade June 2016 |
| GREAT NORTHERN HWY & RUTLAND RD | Roundabout | $757,500 | 1.9 | $398,684 | |
| KARGOTICH RD & THOMAS RD (a) | Roundabout | $757,500 | 1.8 | $420,833 | |
| KARGOTICH RD & THOMAS RD (b) | Protected right turn lane (indented right turn island); Seagull in median (select terminating leg of Tee) not recommended for median widths < 10m. | $450,000 | 0.8 | $562,500 | |
| ROE HWY & TOODYAY RD & TOODYAY RD | Protected right turn lane (indented right turn island) | $300,000 | 0.58 | $517,241 | |
| HUTTON ST ON - H016 STH BOUND & HUTTON ST & H016 STH BOUND - HUTTON ST OFF (a) | Extend left turn pocket to mitigate rear end crashes in through lane | $271,500 | 0.4 | $678,750 | |
| HUTTON ST ON - H016 STH BOUND & HUTTON ST & H016 STH BOUND - HUTTON ST OFF (b) | Bridge widening (cost as for 0.5 grade sep); Protected right turn lane (indented right turn island) | $7,728,750 | 1.44 | $5,367,188 | |

| | | | | | |
|---|---|---|---|---|---|
| GREAT EASTERN HWY & FAUNTLEROY AV | Protected right turn lane (indented right turn island); Protected right turn lane (indented right turn island) | $600,000 | 0.7 | $857,143 | bus lane and right turning lane/uturn lane added end 2016 |
| WHITFORDS AV ON - H016 STH BOUND & WHITFORDS AV & H016 STH BOUND - WHITFORDS AV | Protected right turn lane (indented right turn island); widen bridge | $1,650,000 | 0.8 | $2,062,500 | |
| REID HWY & BEECHBORO RD NORTH | Grade separation | $15,003,750 | 4 | $3,750,938 | |
| TONKIN HWY & BENARA RD | Grade separation | $37,503,750 | 3 | $12,501,250 | under construction |
| REID HWY & REID HWY - MITCHELL FWY STH ON & H016 STH BOUND - REID HWY OFF & BALC | | - | - | - | Upgraded last quarter 2015 - more lanes added going straight ahead⁑ |
| TONKIN HWY & CHAMPION DR | Protected right turn lane (indented right turn island) | $150,000 | 0 | - | Right turning lane added to Champion Dr in June 2012⁑ |

| | | | | | |
|---|---|---|---|---|---|
| ROE HWY & MORRISON RD & MORRISON RD | Protected right turn lane (indented right turn island) | $225,000 | 0 | - | extra right turning lane added Roe hwy north in June 2012⁑ |
| H016 NTH BND END & BURNS BEACH RD | | - | - | - | Extension of Mitchell Freeway 2017 |
| ROE HWY & BERKSHIRE RD | - | - | - | - | Grade separation June 2016 |
| KWINANA FWY NTH - RUSSELL RD & RUSSELL RD & RUSSELL RD - KWINANA FWY NTH | - | - | - | - | junction modified due to new train station 2016/7 |
| TONKIN HWY & HORRIE MILLER DR & KEWDALE RD | Grade separation | - | - | - | Improvement to airport access roads 2016/17 |
| WANNEROO RD & NEWCASTLE ST & CHARLES ST ON - H016 STH BOUND & H016 NTH BOUND - C | - | - | - | - | Ease congestion by adding bus bridge. Additional traffic lanes added. |

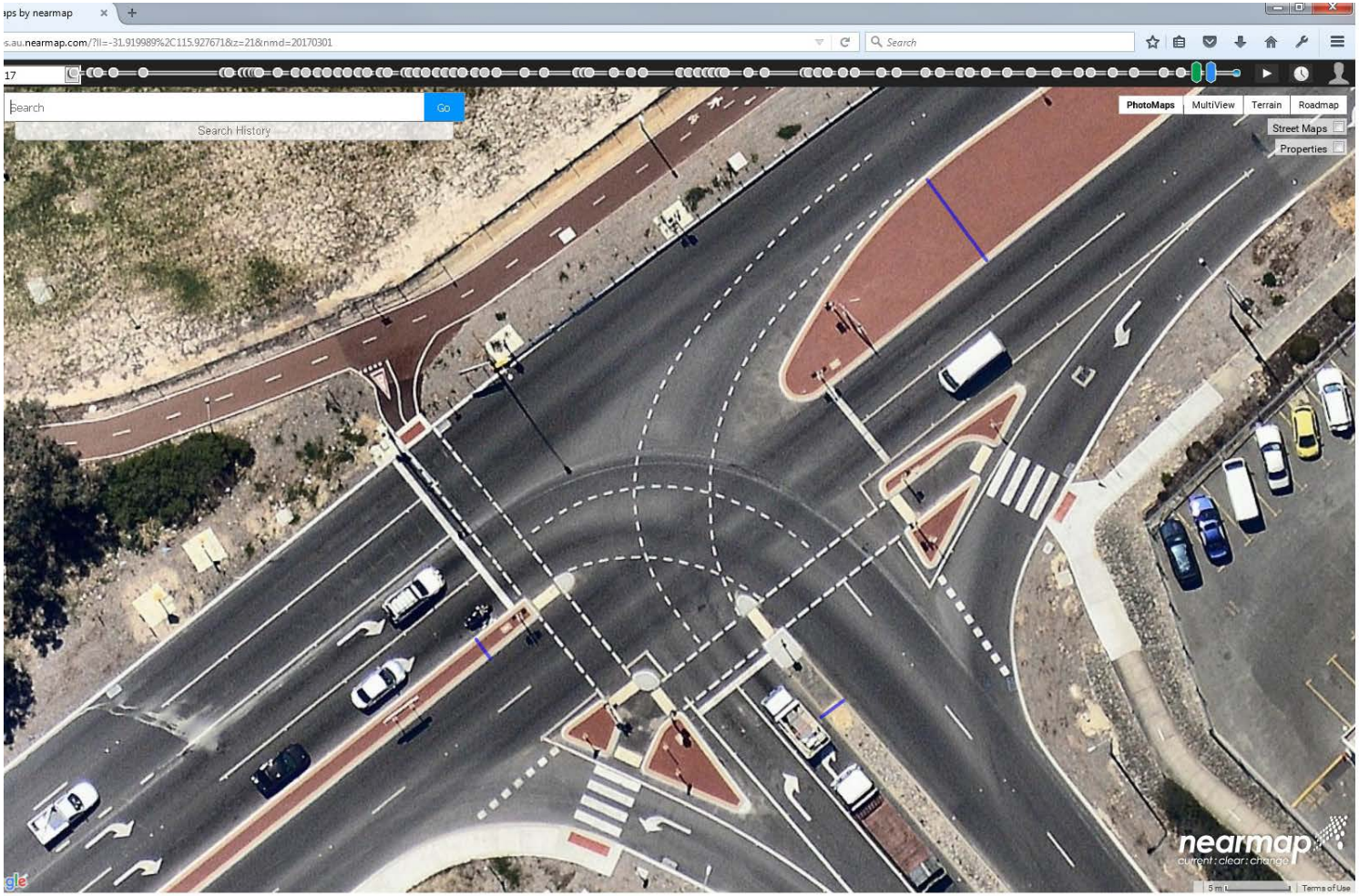
*Intersections have been ranked according to cost-effectiveness, but where multiple options are available, they are ordered by the most cost-effective of the available options.

‡Results have not been adjusted to reflect implementation of countermeasures prior to the end of 2015. This may result in underestimation of cost-effectiveness.

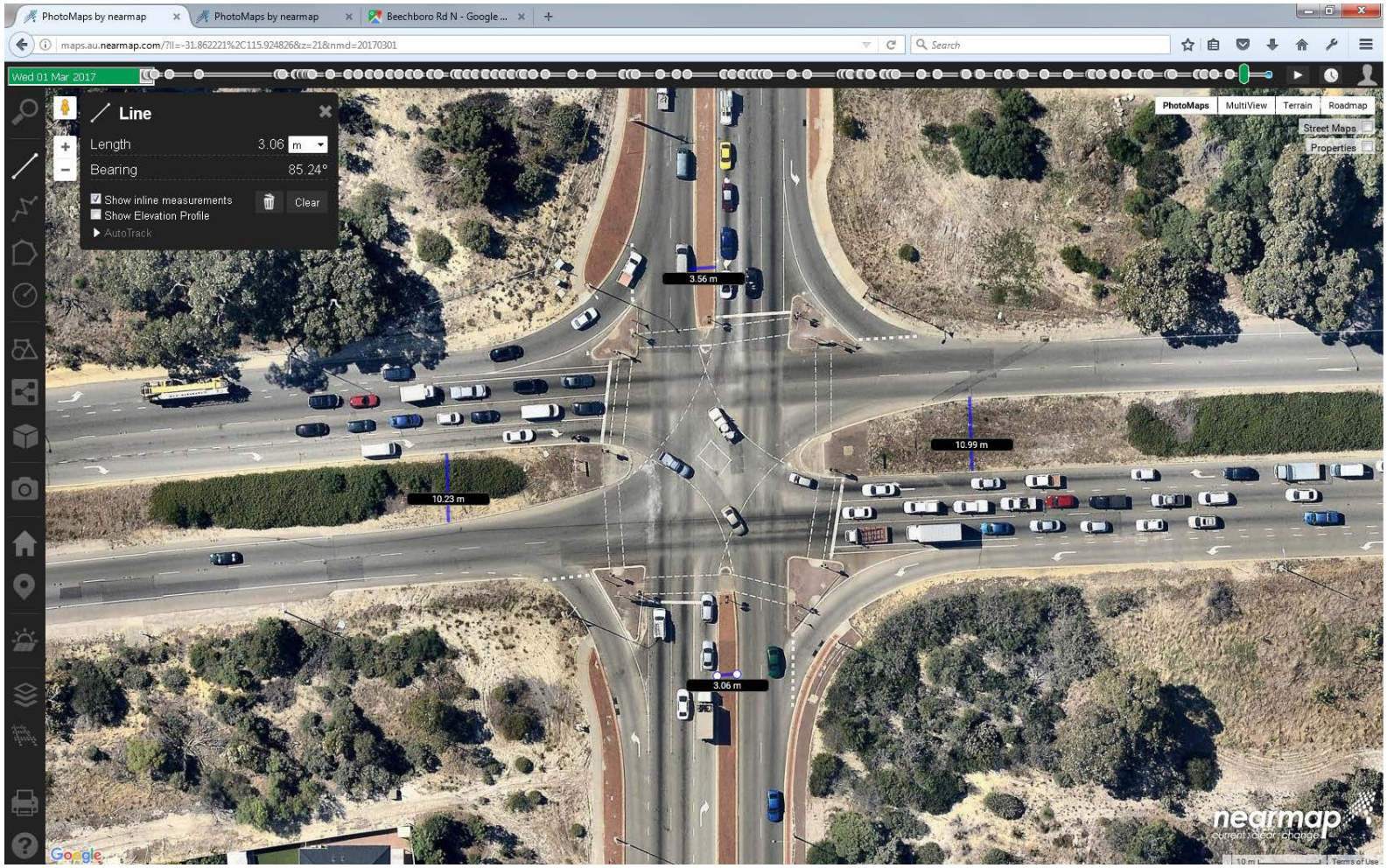
α Cost does not include traffic surveys and modelling or traffic management.

## APPENDIX B – Aerial photographs of high risk intersections

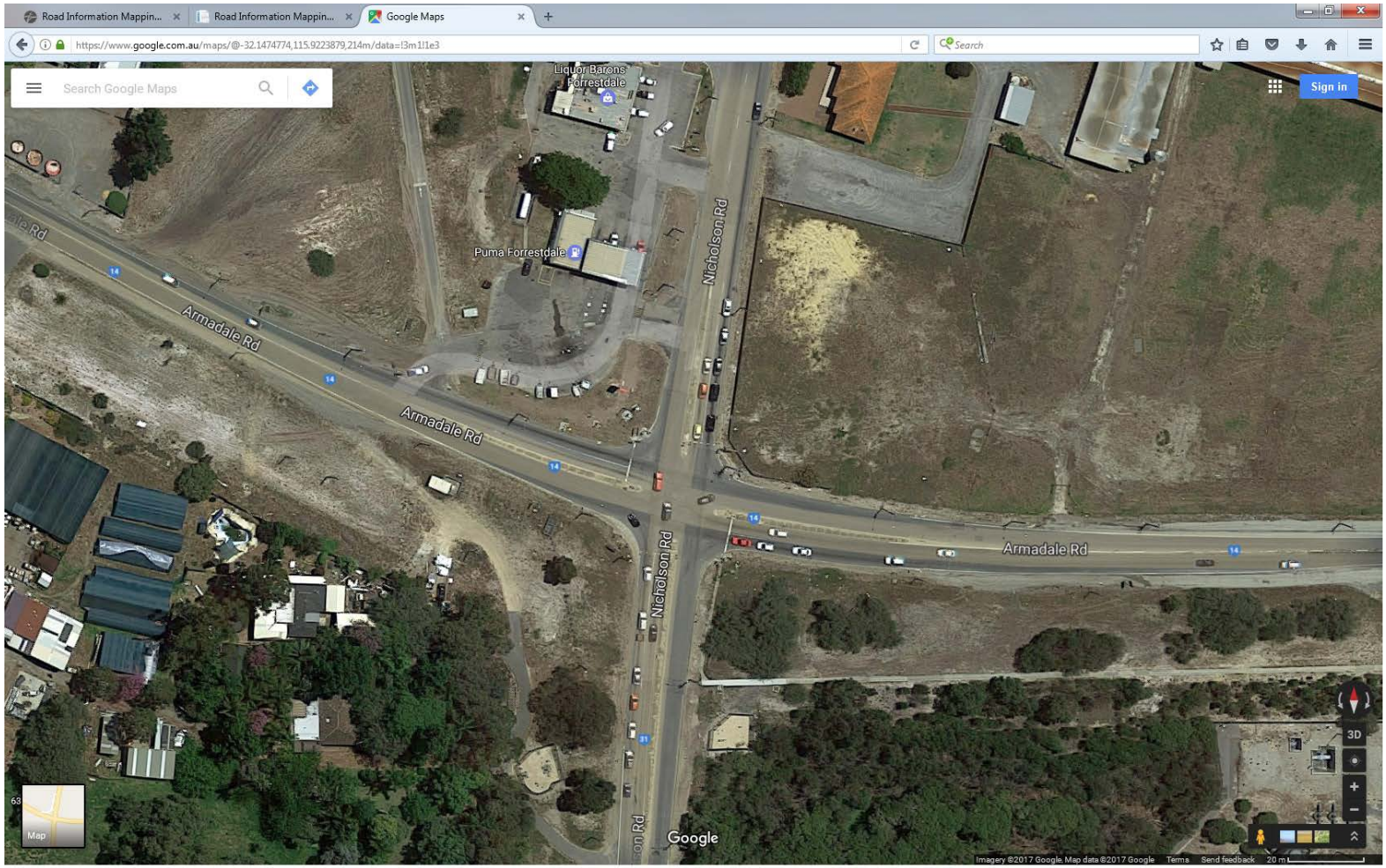
1. GUILDFORD RD & H017 STH BOUND ON & OFF RAMPS



