EB 035

Chelmsford Traffic and Access Strategy

Essex County Council

Cycling Model – Technical Note

Cycling Model | Final

August 2017

Chelmsford Traffic and Access Strategy

Project no:	B3553T37
Document title:	Cycling Model Report
Document No.:	Cycling Model Report
Revision:	Final
Date:	23/08/2017
Client name:	Essex County Council
Client no:	Essex County Council
Project manager:