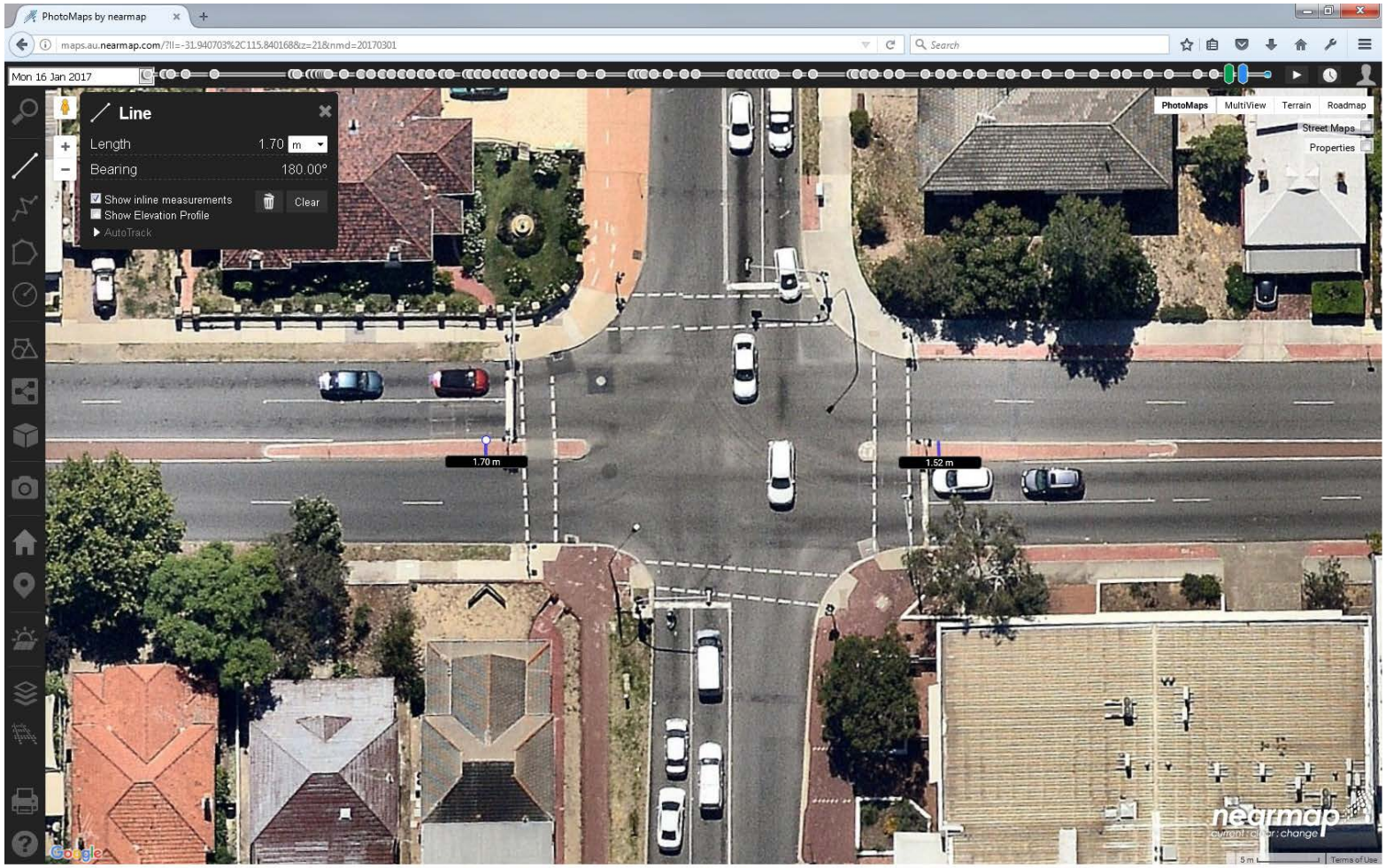
2. REID HWY & BEECHBORO RD NORTH



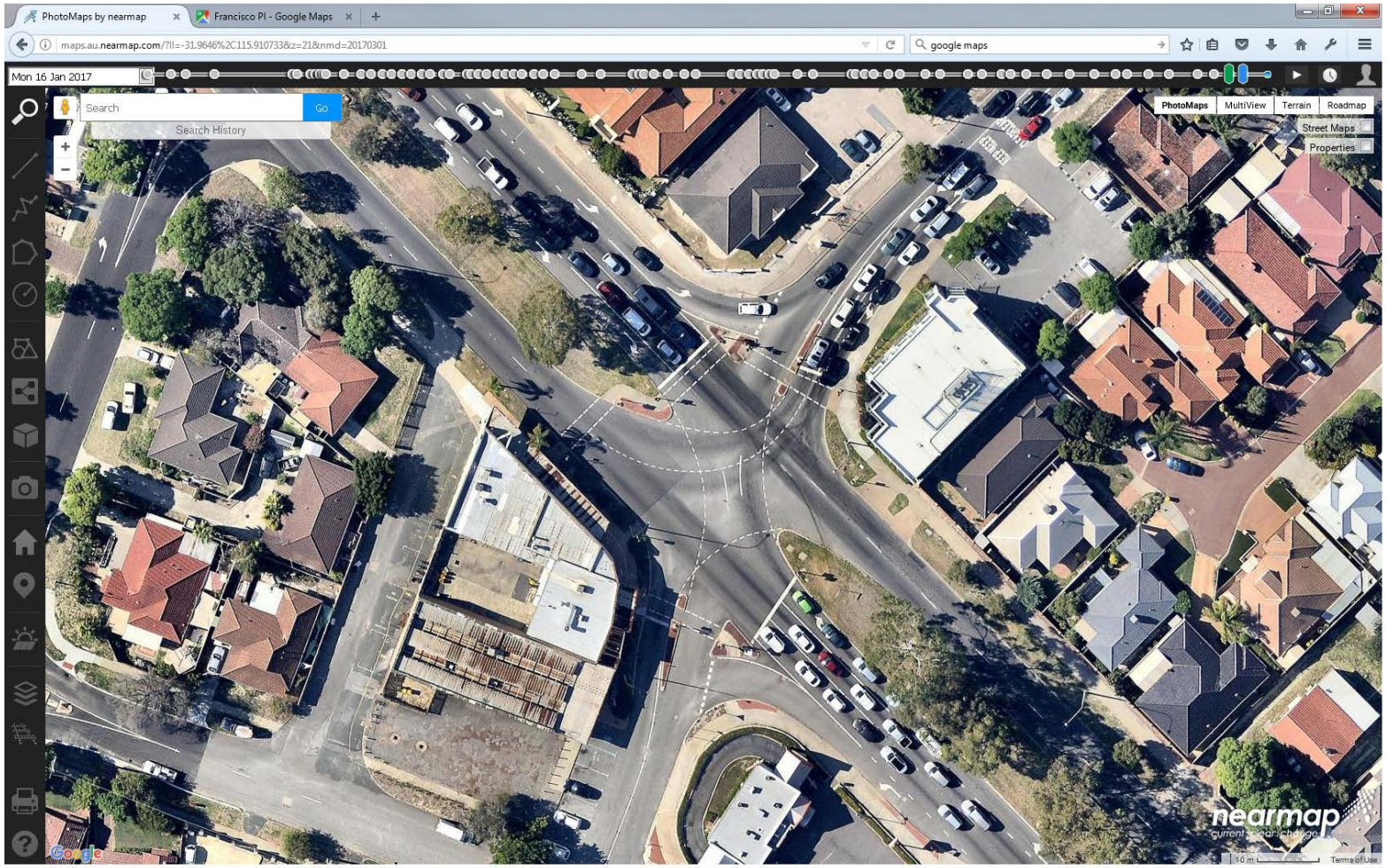
3. ARMADALE RD & NICHOLSON RD



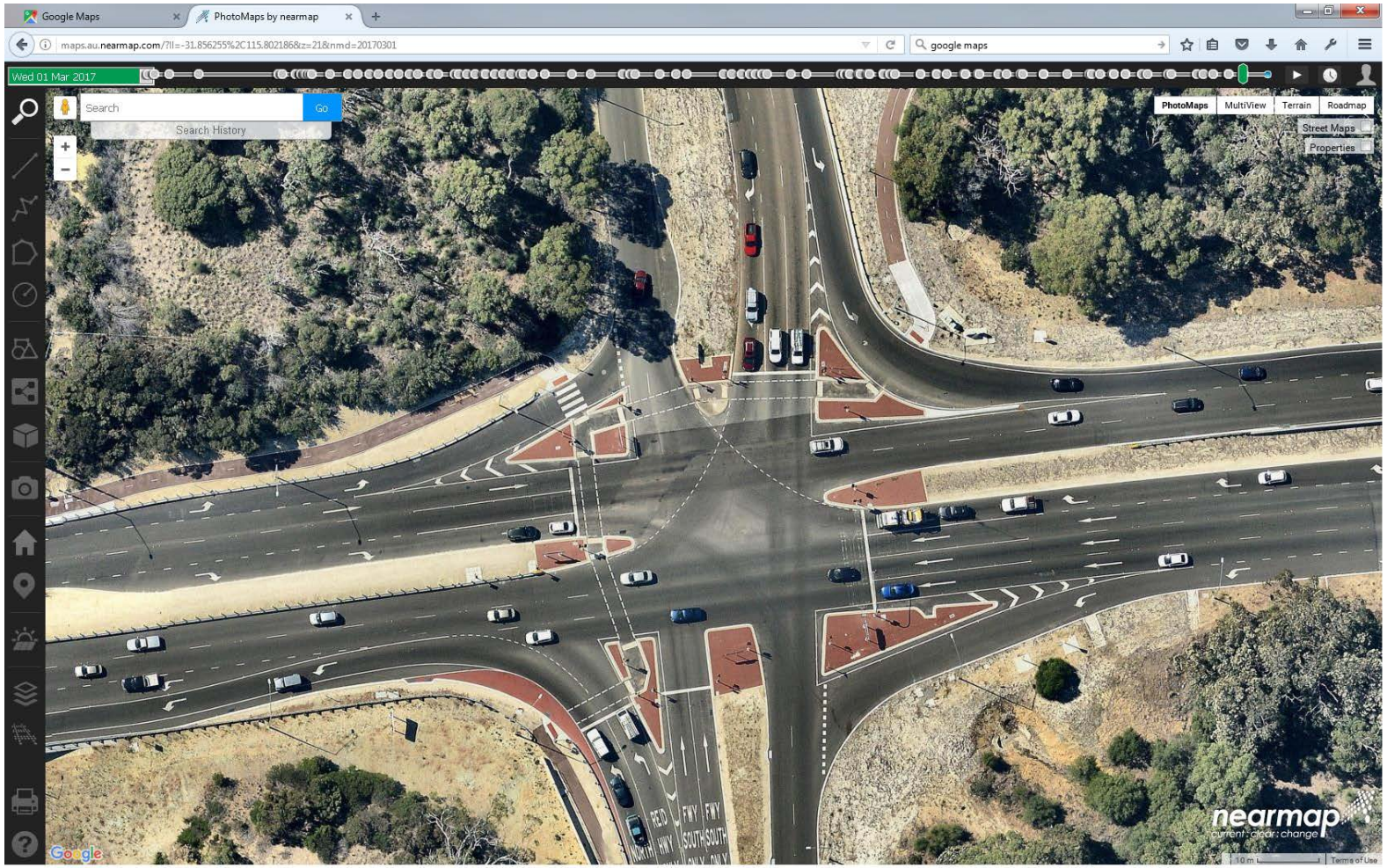
4. SOUTHPORT ST & CAMBRIDGE ST



5. FRANCISCO ST & ORRONG RD & FRANCISCO PL

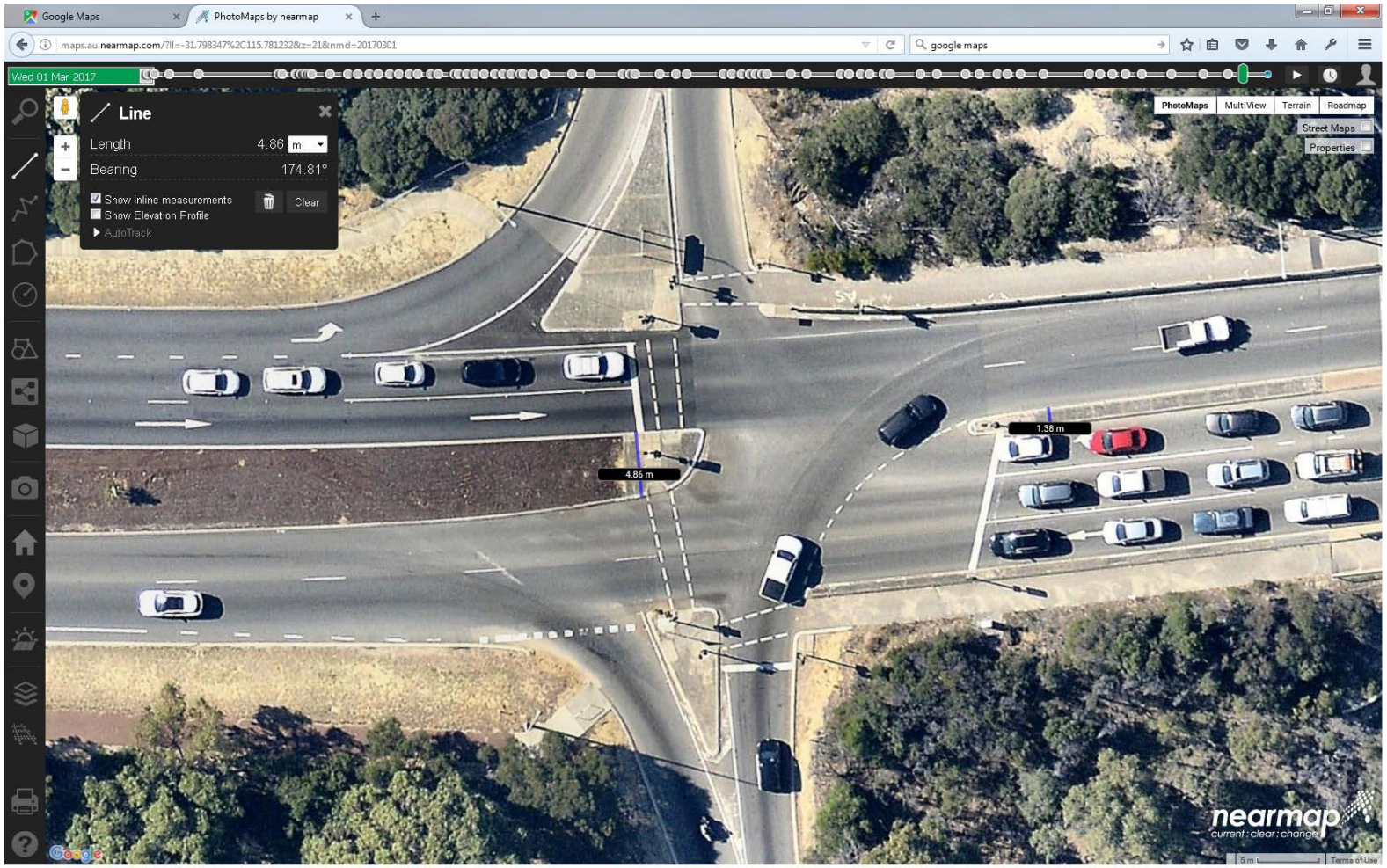


6. REID HWY & REID HWY - MITCHELL FWY STH ON & H016 STH BOUND - REID HWY OFF & BALCATTA RD

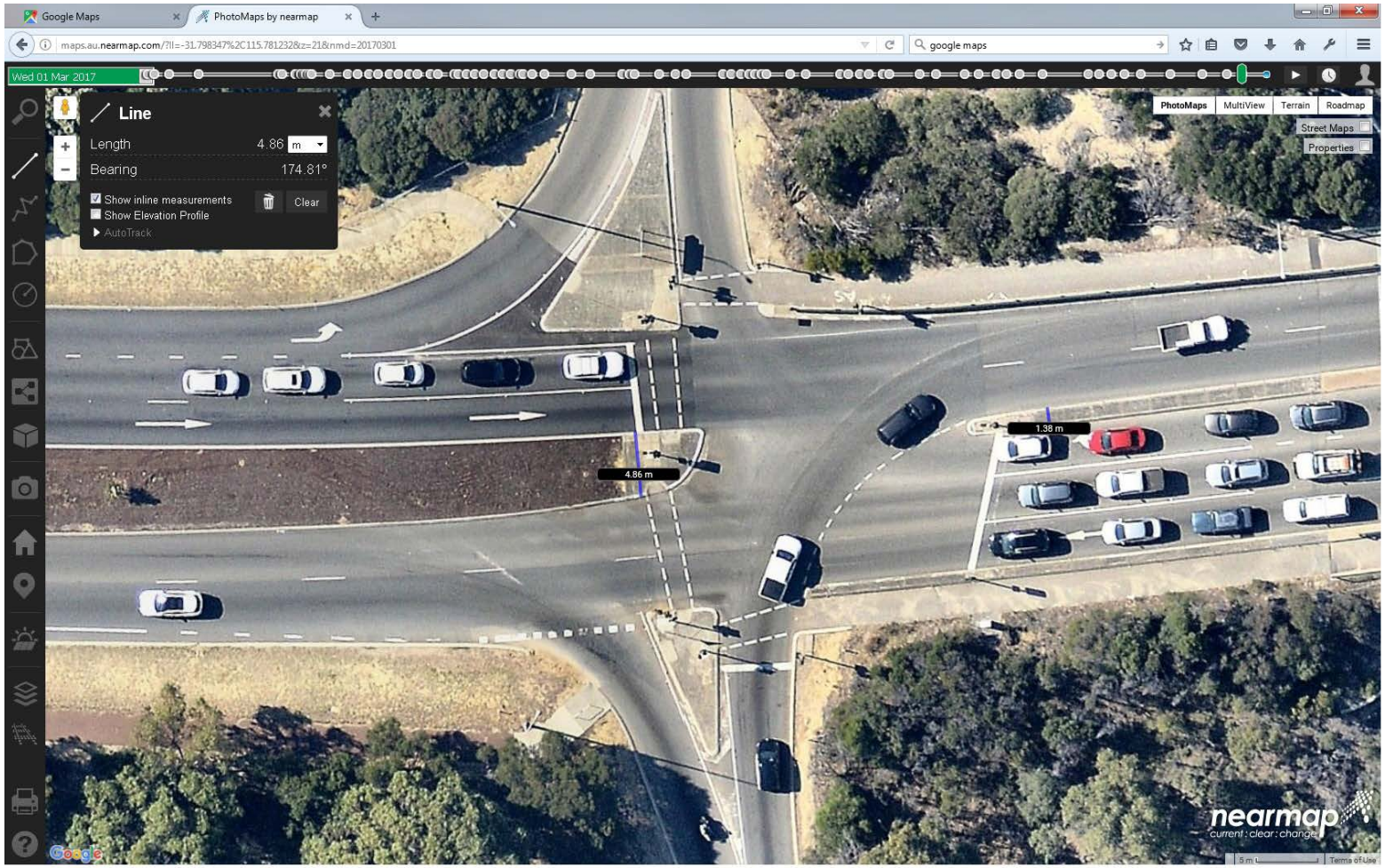


7. ALBANY HWY (END DUAL) & DUNCAN ST

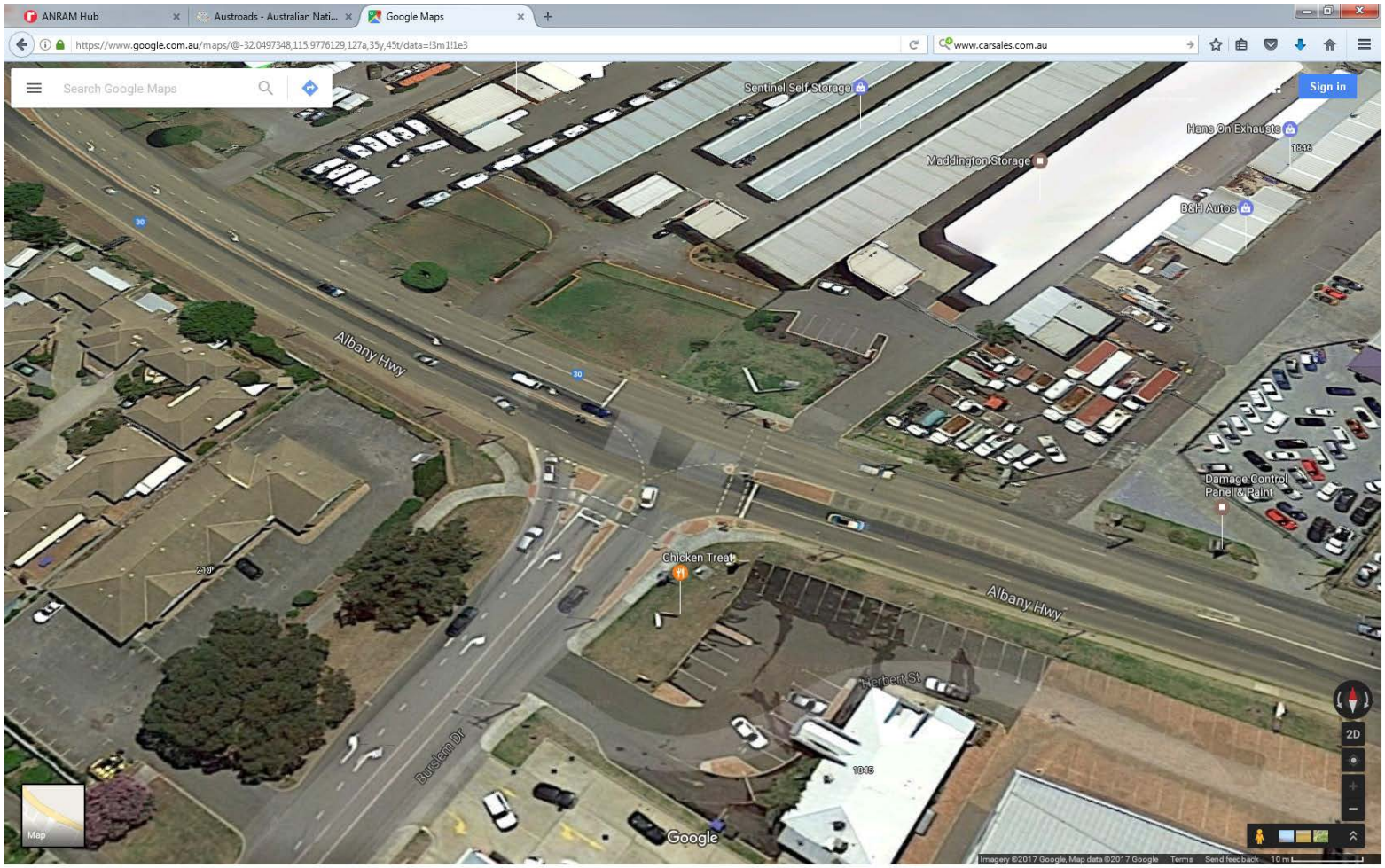
8. HUTTON ST ON - H016 STH BOUND & HUTTON ST & H016 STH BOUND - HUTTON ST OFF



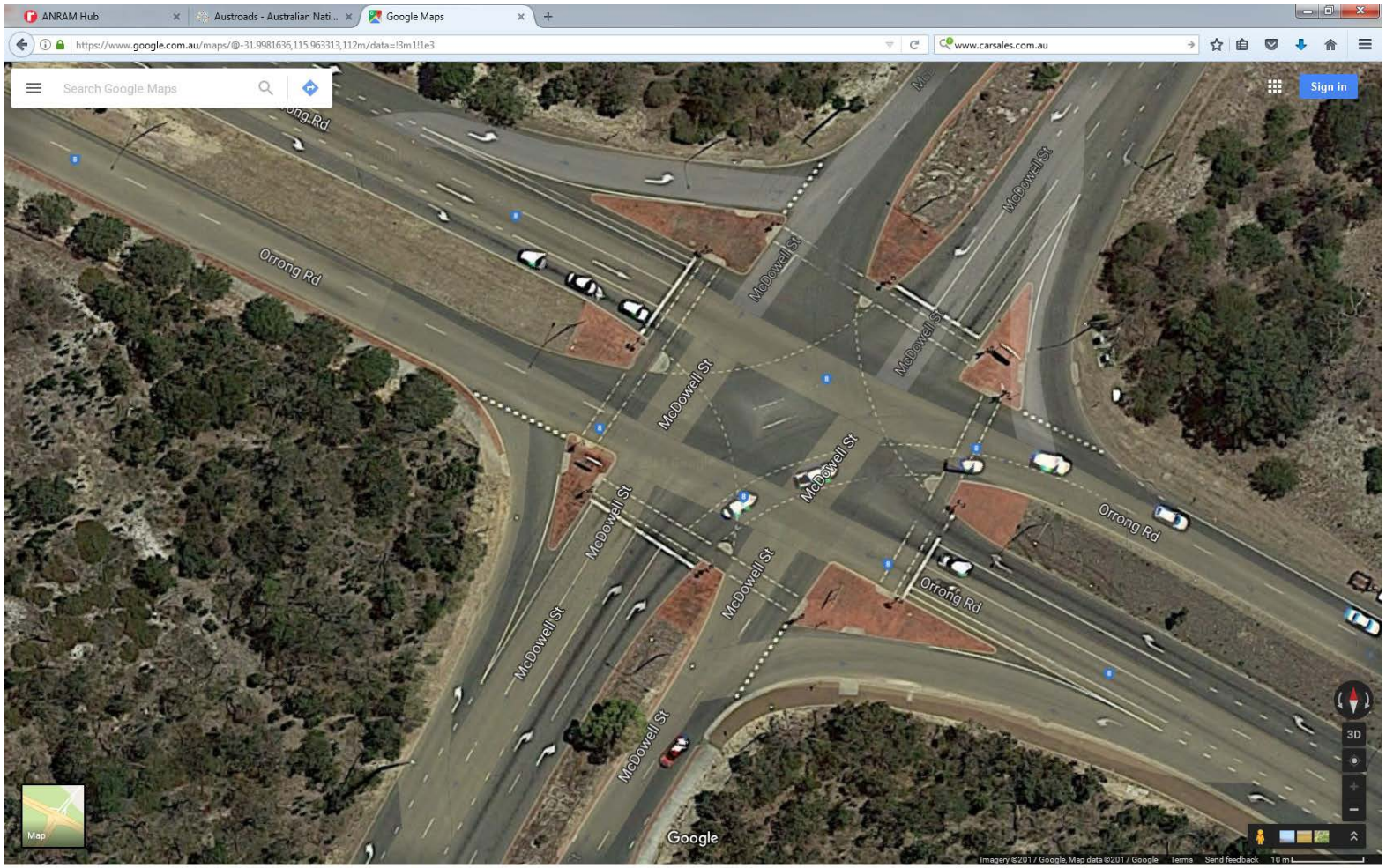
9. H016 NTH BND - WHITFORDS AV OFF & WHITFORDS AV & WHITFORDS AV OFF - H016 NTH BND



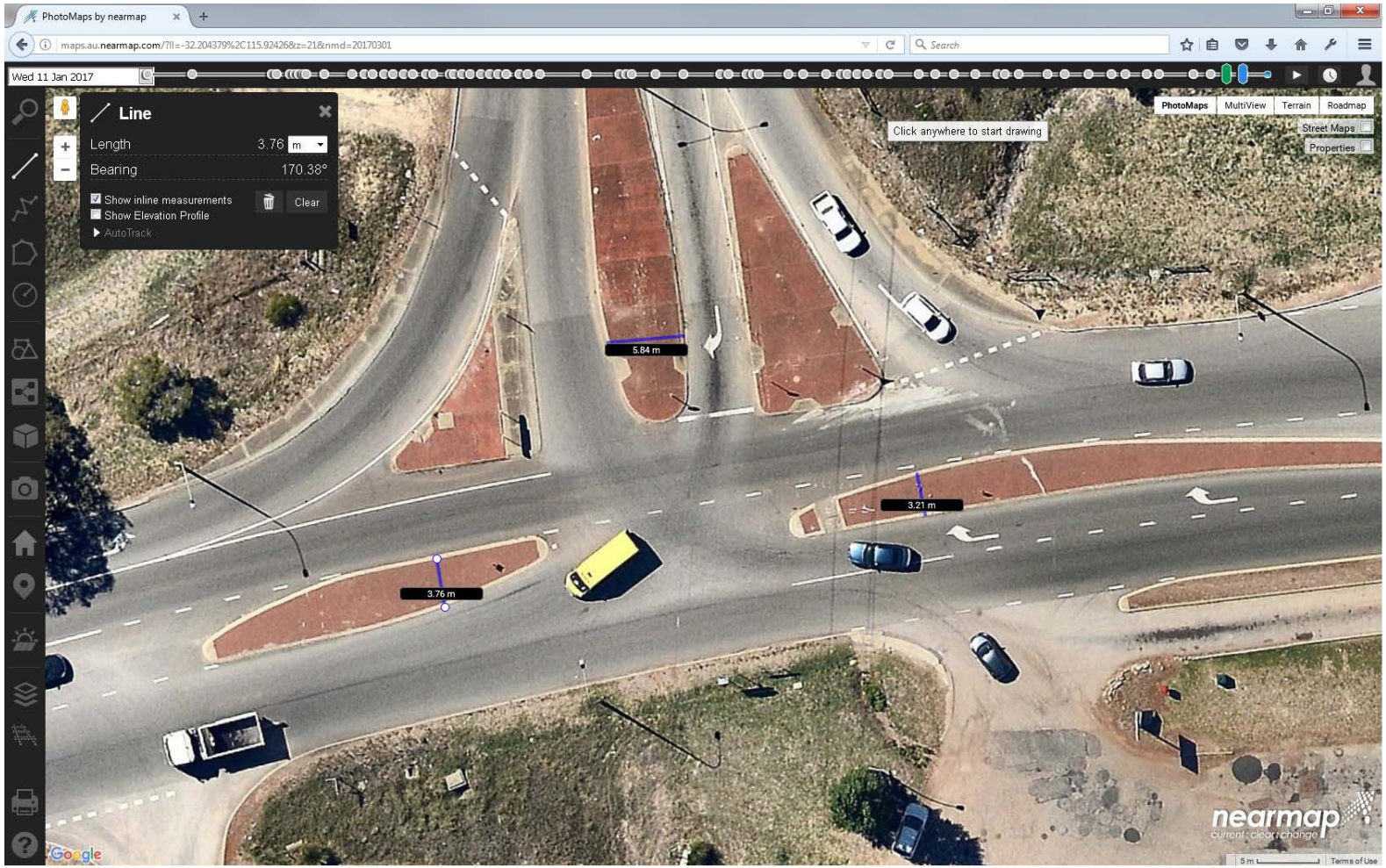
10. ALBANY HWY & BURSLEM DR



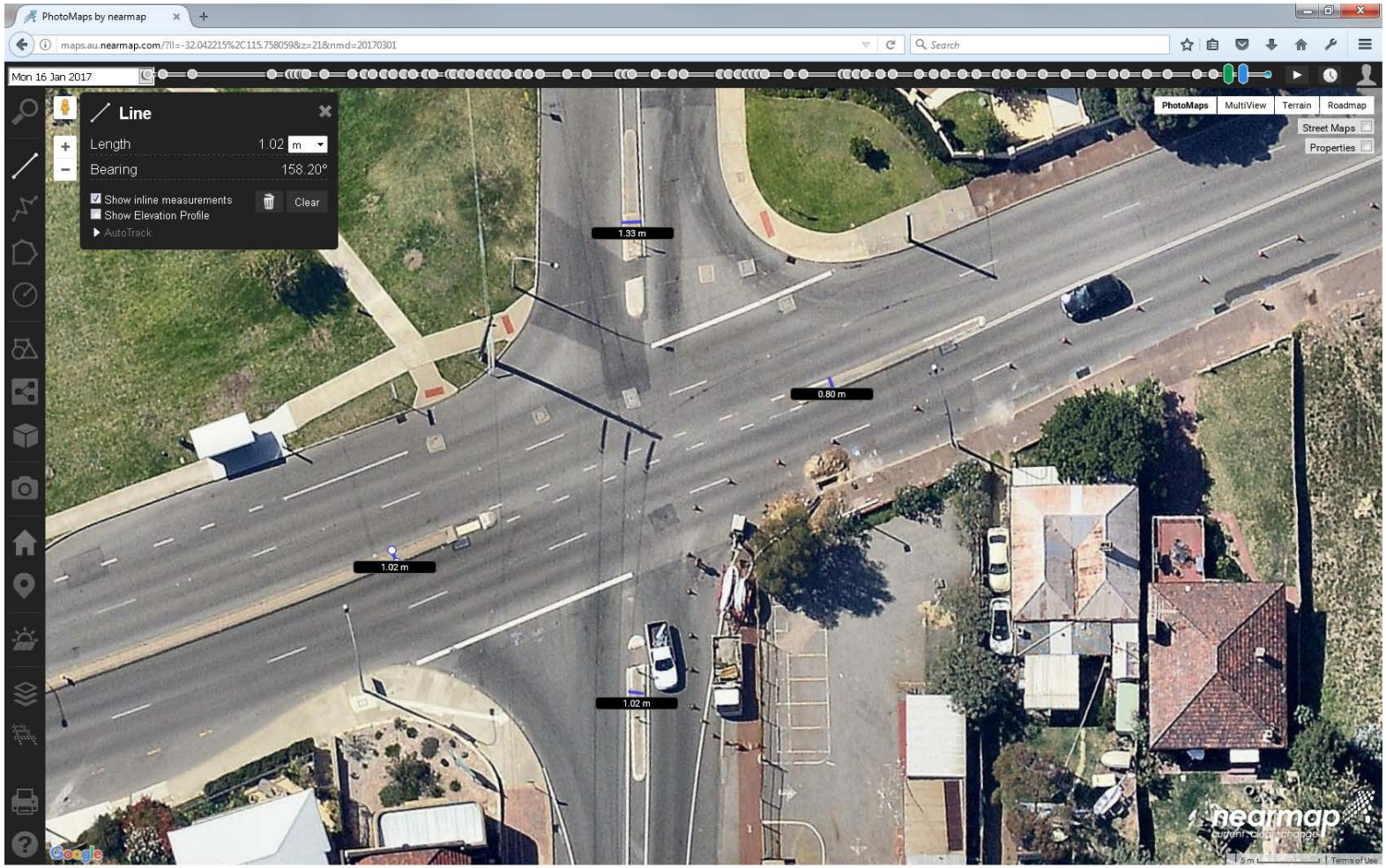
11. MCDOWELL ST & ORRONG RD



12. NICHOLSON RD & THOMAS RD

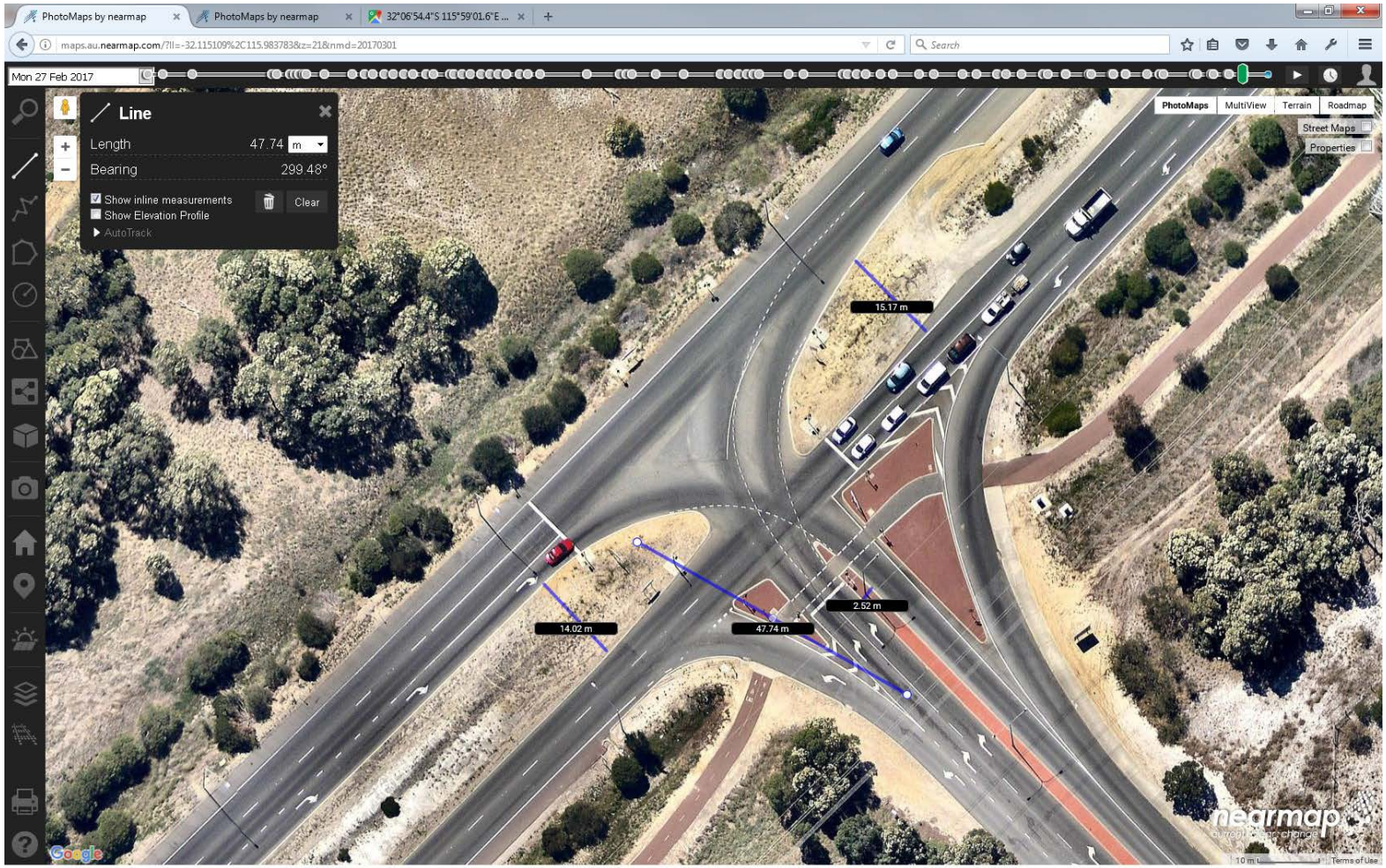


13. CANNING HWY & EAST ST

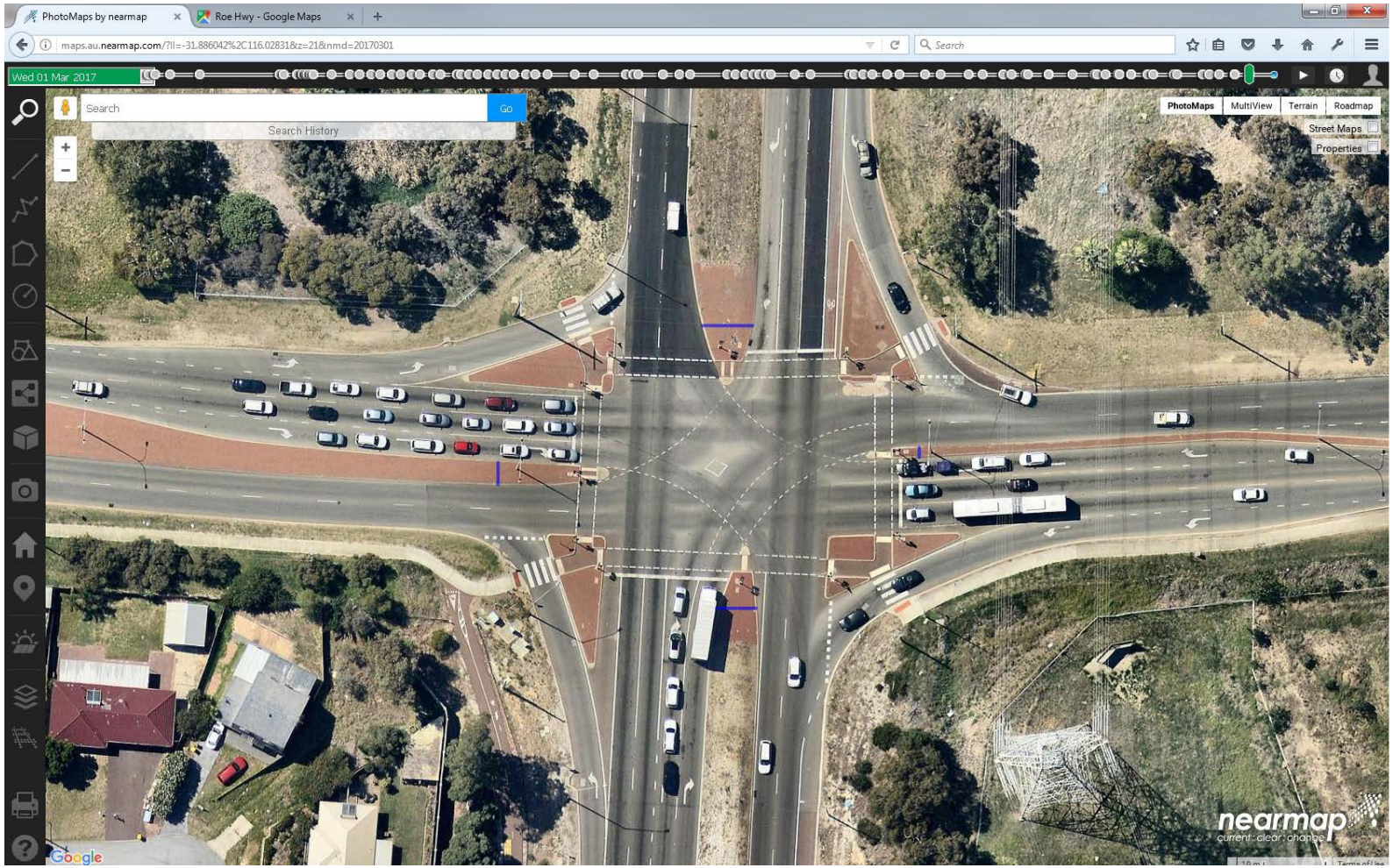


14. ARMADALE RD & WARTON RD

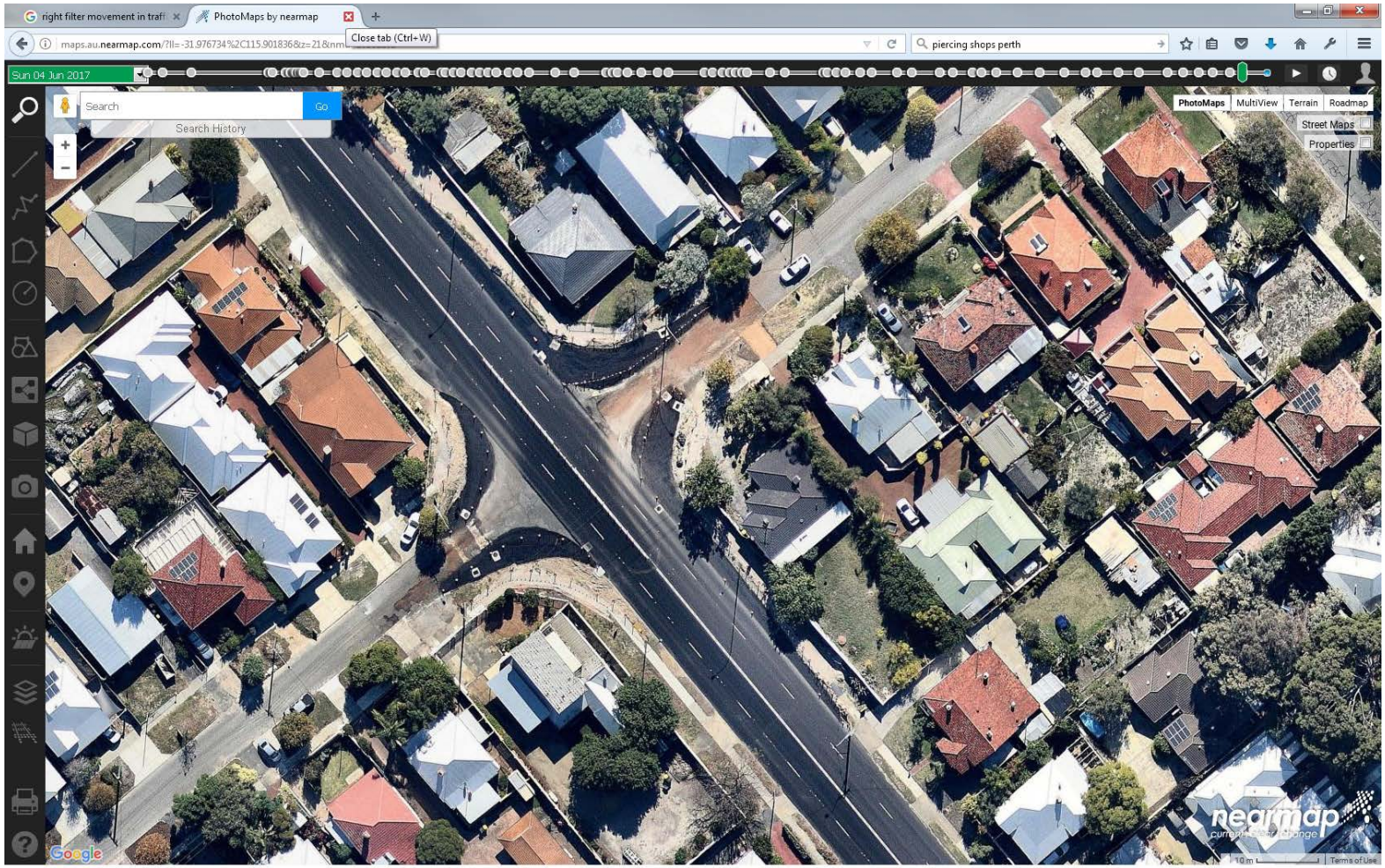
15. TONKIN HWY & CHAMPION DR



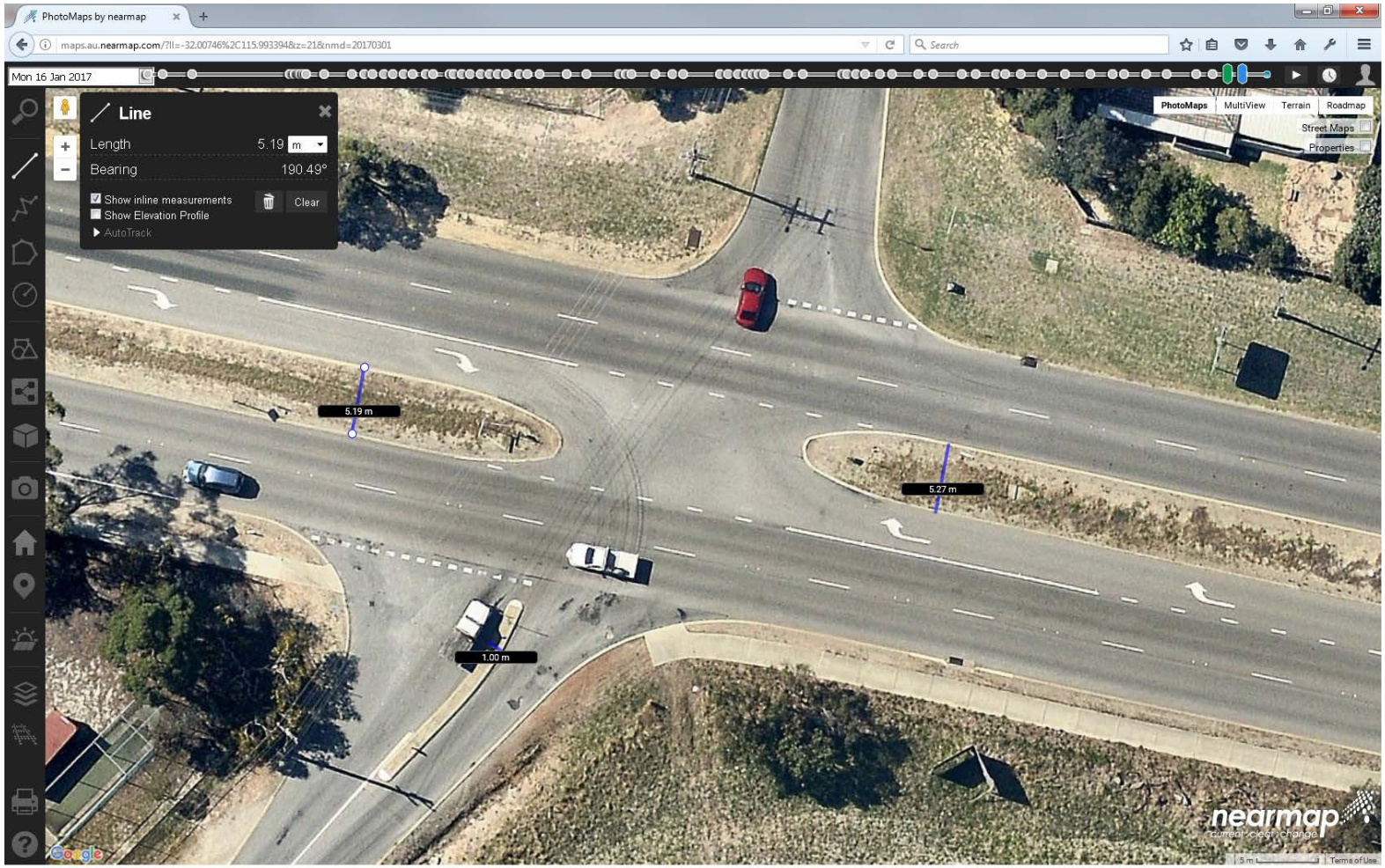
16. ROE HWY & MORRISON RD & MORRISON RD



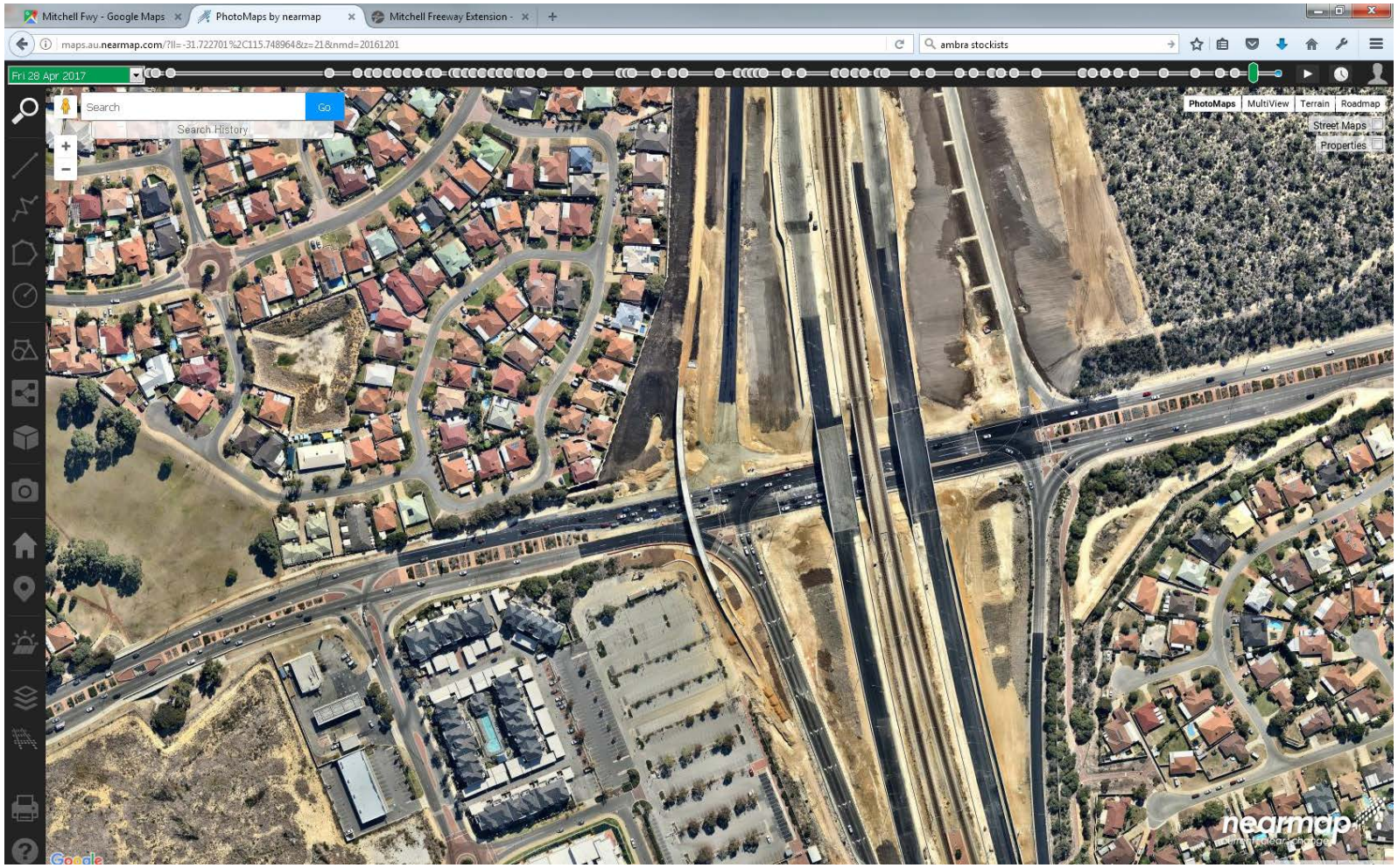
17. ALBANY HWY & GRESHAM ST



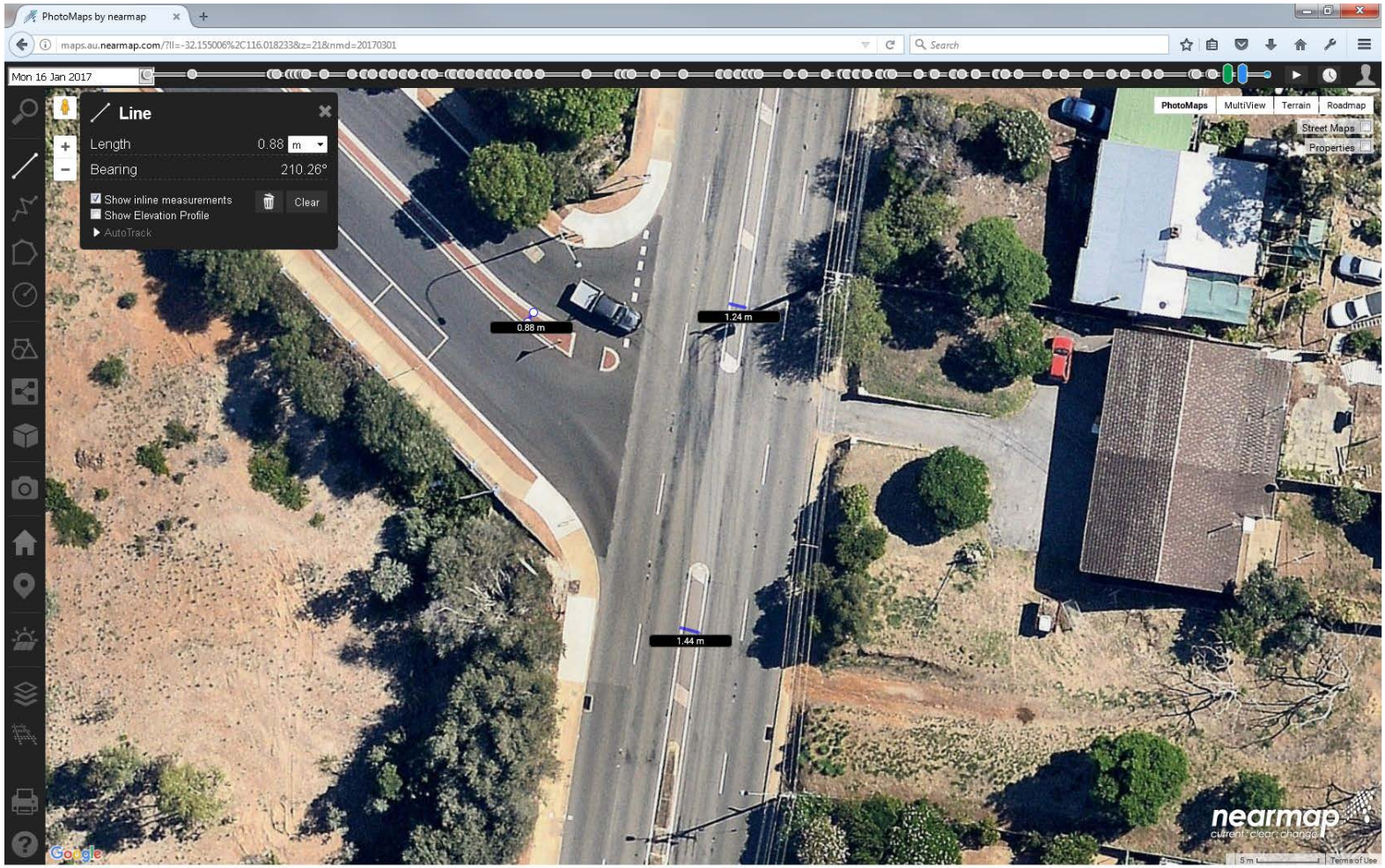
18. WELSHPOOL RD EAST & BRUCE RD & BROOK RD



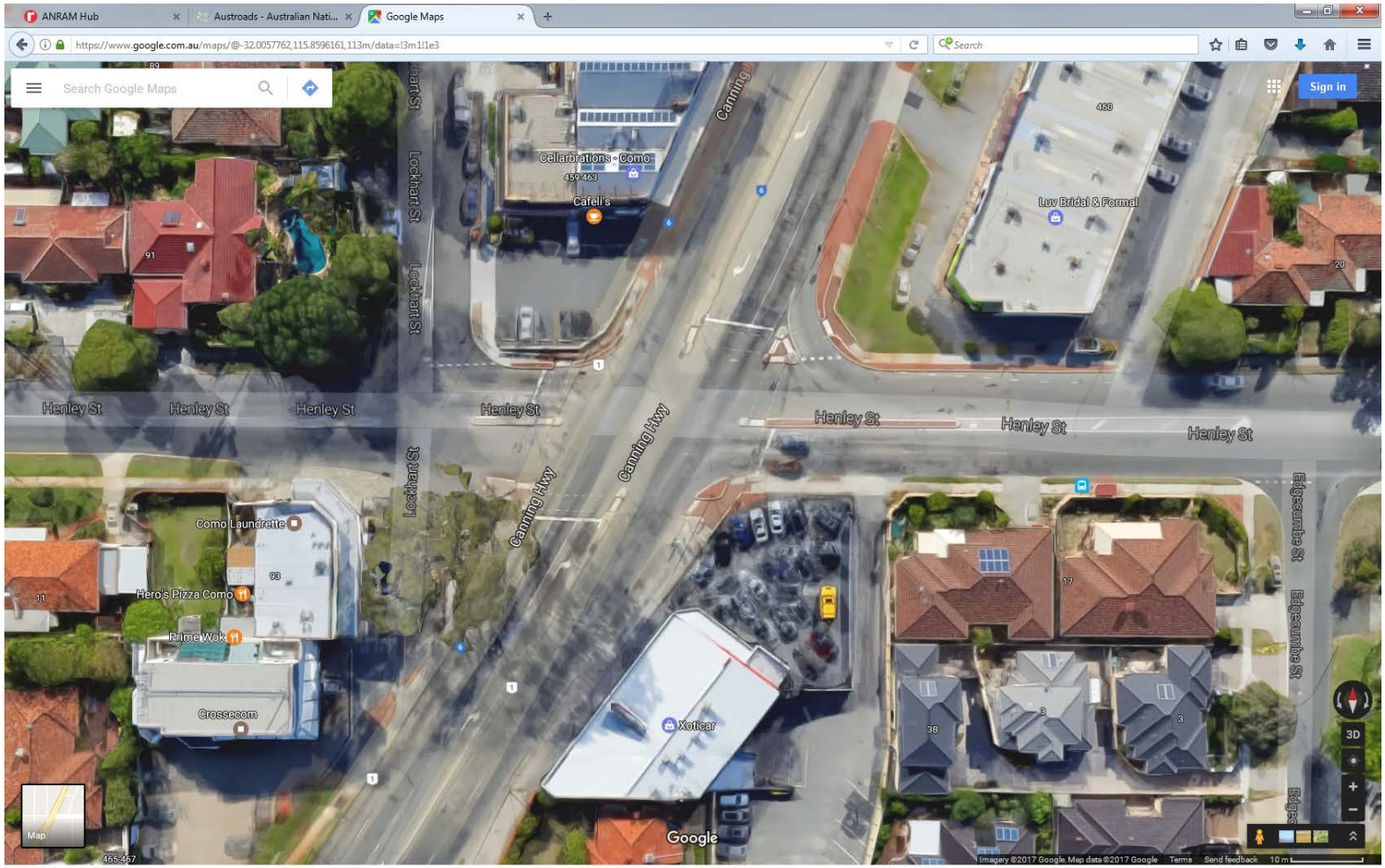
19. H016 NTH BND END & BURNS BEACH RD



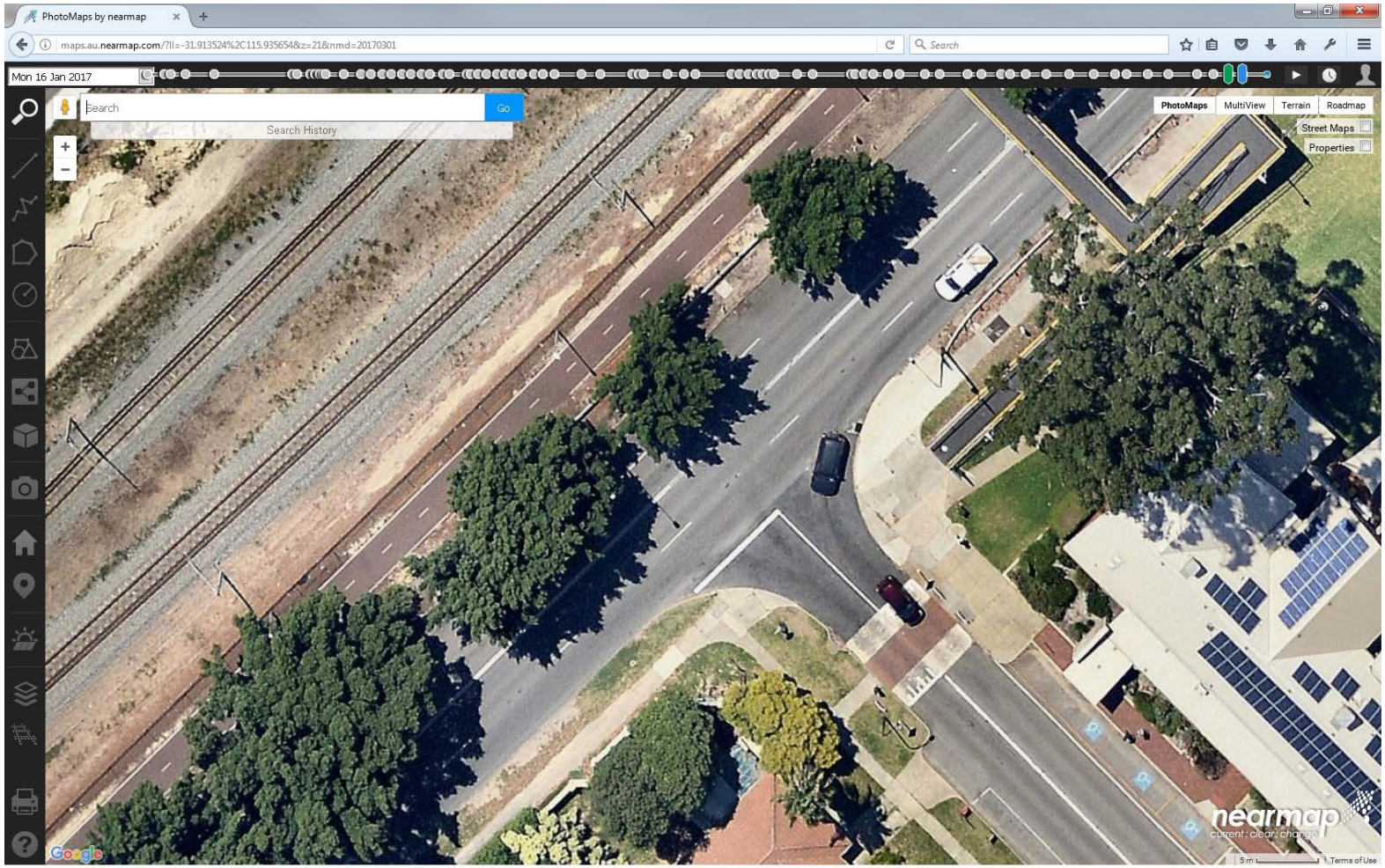
20. SOUTH WESTERN HWY & THIRD RD



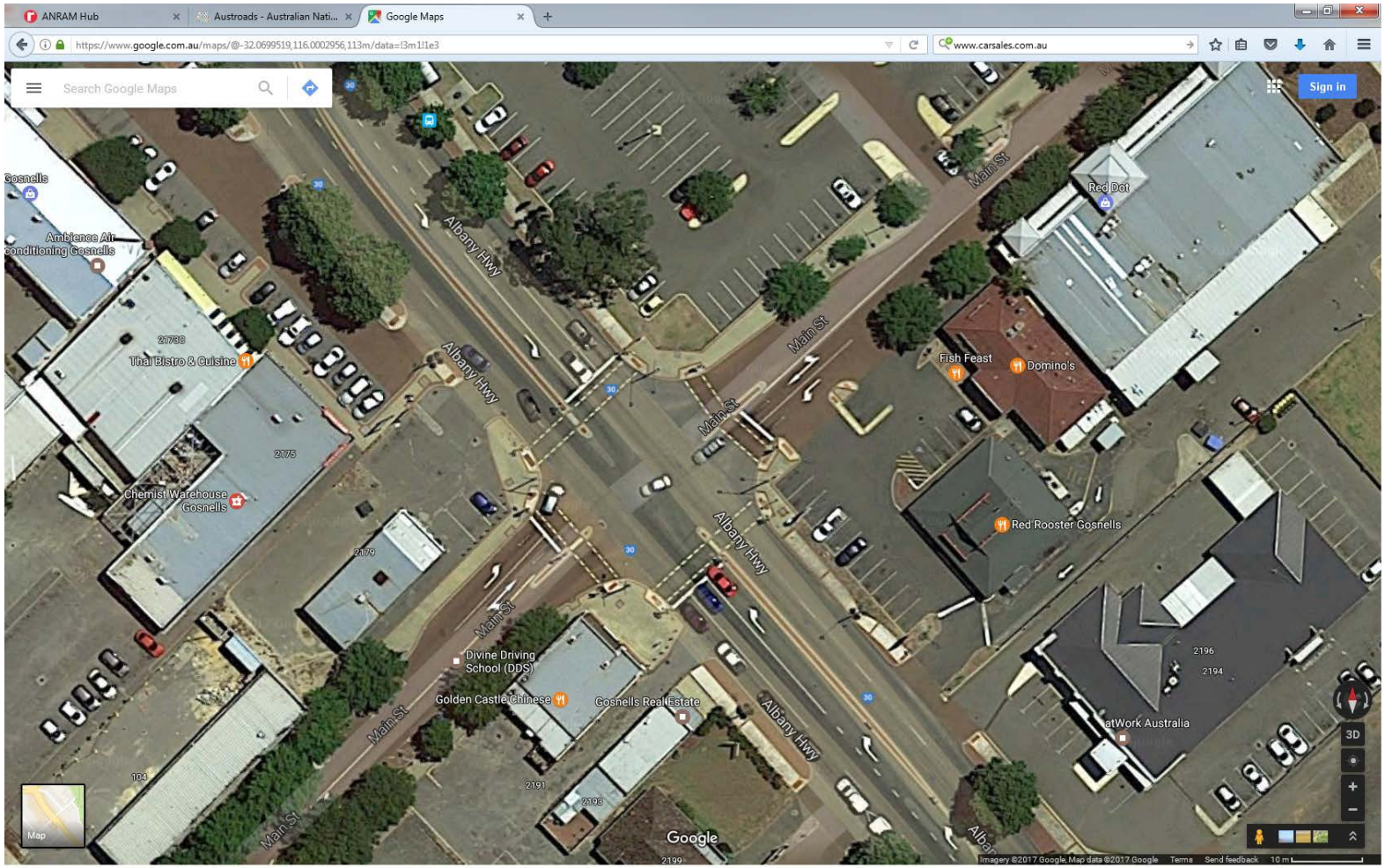
21. ALBANY HWY & DENNY AV



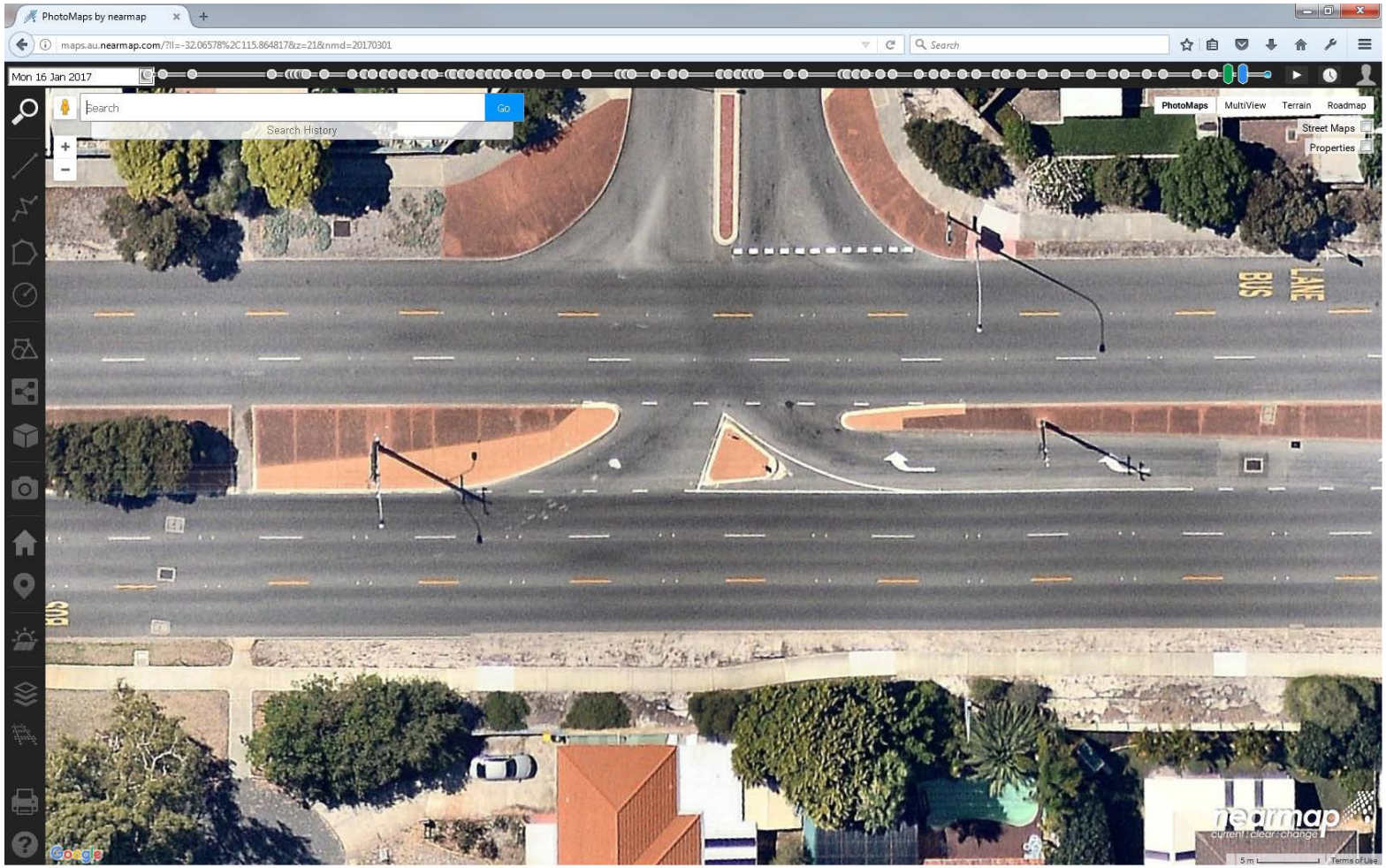
22. GUILDFORD RD & COLSTOUN RD



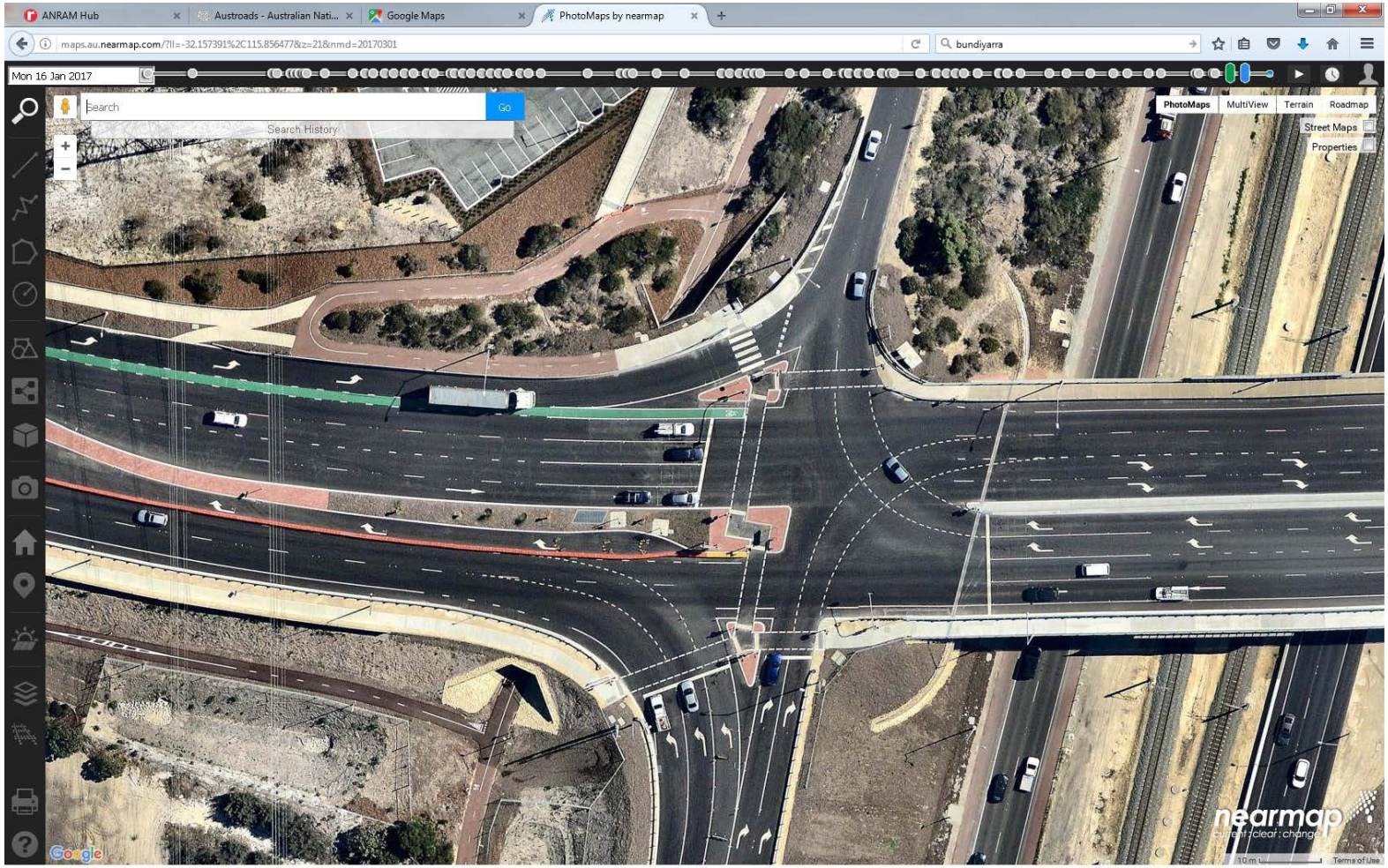
23. ALBANY HWY (END DUAL) & MAIN ST



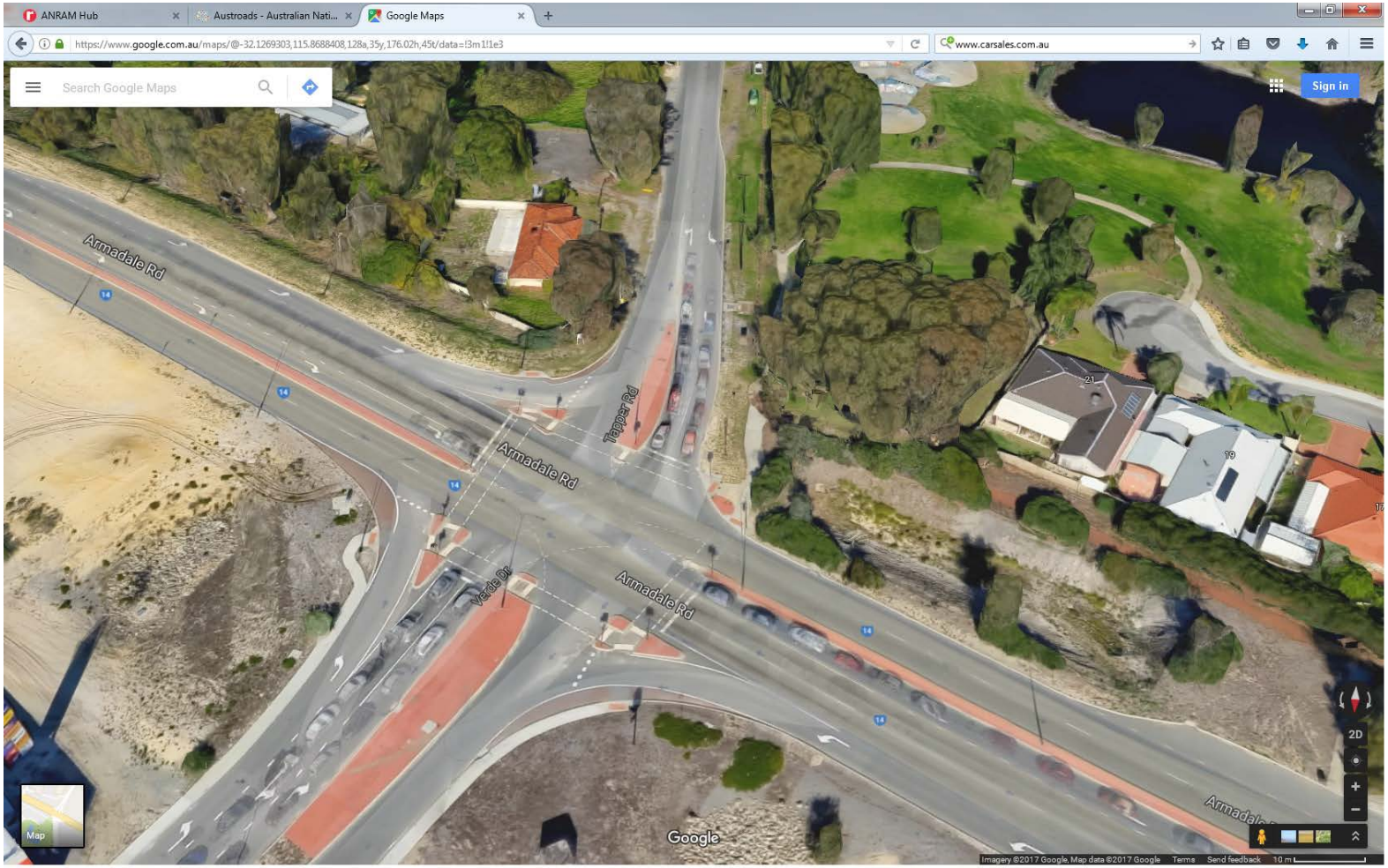
24. SOUTH ST & WHEATLEY DR



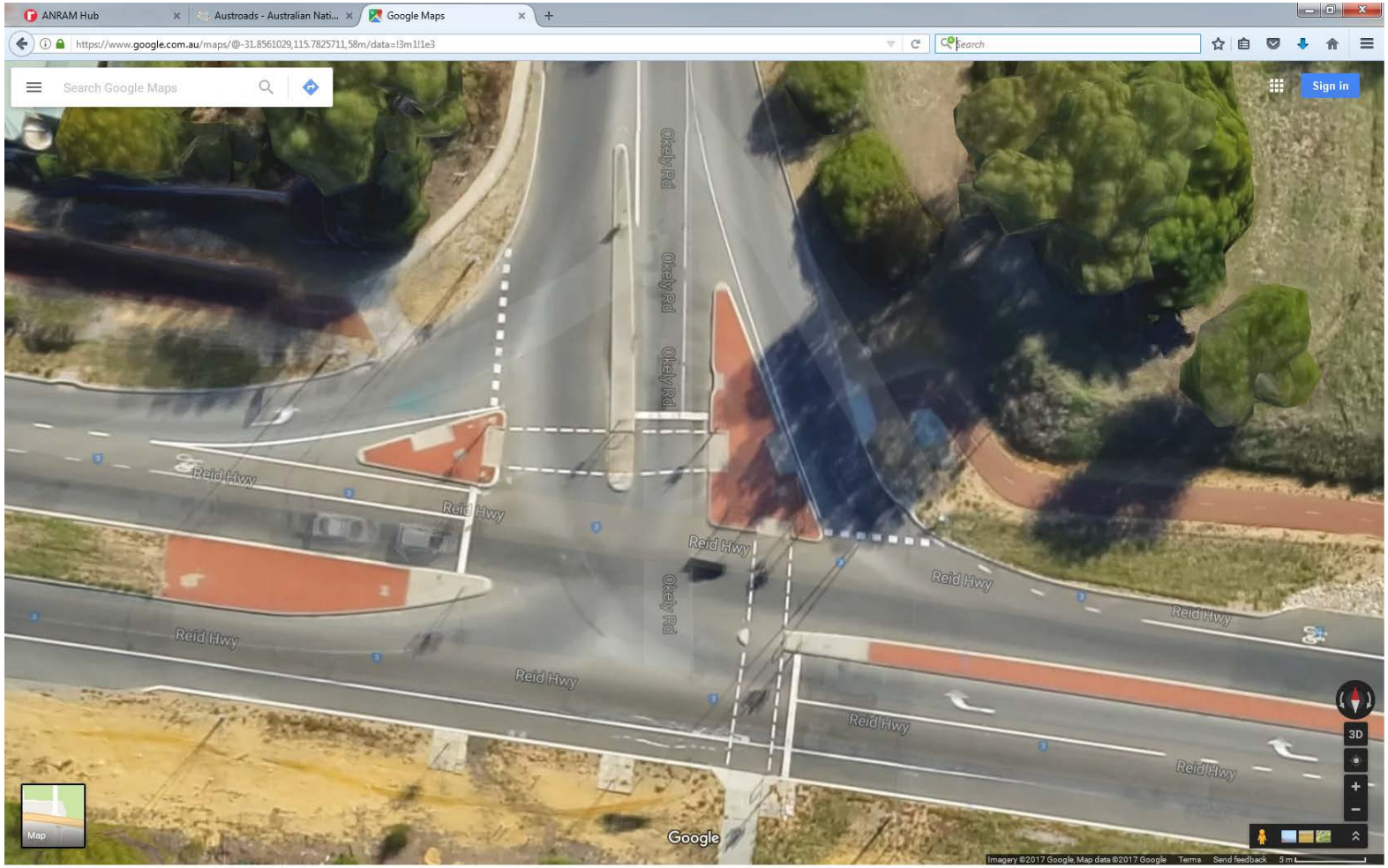
25. ROE HWY & BERKSHIRE RD



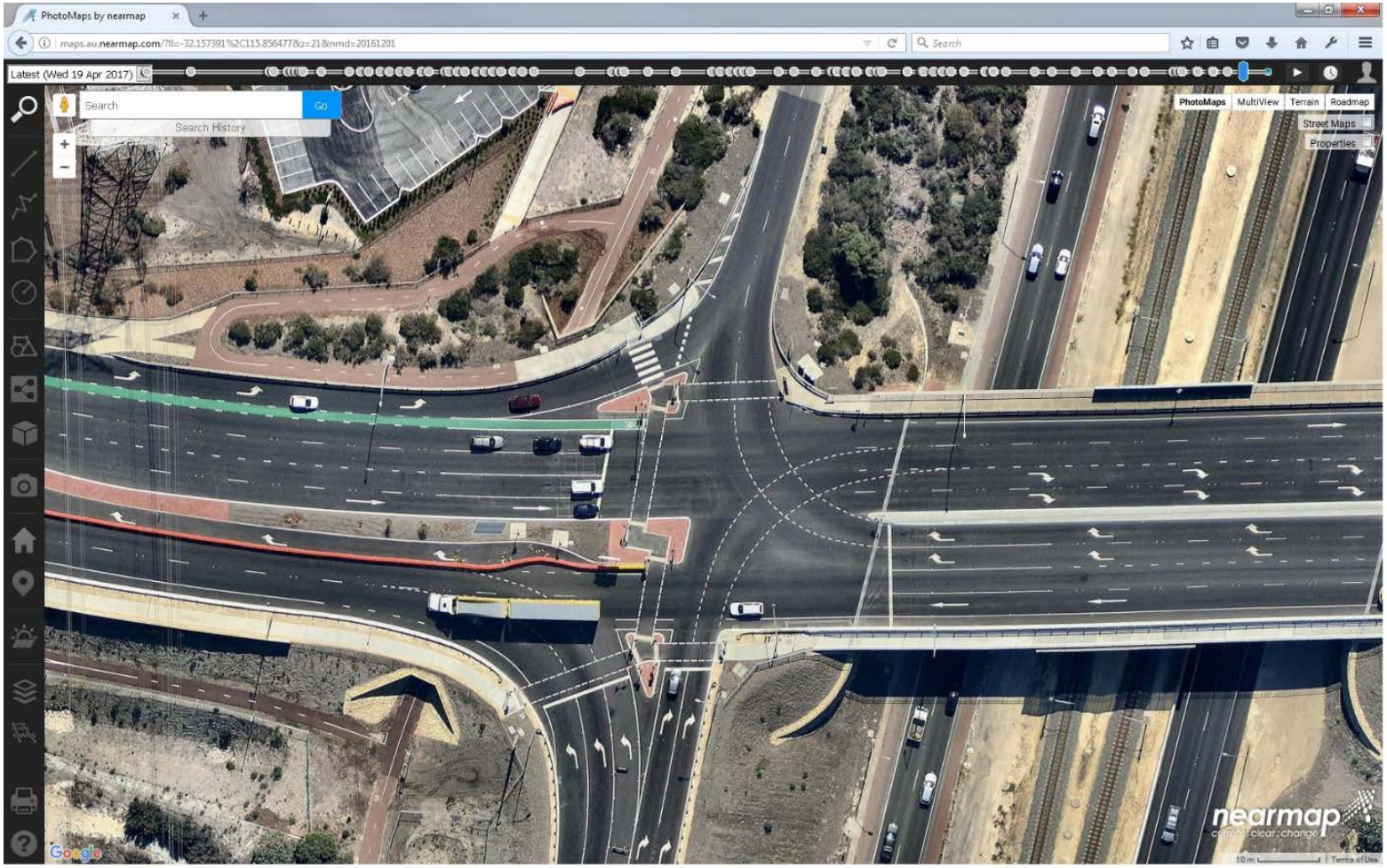
26. ARMADALE RD & TAPPER RD & VERDE DR



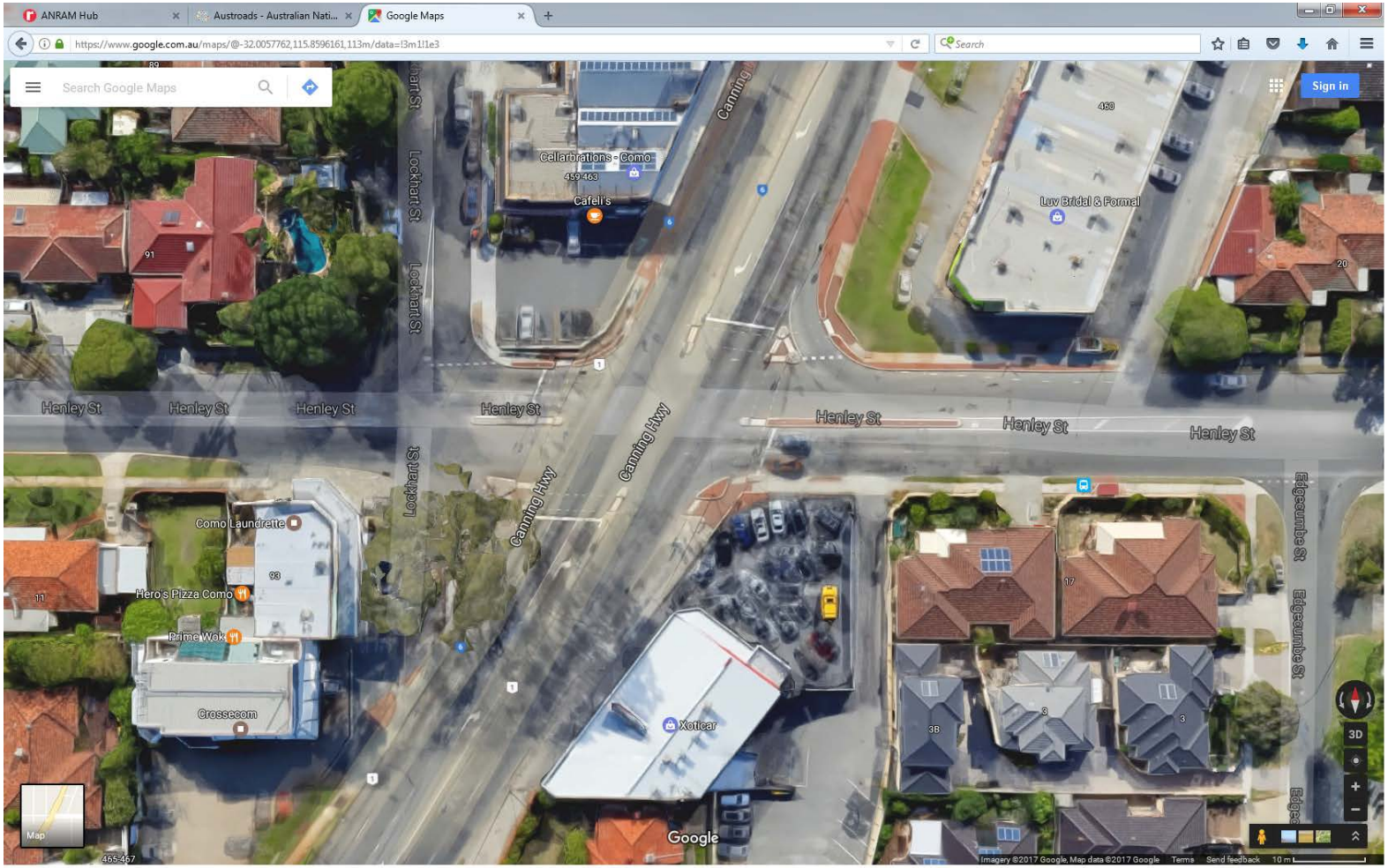
27. REID HWY & OKELY RD (NORTH)



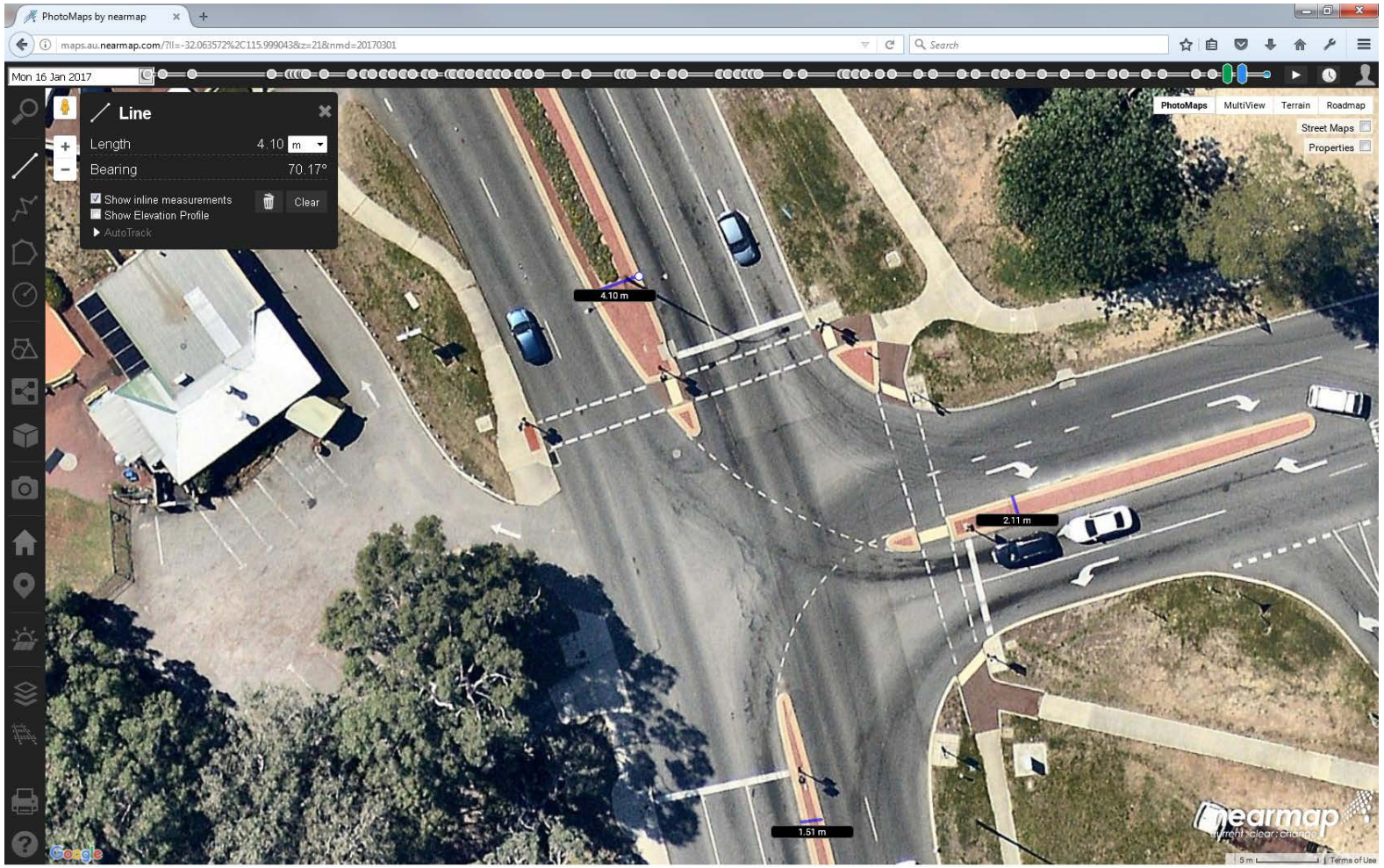
28. KWINANA FWY NTH - RUSSELL RD & RUSSELL RD & RUSSELL RD - KWINANA FWY NTH



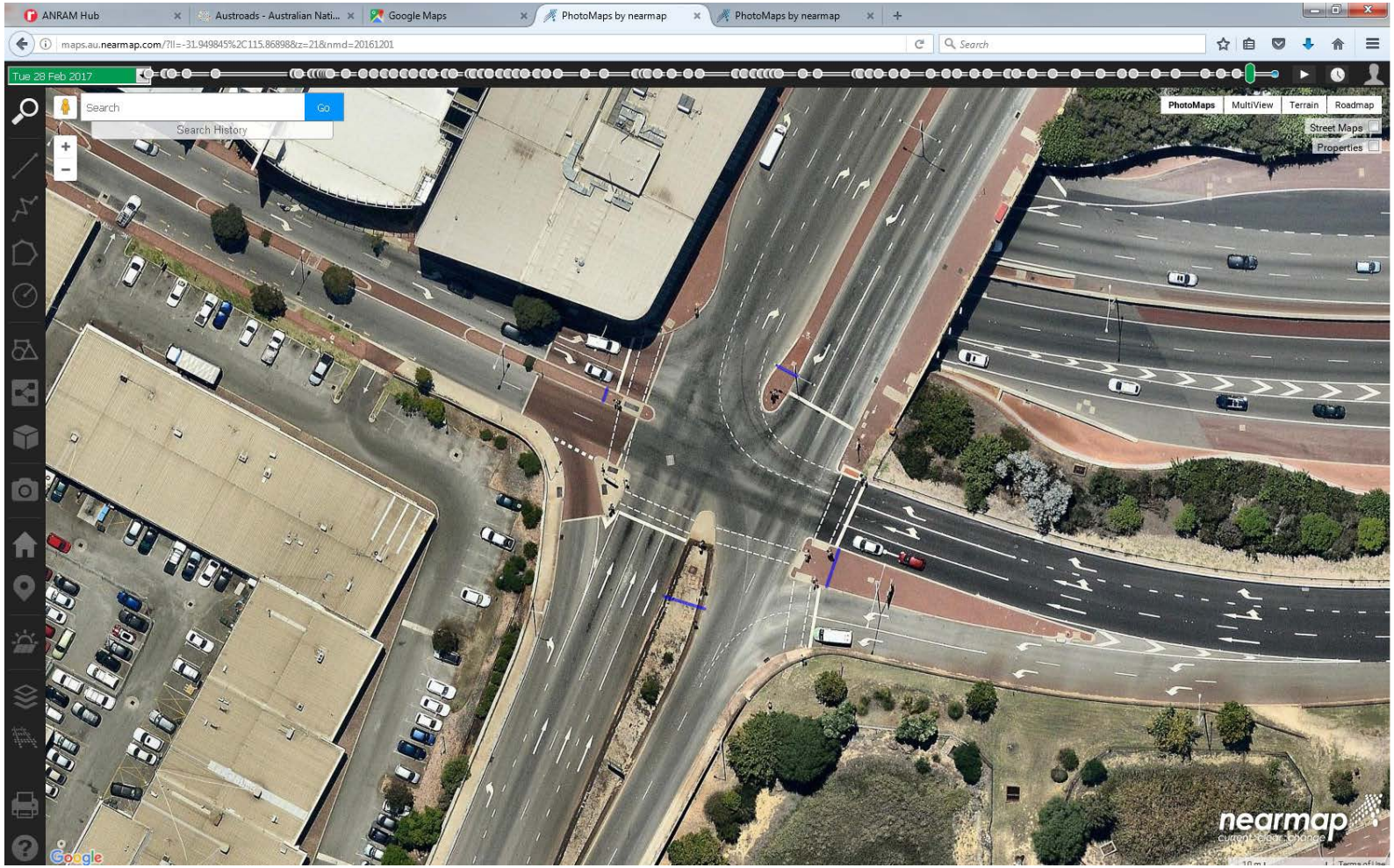
29. CANNING HWY & HENLEY ST



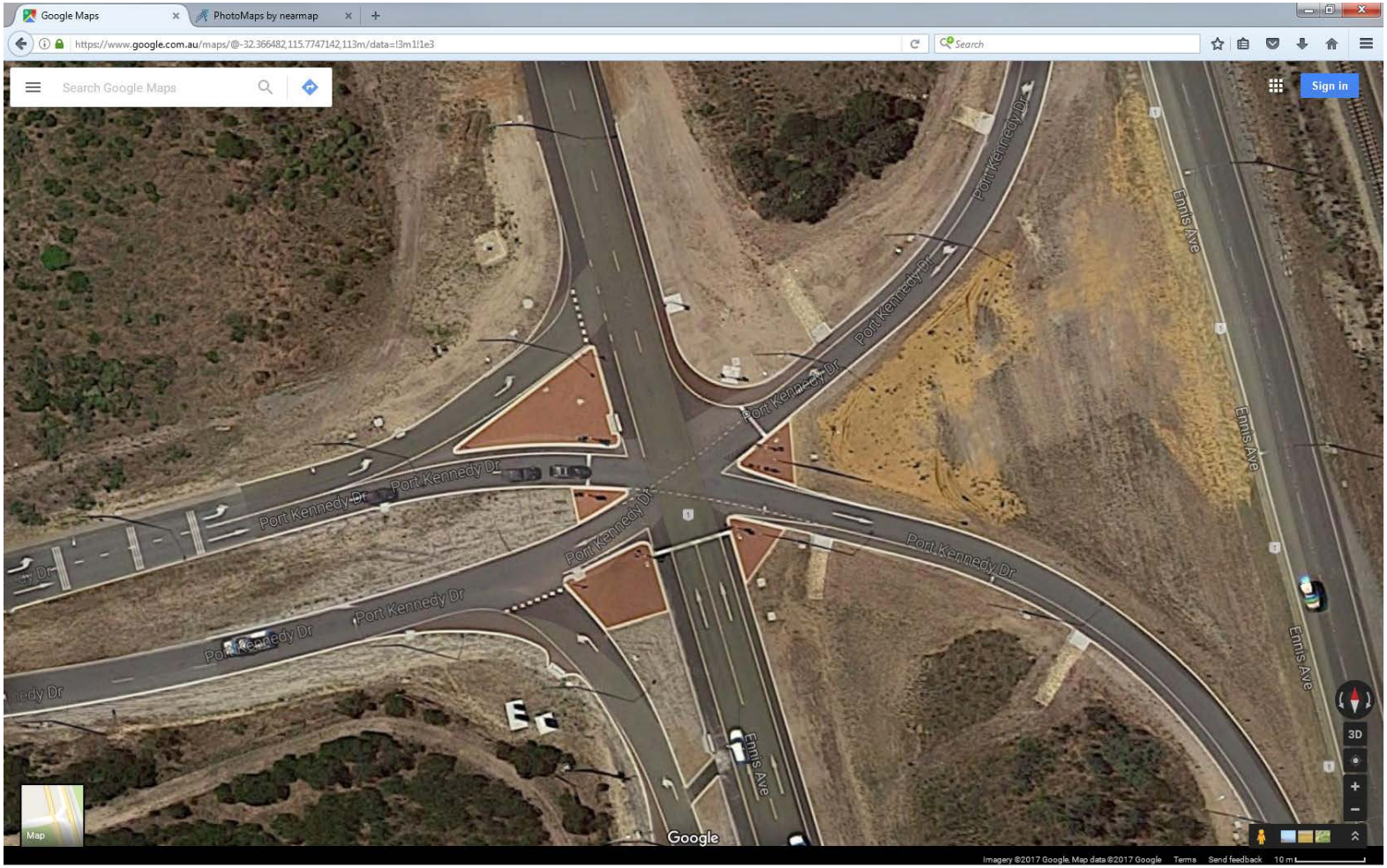
30. ALBANY HWY & GOSNELLS RD WEST



31. EAST PDE - LORD ST & LORD ST & NEWCASTLE ST

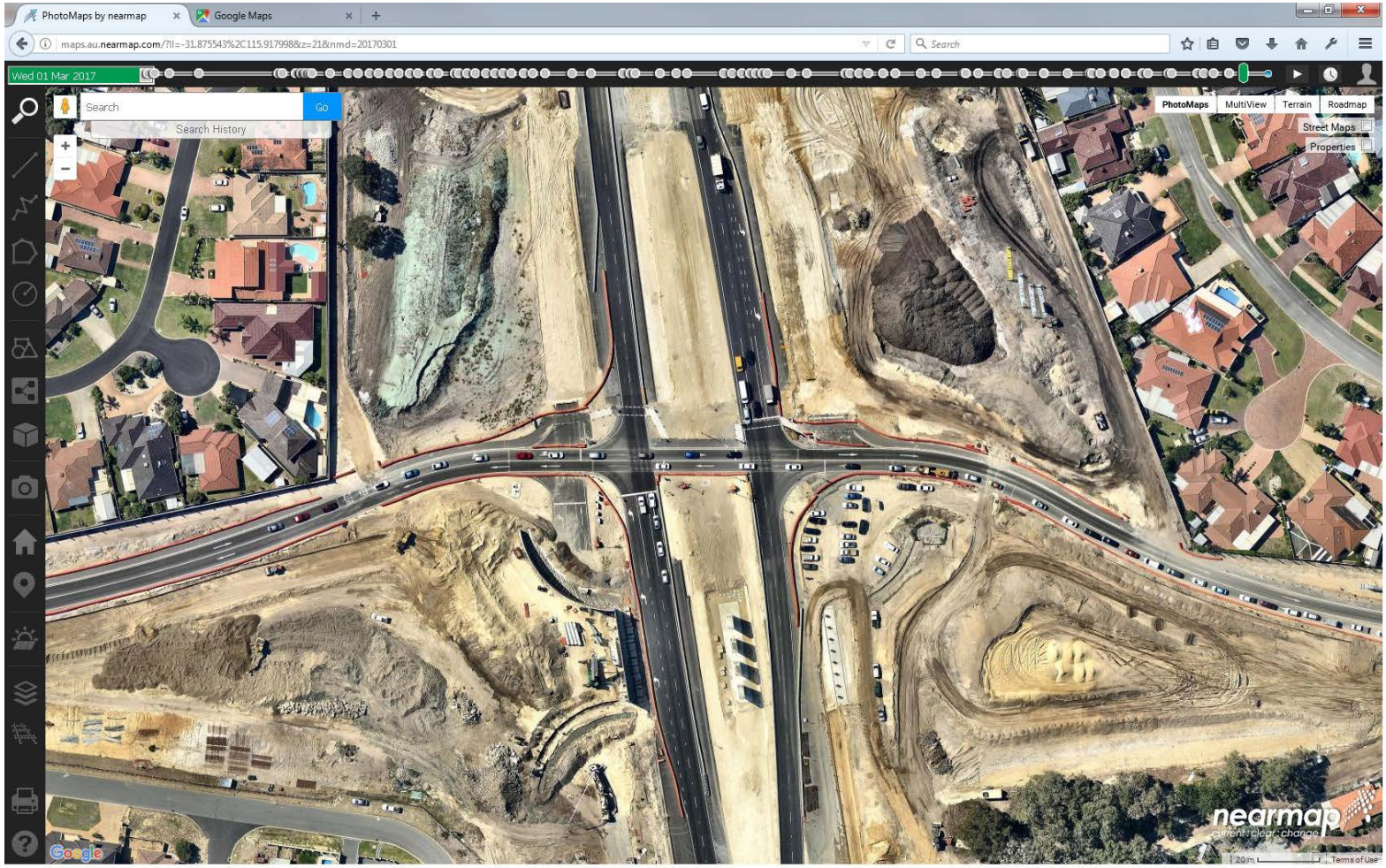


32. ENNIS AV (NTH BND) & PORT KENNEDY DR

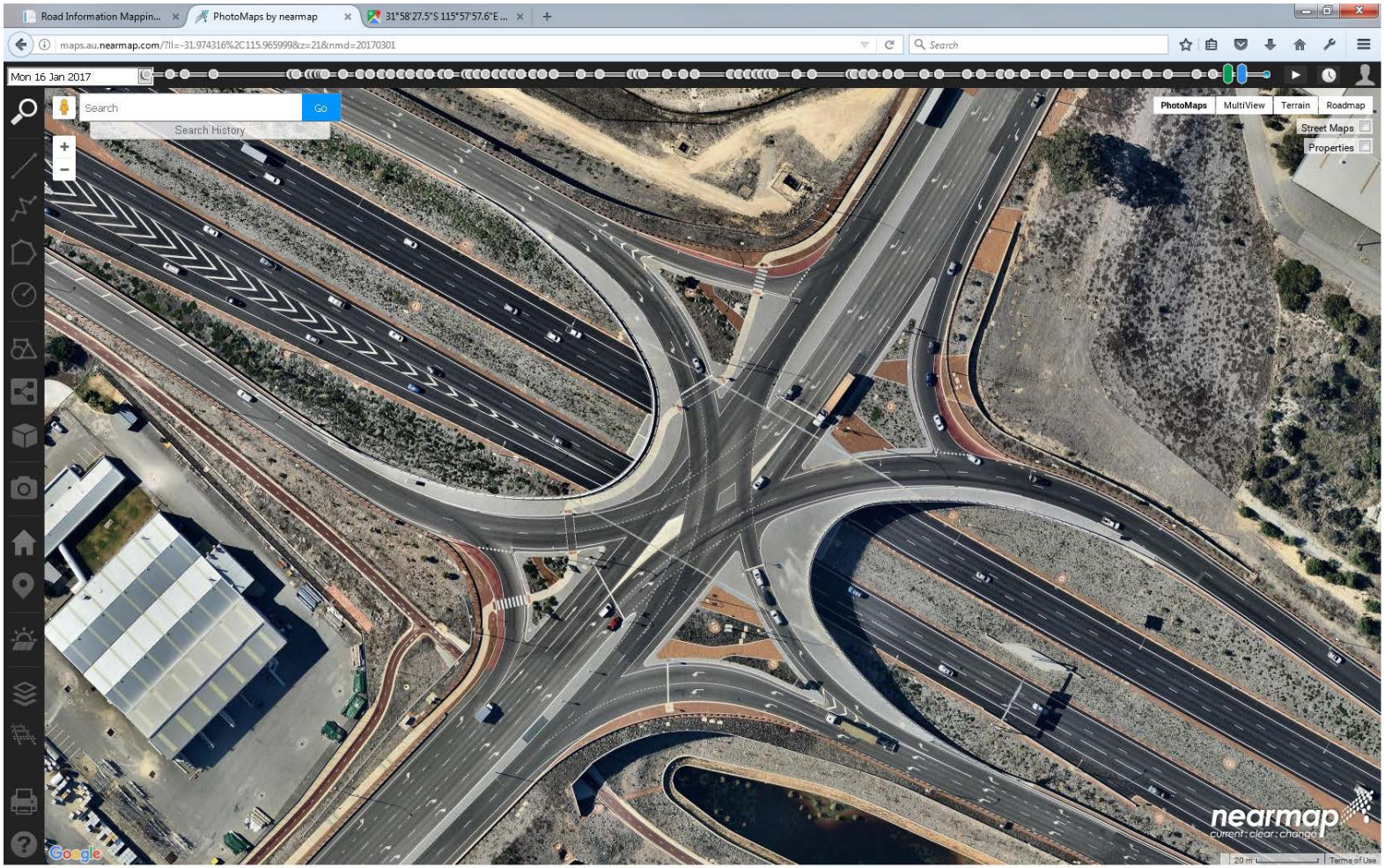


33. TONKIN HWY & GOSNELLS RD WEST

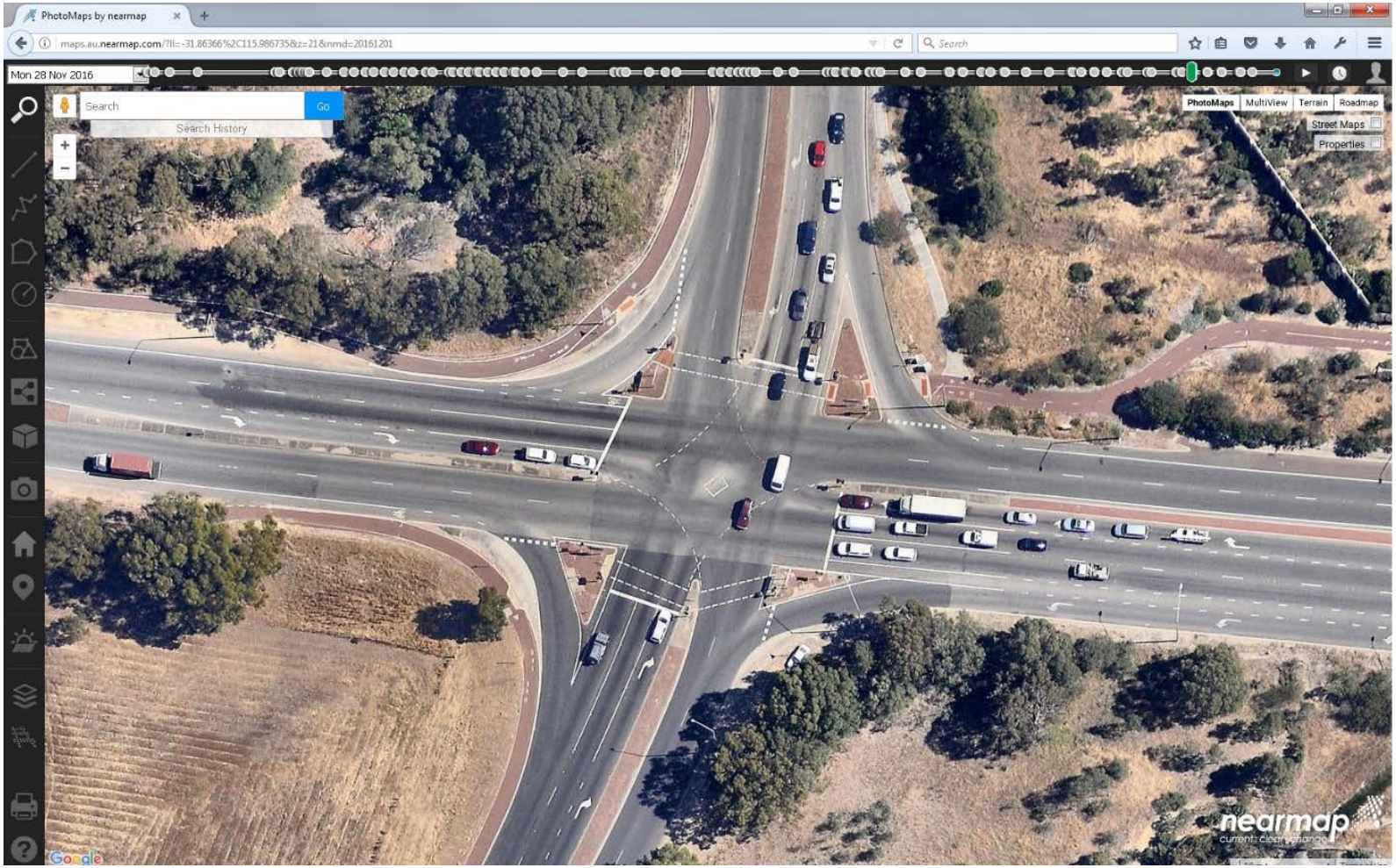
34. TONKIN HWY & BENARA RD



35. TONKIN HWY & HORRIE MILLER DR & KEWDALE RD

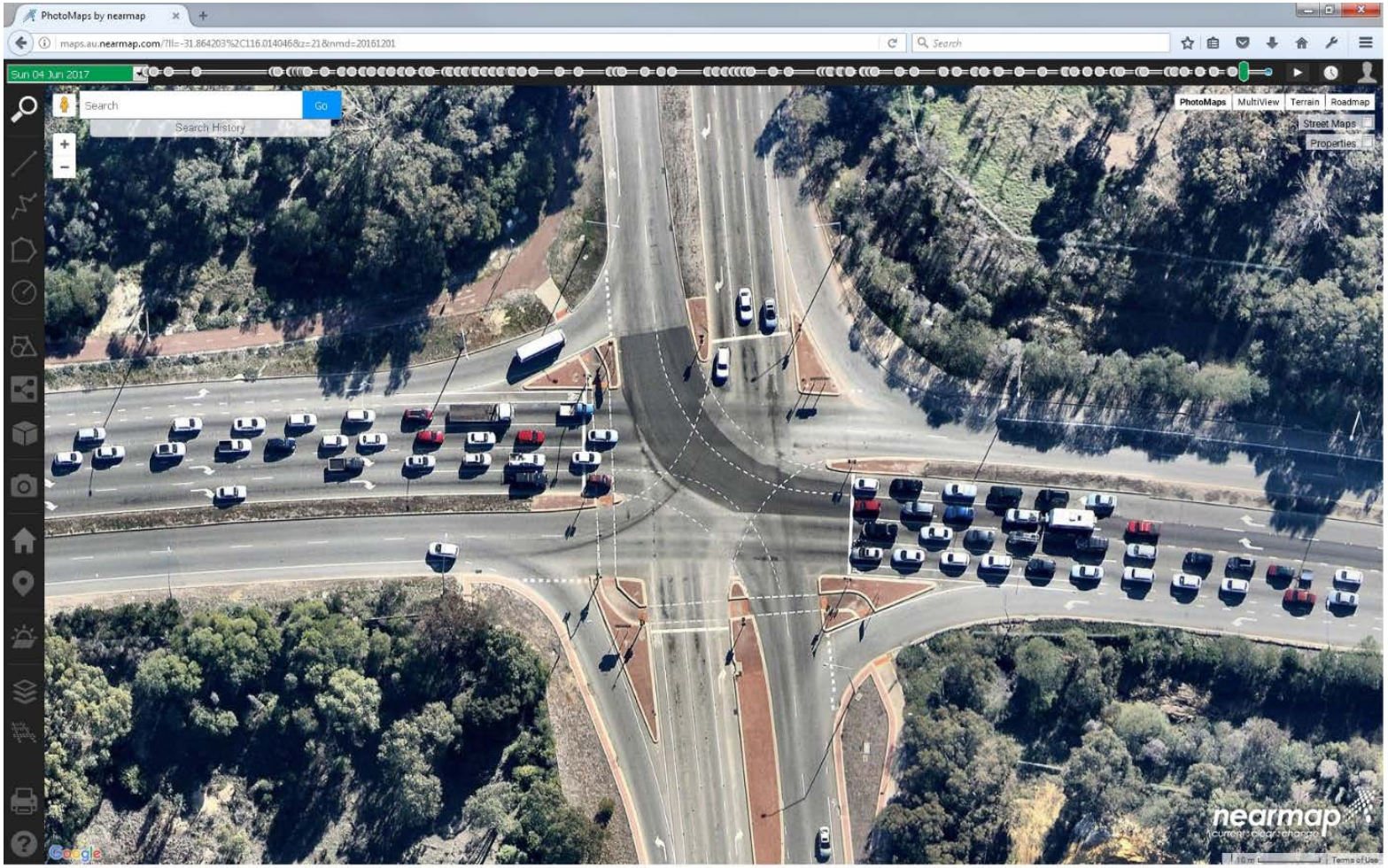


36. REID HWY & WEST SWAN RD

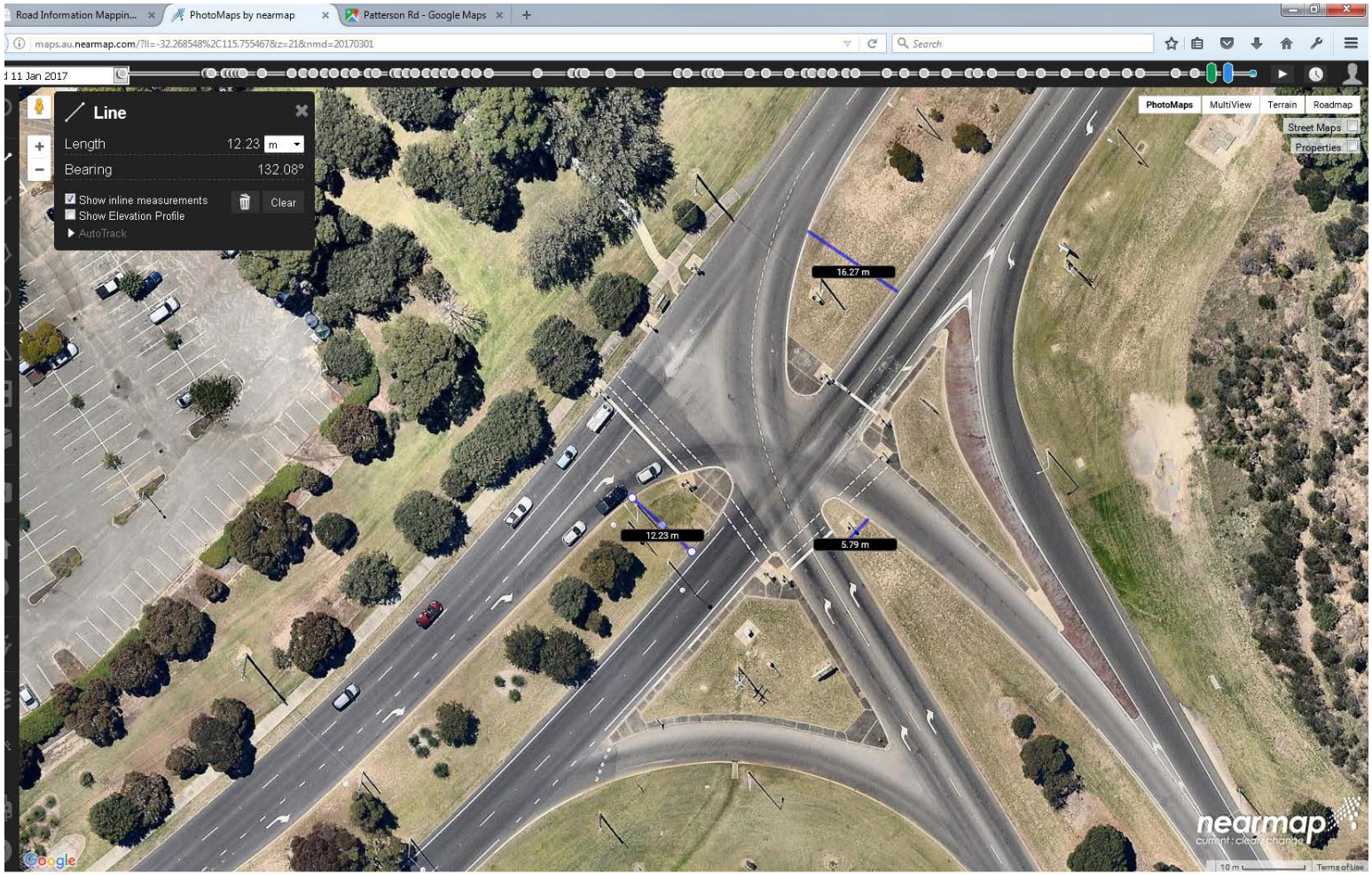


37. ROE HWY & KALAMUNDA RD

38. GREAT NORTHERN HWY & ROE HWY & GREAT NORTHERN HWY & REID HWY

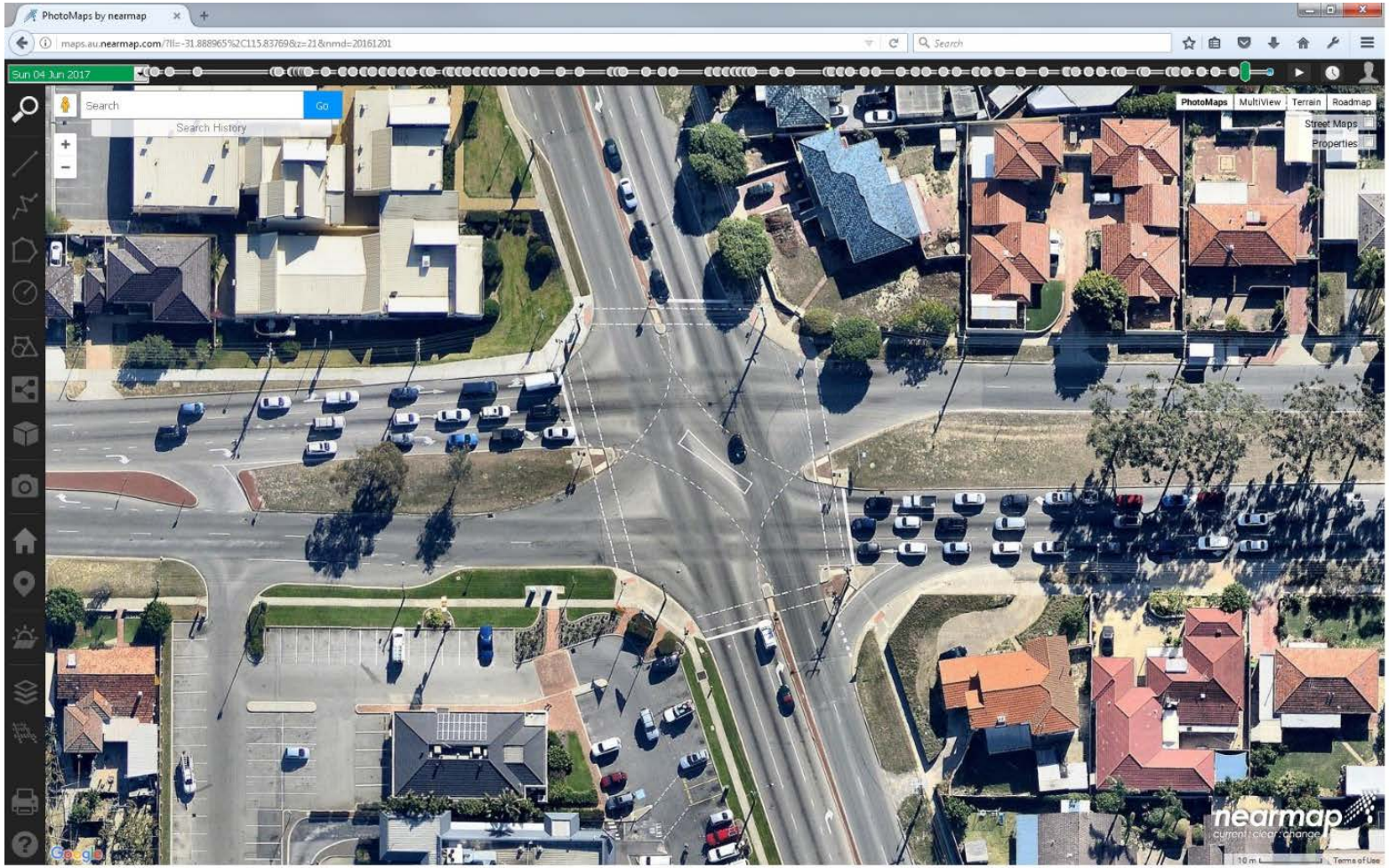


39. PATTERSON RD & ENNIS AV

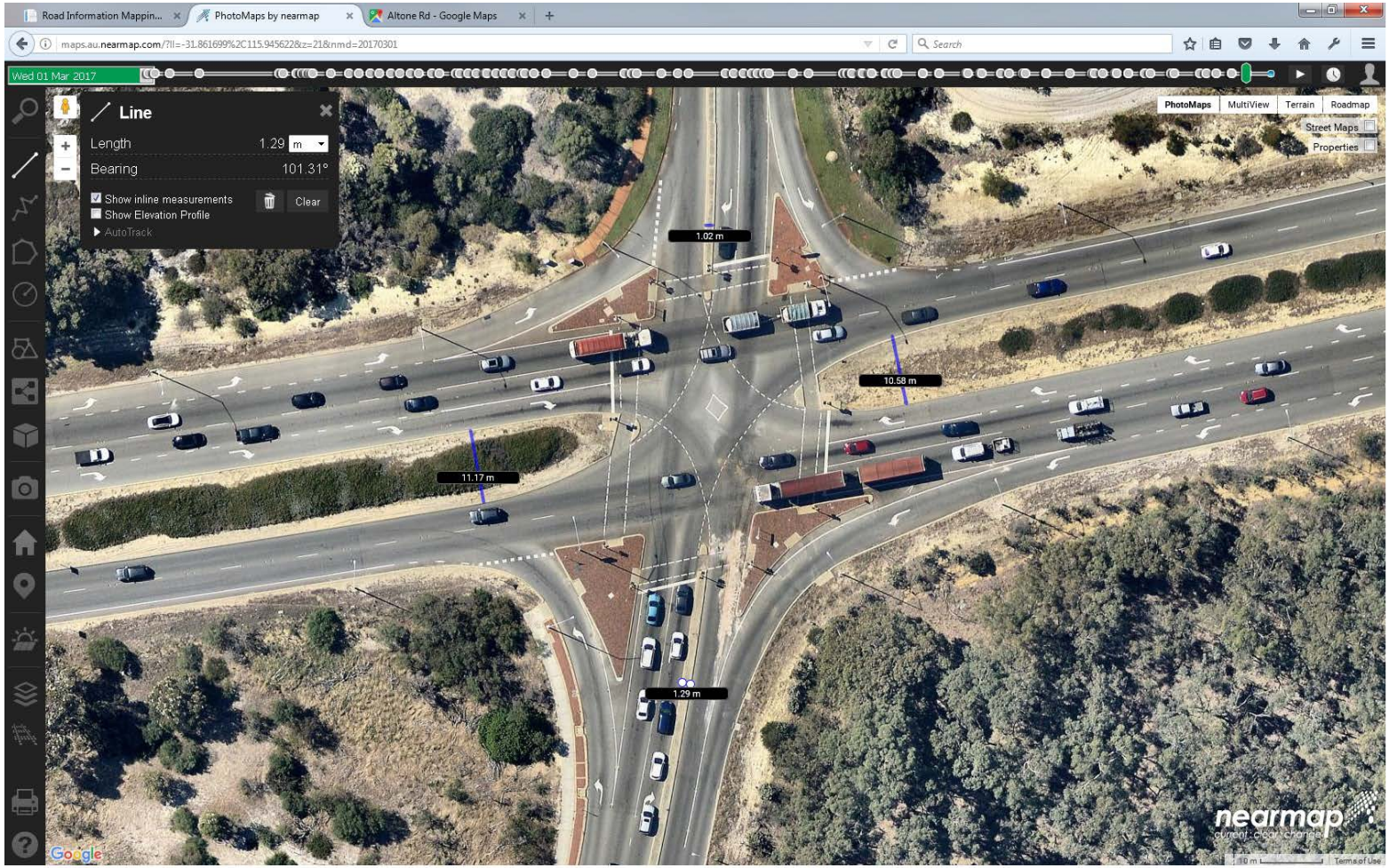


40. WANNEROO RD & NEWCASTLE ST & CHARLES ST ON - H016 STH BOUND & H016 NTH BOUND – CHARLES ST

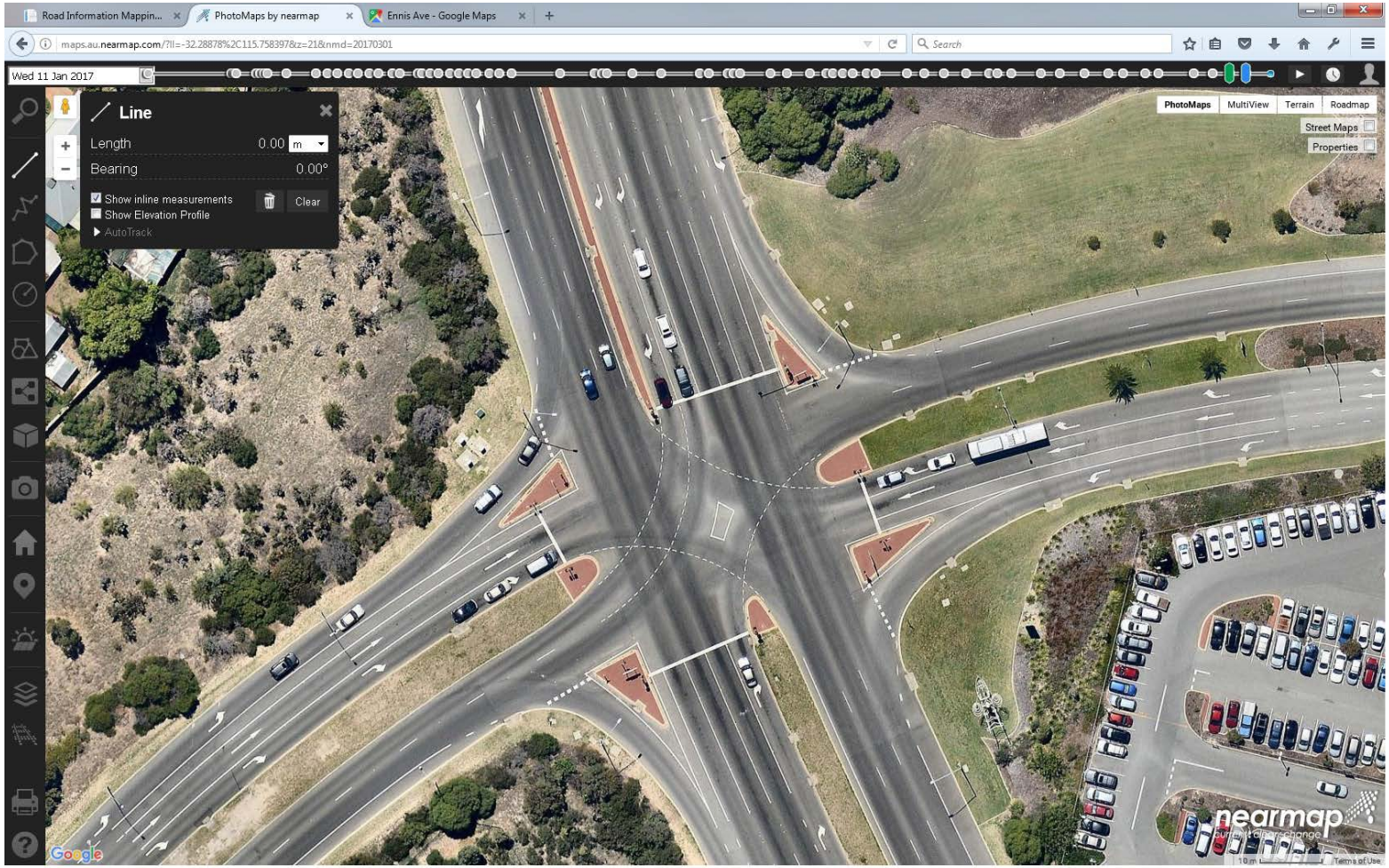
41KARRINYUP - MORLEY HWY & WANNEROO RD



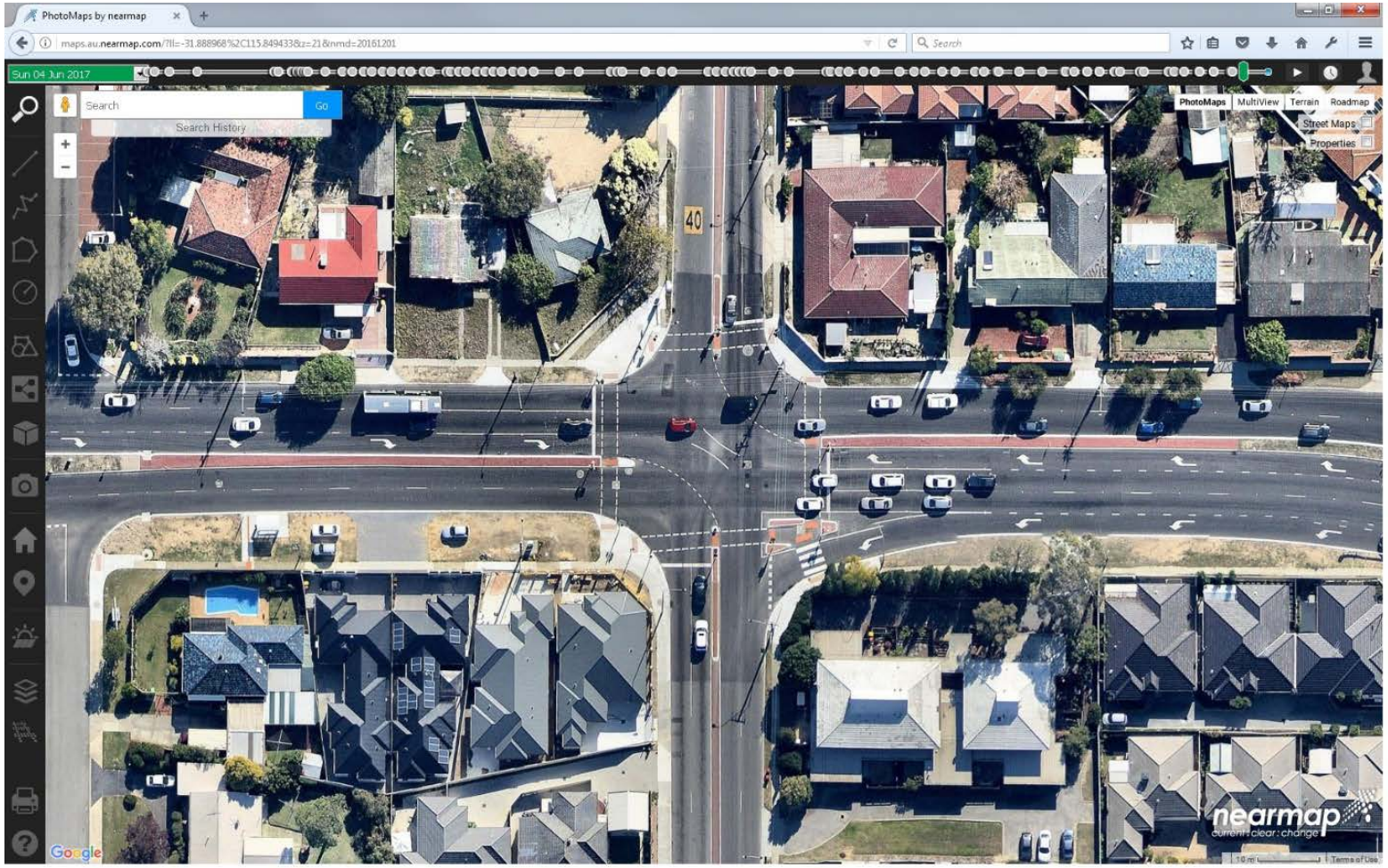
42. REID HWY & ALTONE RD



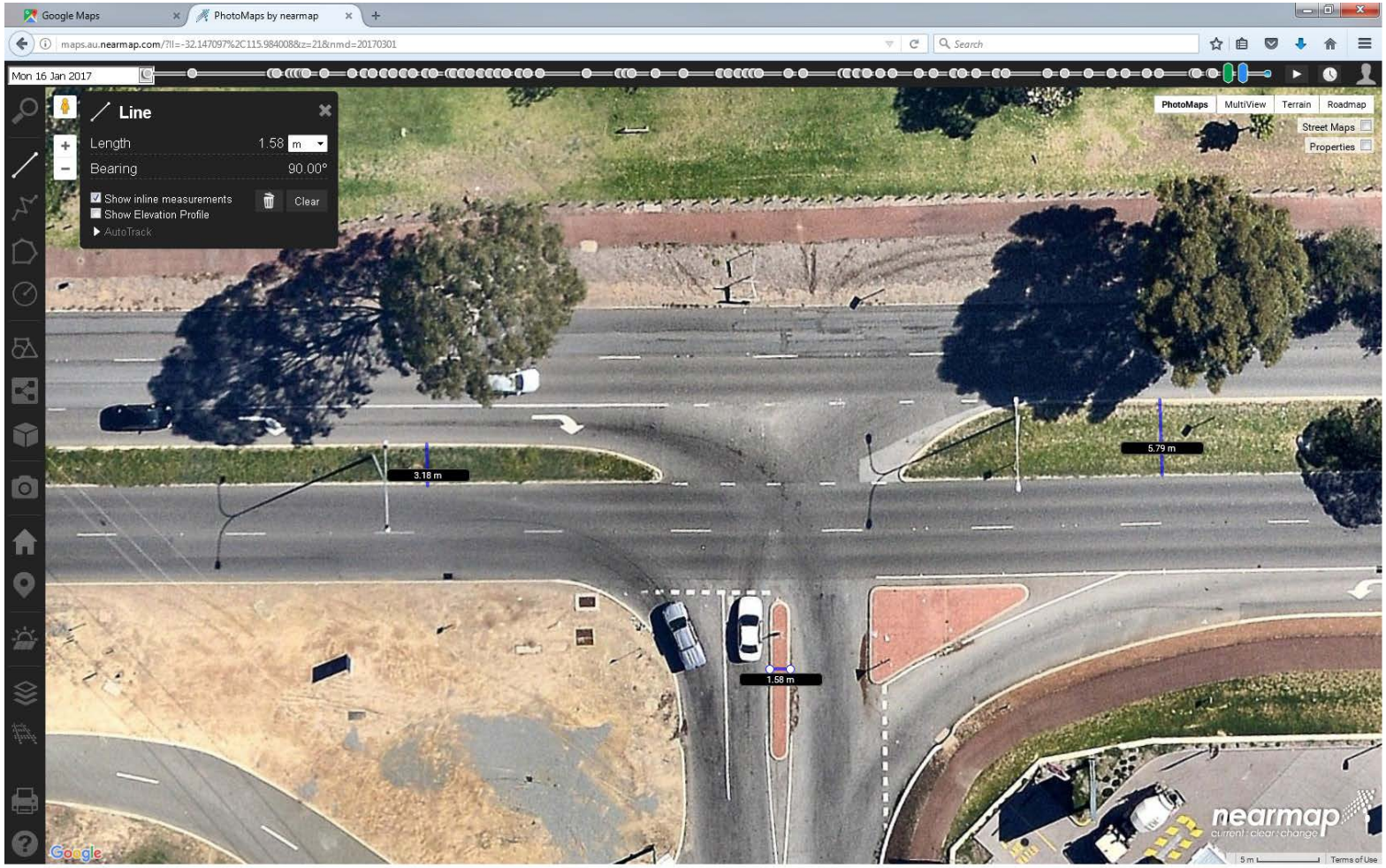
## 43. ENNIS AV & ROCKINGHAM STATION ACCESS RD & RAE RD



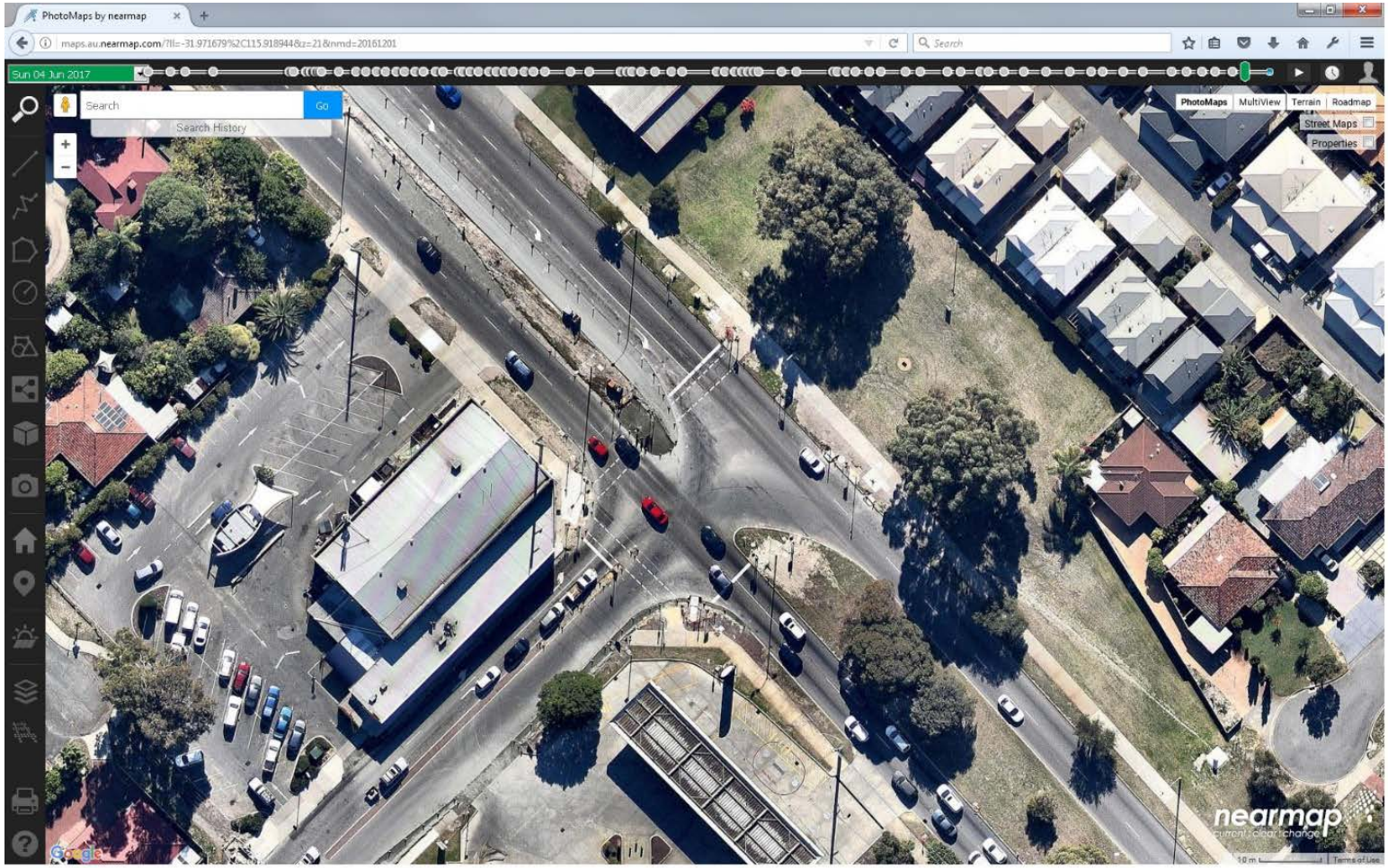
44. KARRINYUP - MORLEY HWY & FLINDERS ST



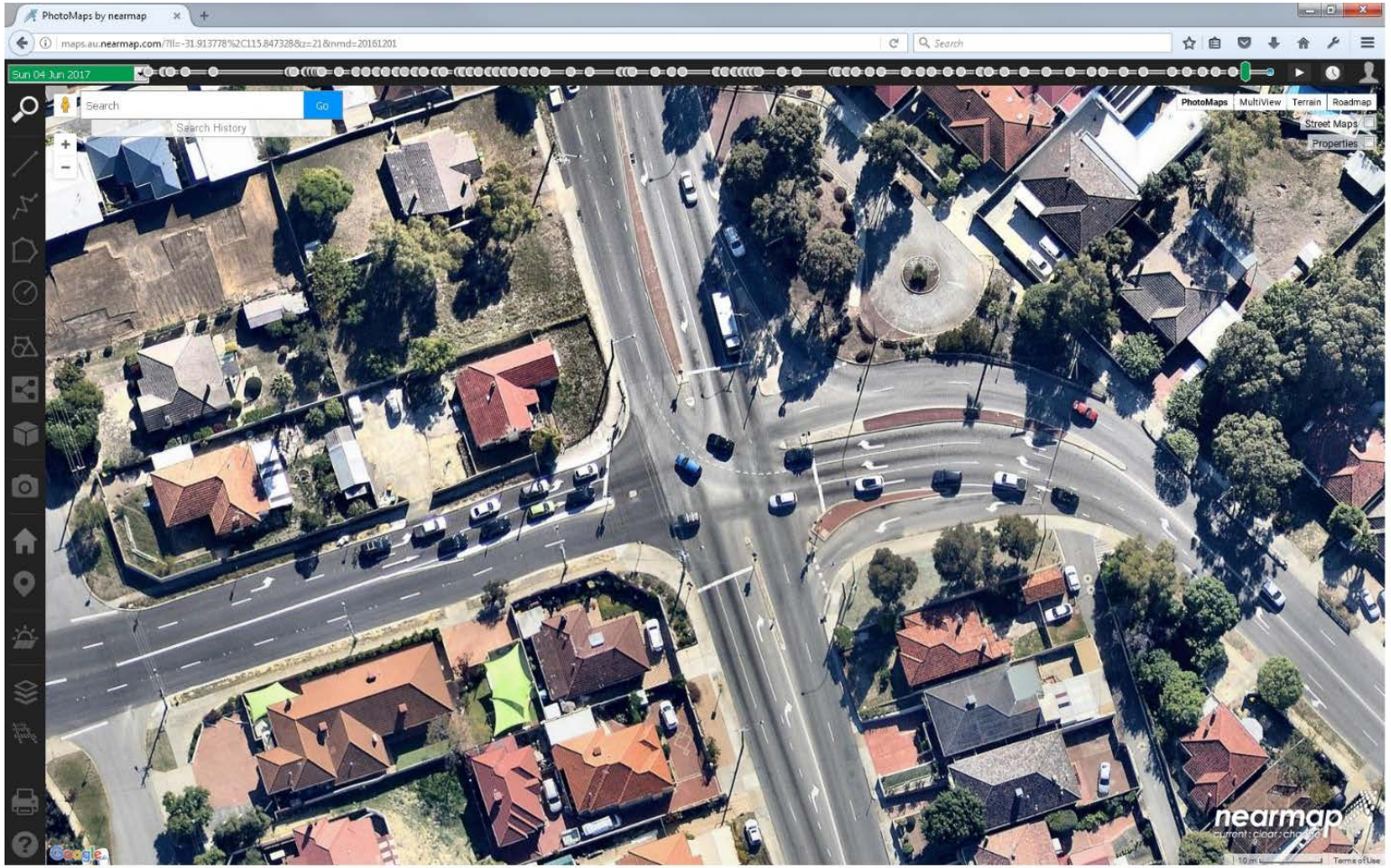
45. ARMADALE RD & EIGHTH RD



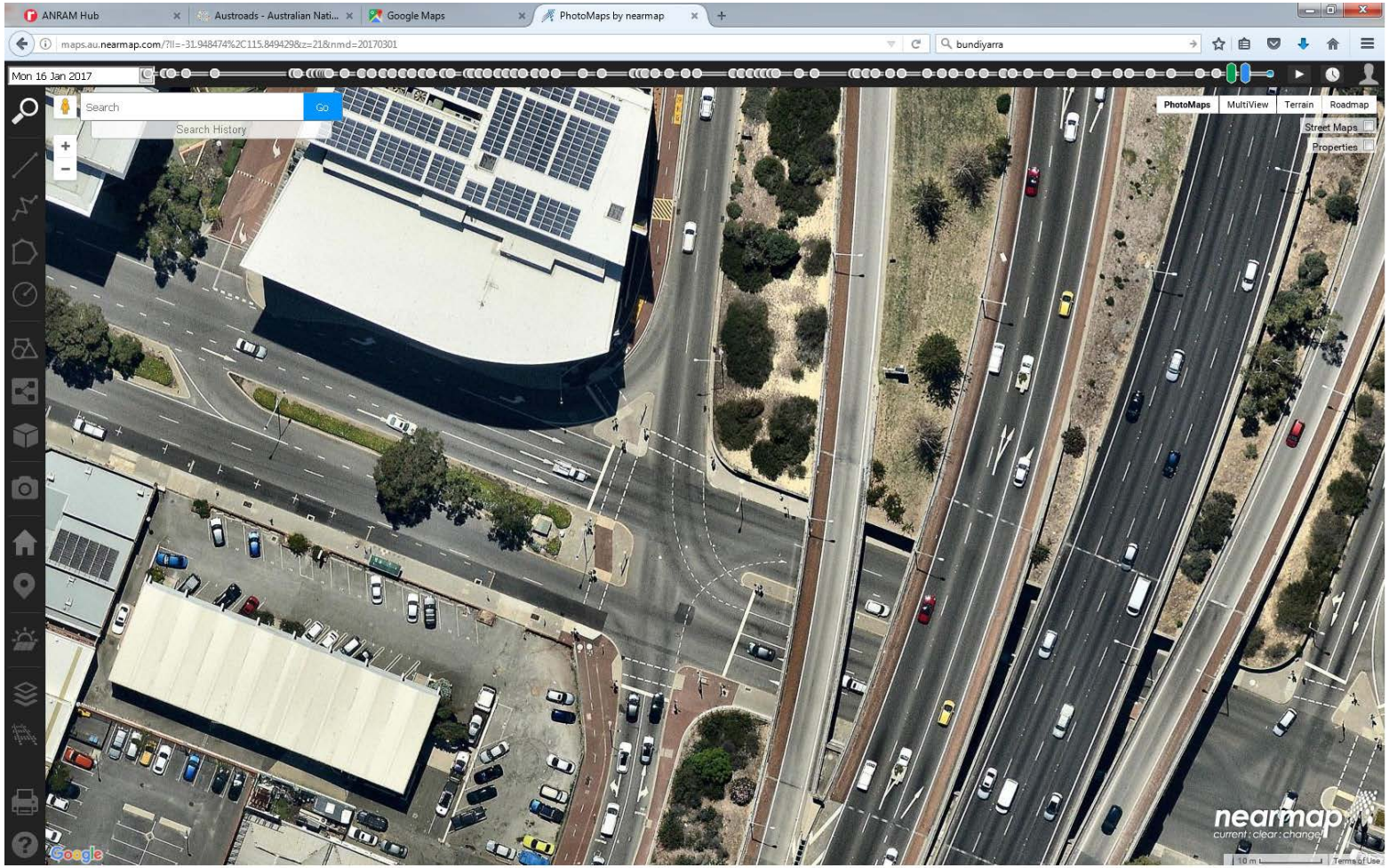
46. ORRONG RD & ARCHER ST



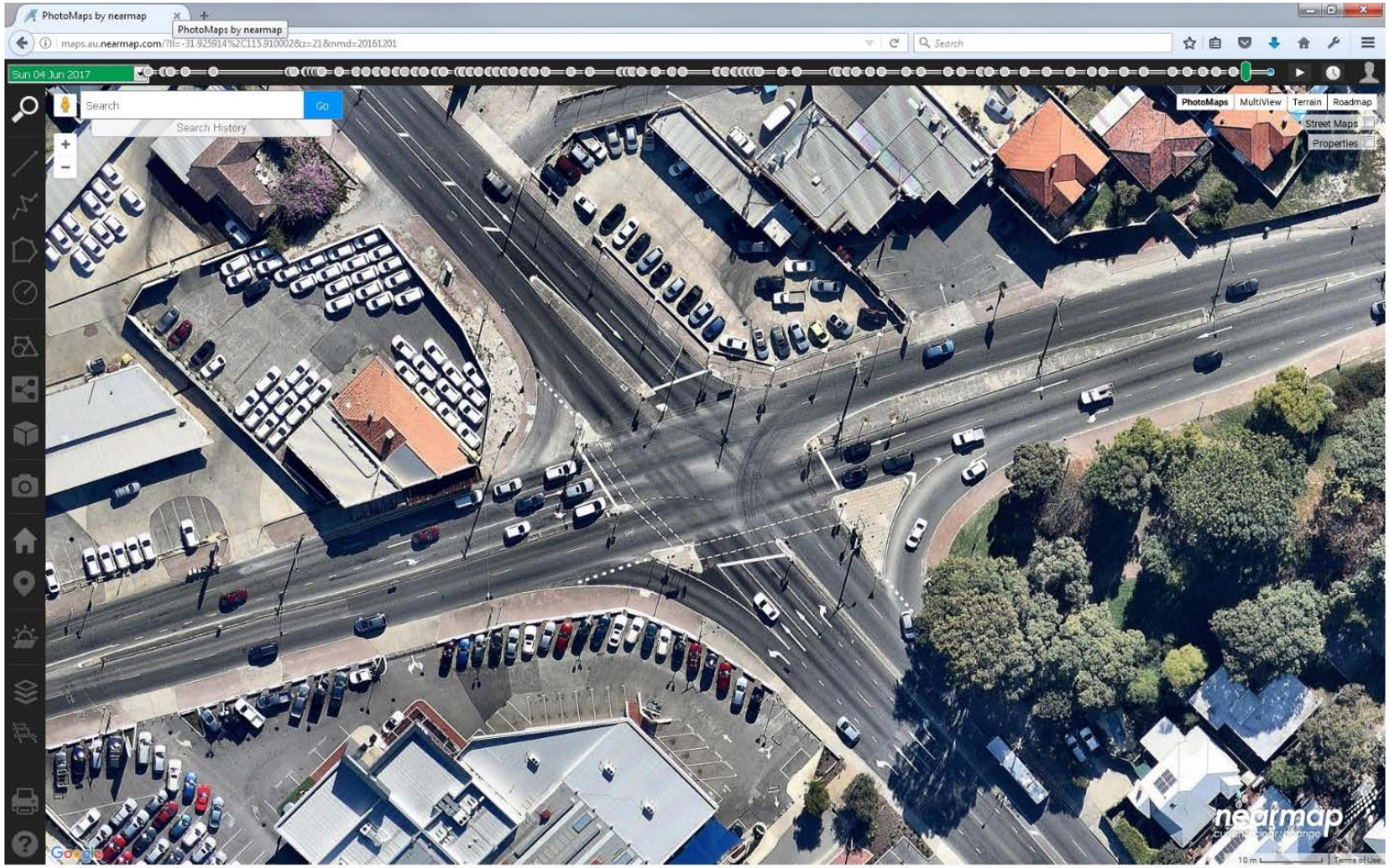
47. WANNEROO RD & GREEN ST & WALCOTT ST



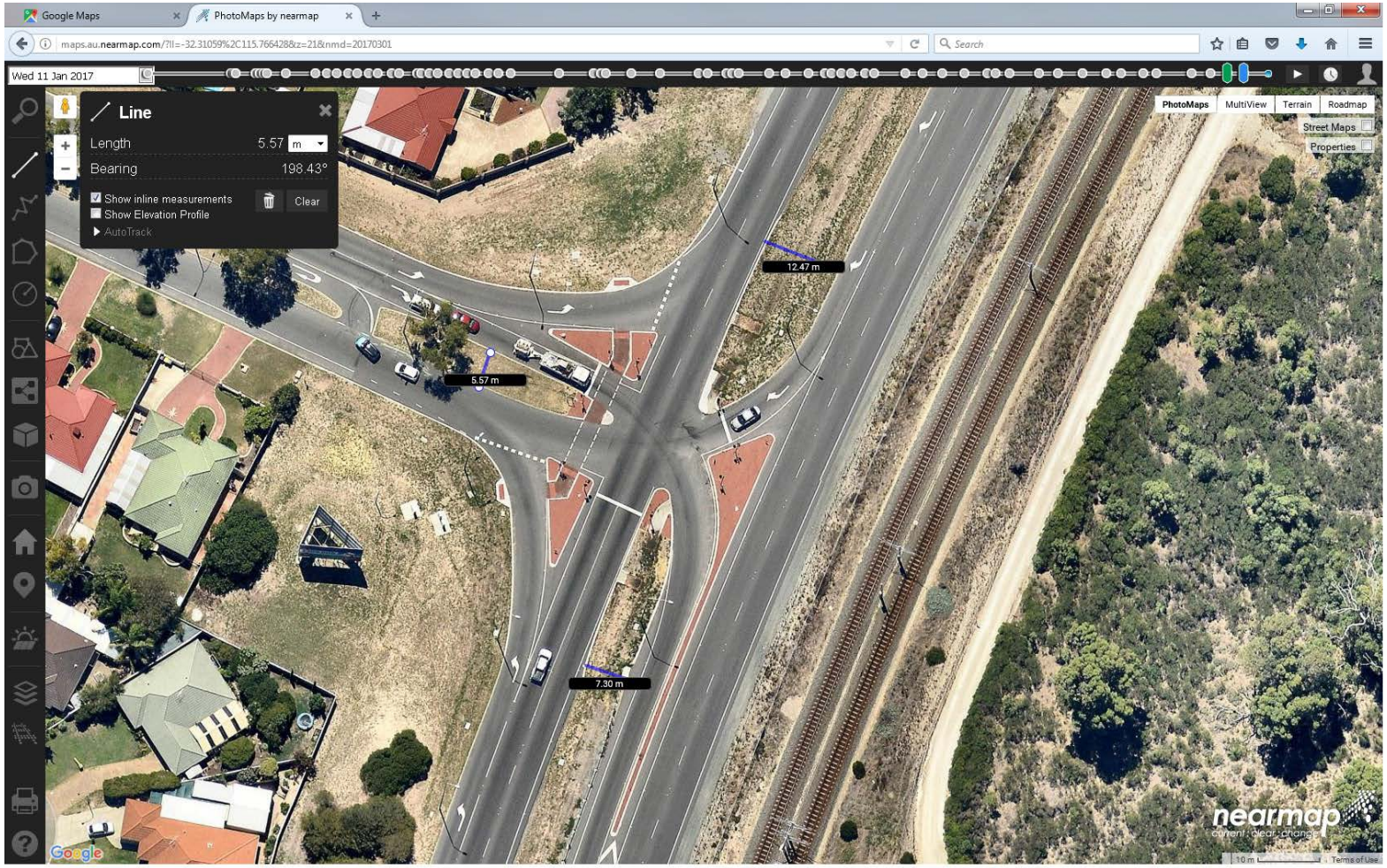
48. WELLINGTON ST 124 0116 - H016 & WELLINGTON ST & GEORGE ST



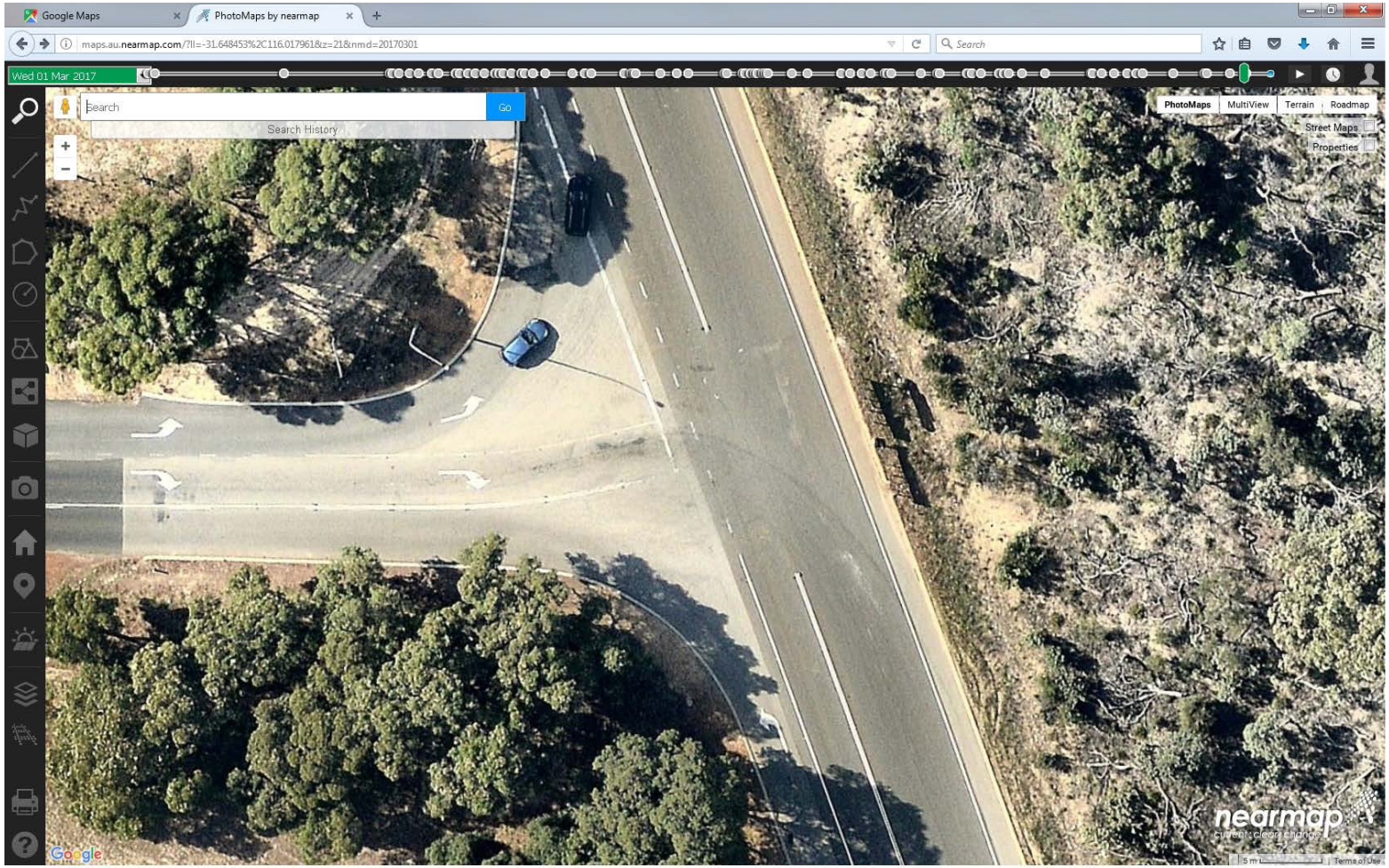
49. GUILDFORD RD & GARRATT RD



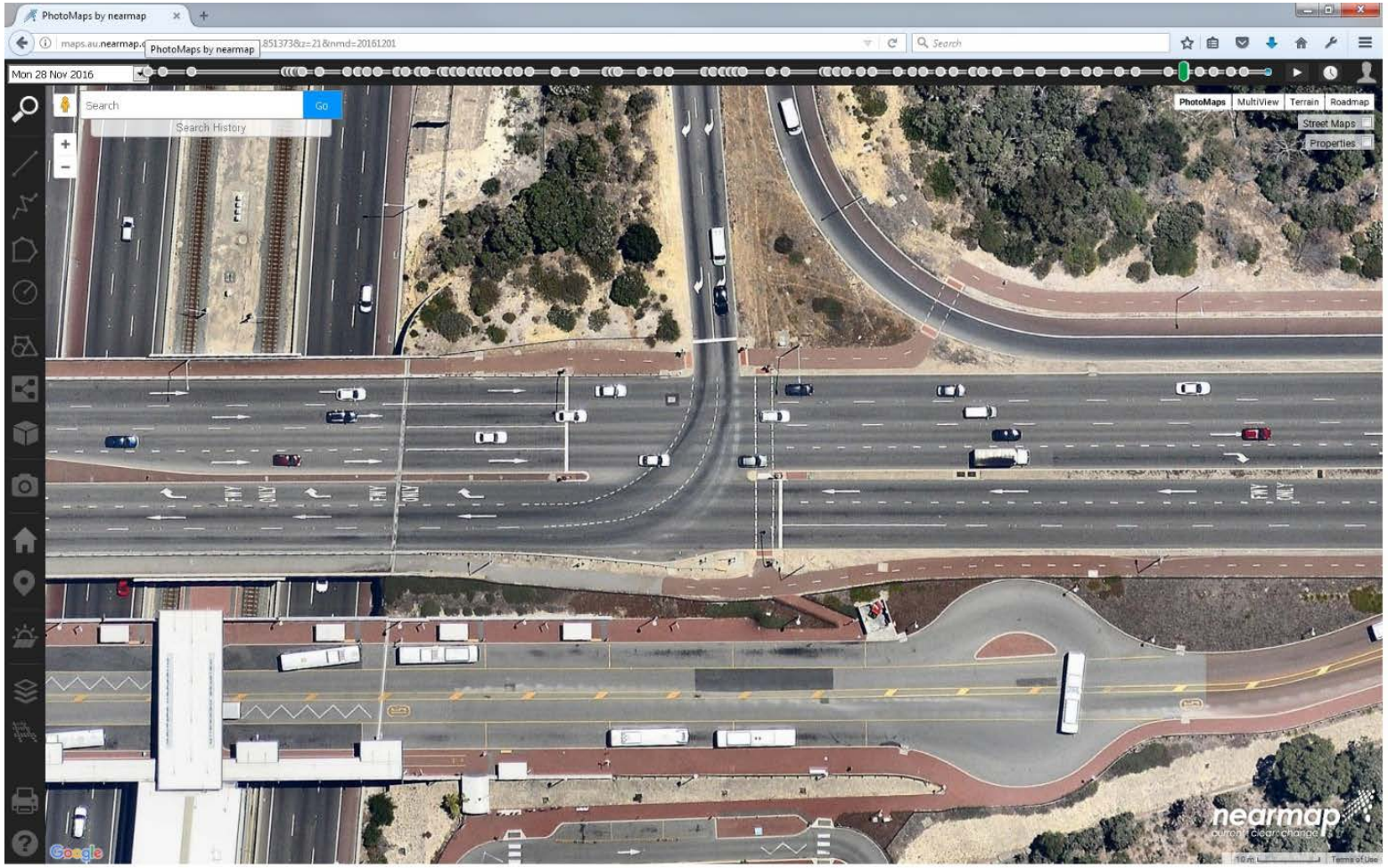
50. ENNIS AV & WILLMOTT DR



51. GREAT NORTHERN HWY & RUTLAND RD

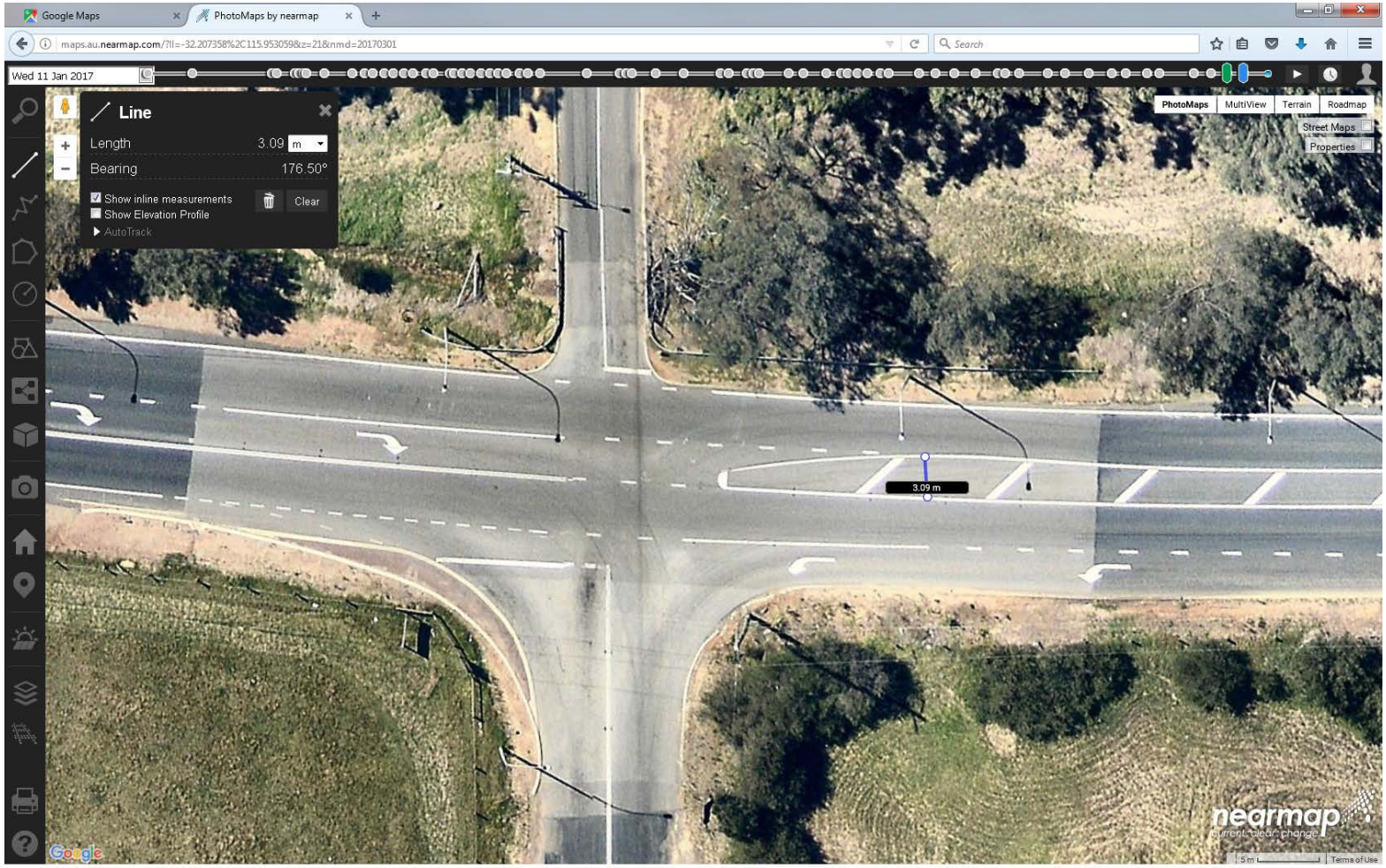


52. SOUTH ST & H015 STH BOUND - SOUTH ST WEST

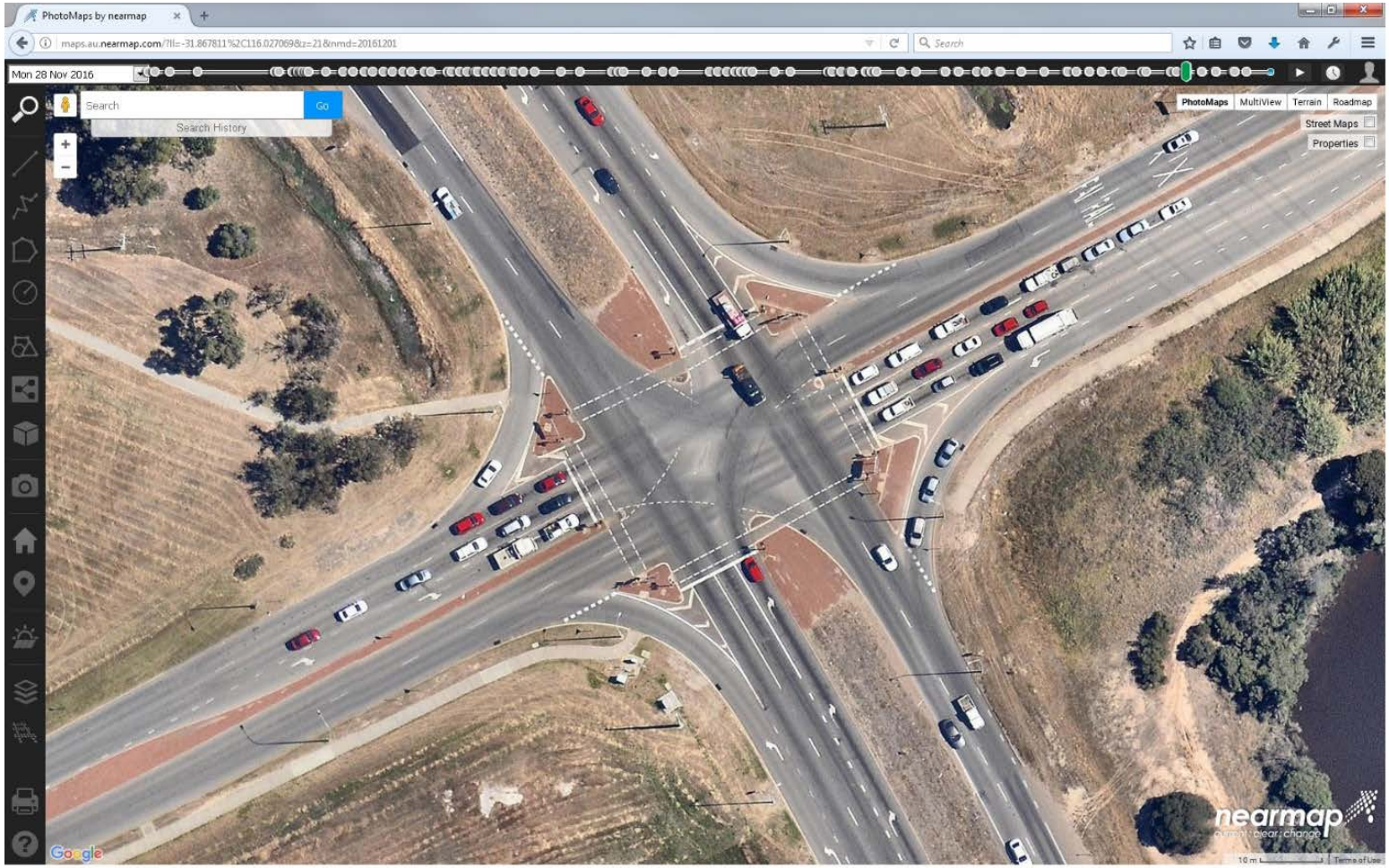


53. ROCKINGHAM RD & ANKETELL RD

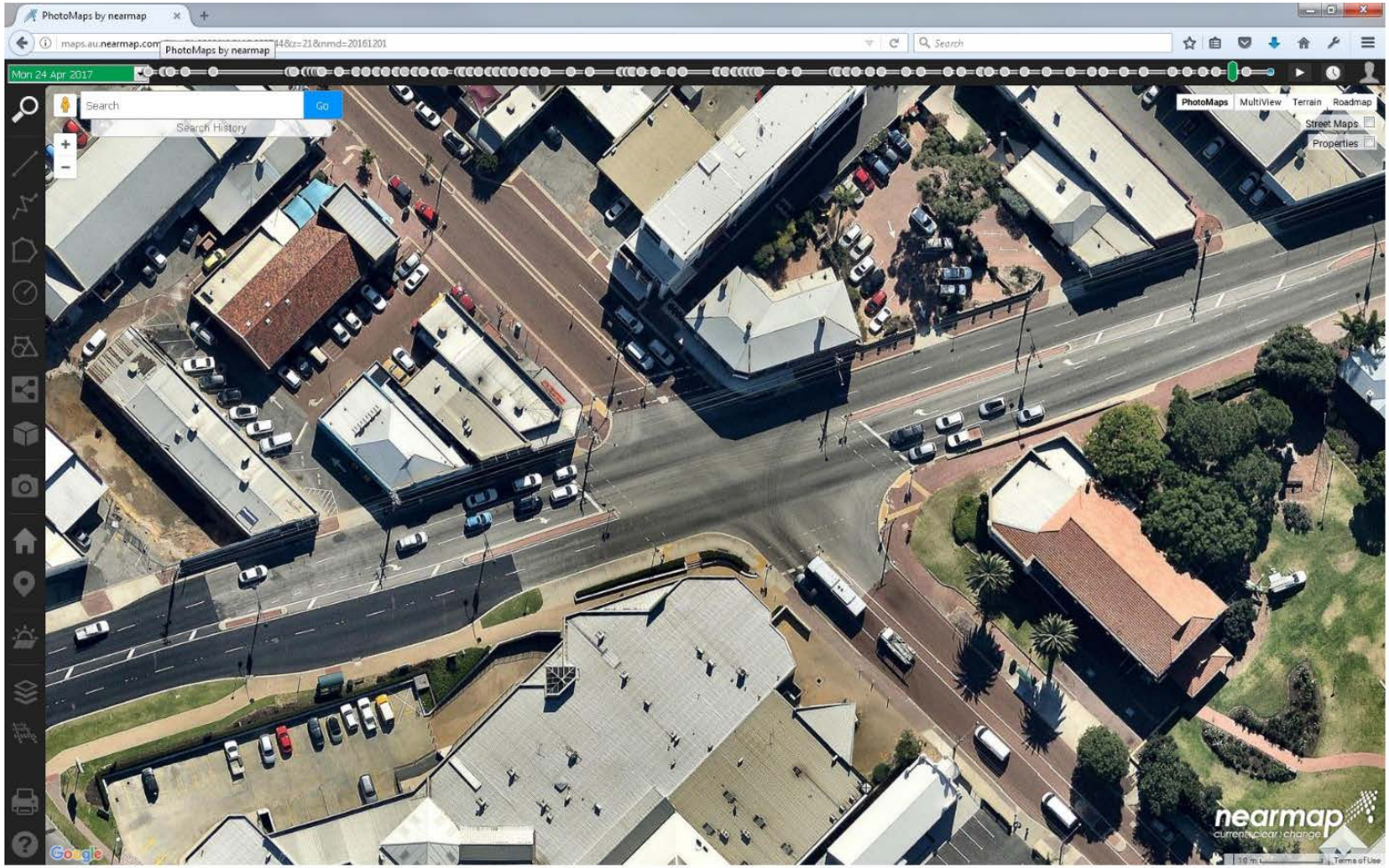
54. KARGOTICH RD & THOMAS RD



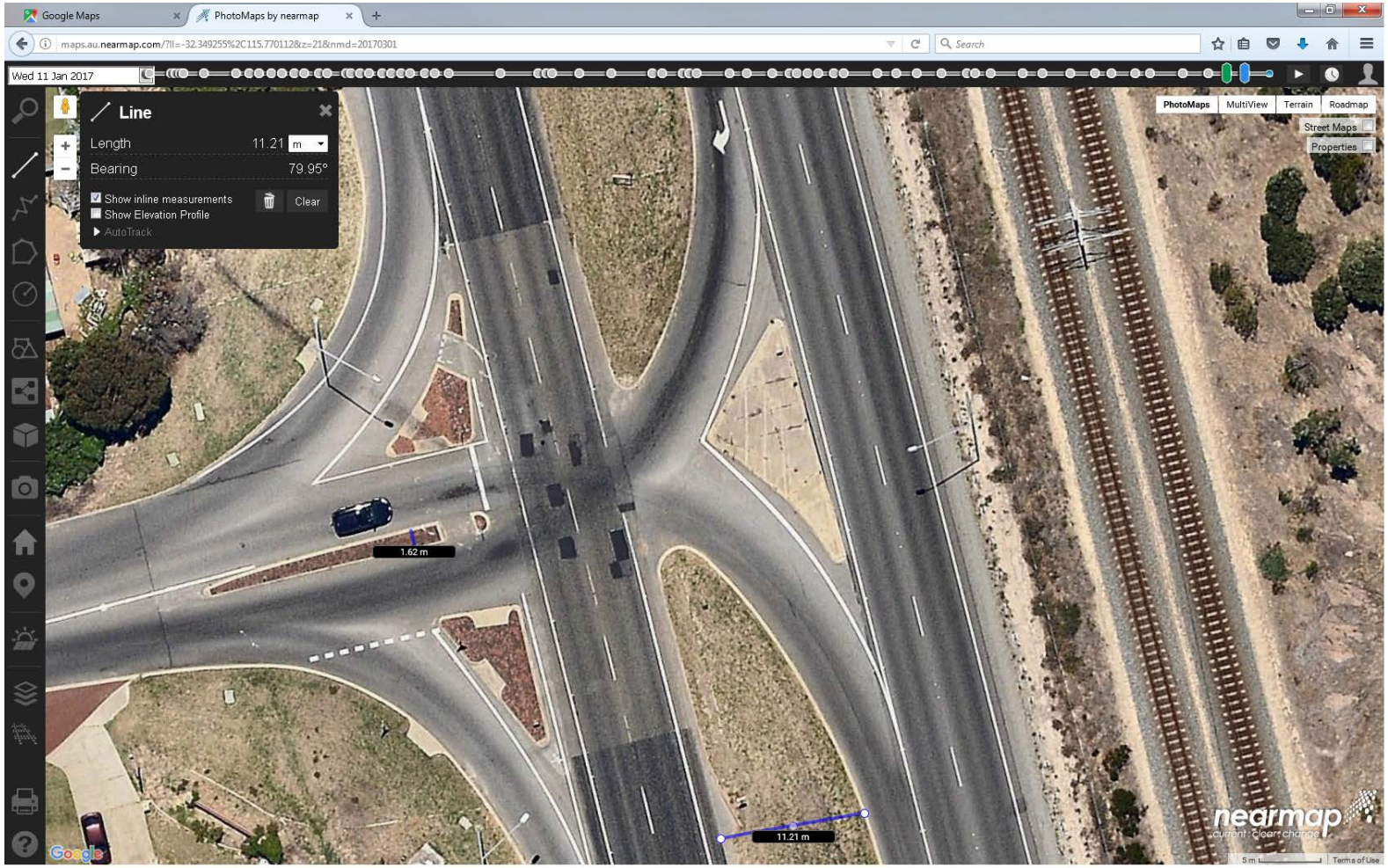
55. ROE HWY & TOODYAY RD & TOODYAY RD



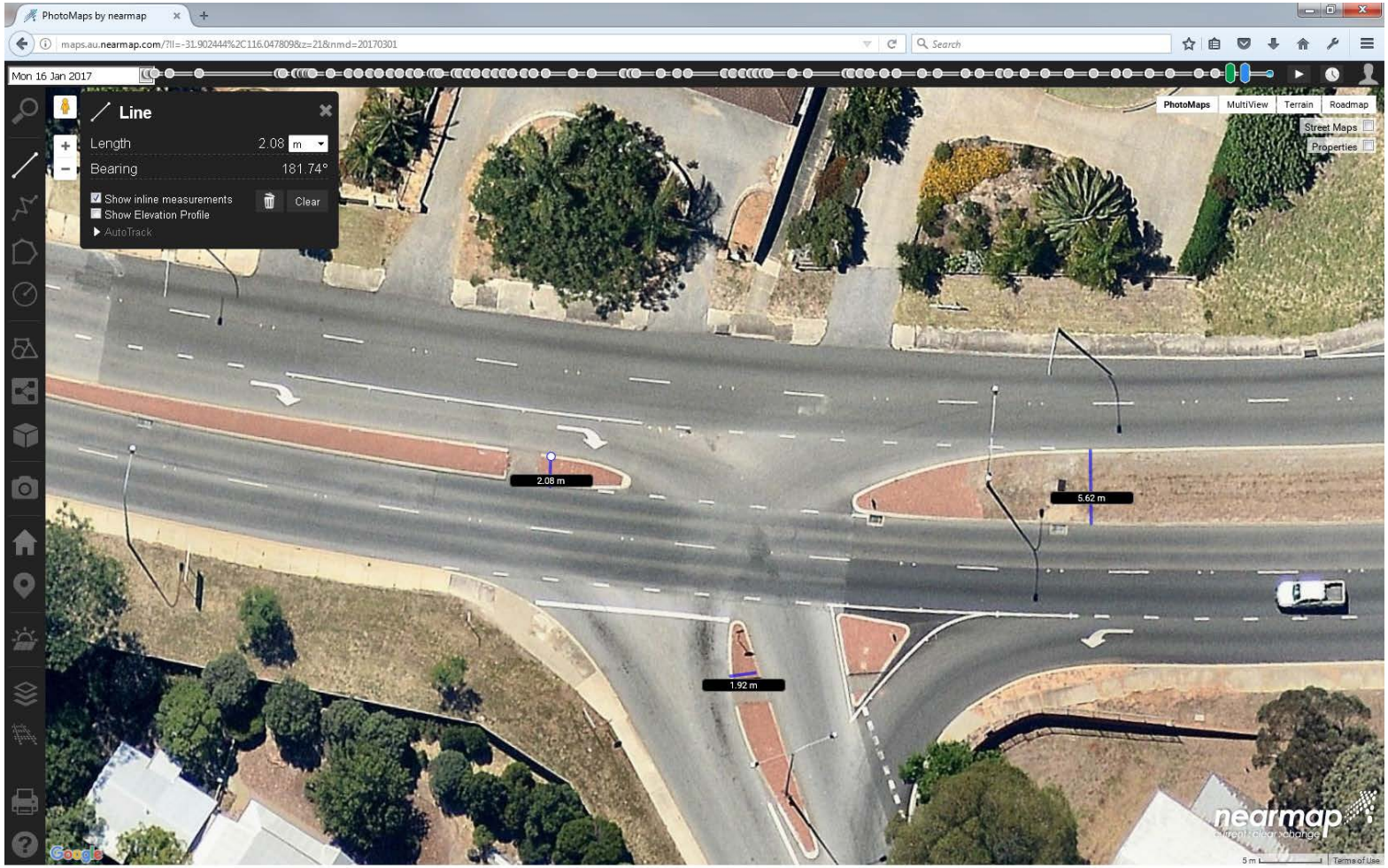
56. GUILDFORD RD & EIGHTH AV



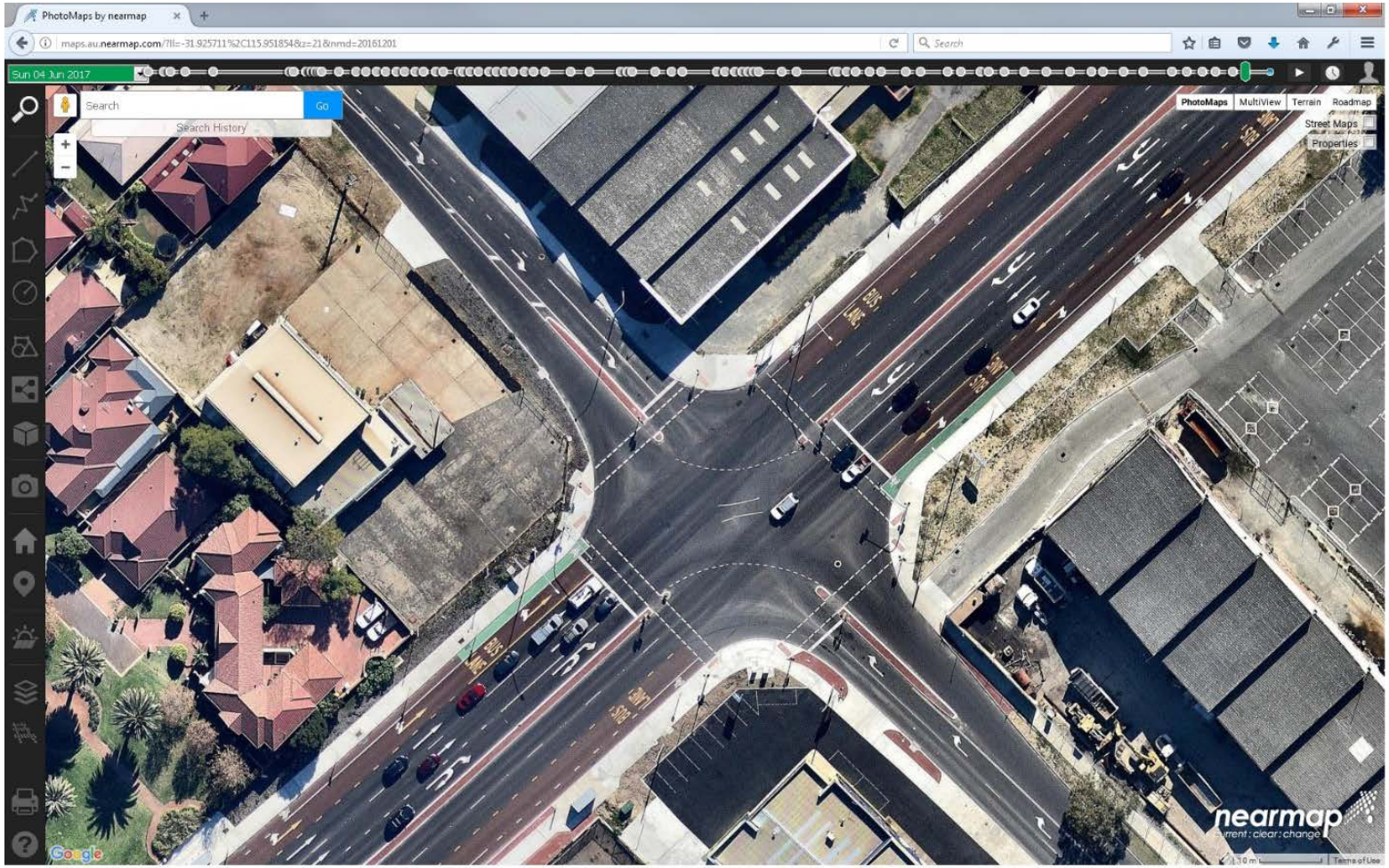
57. ENNIS AV & ROYAL PALM DR



58. GREAT EASTERN HWY & SCOTT ST



59. GREAT EASTERN HWY & FAUNTLEROY AV



60. WHITFORDS AV ON - H016 STH BOUND & WHITFORDS AV & H016 STH BOUND - WHITFORDS AV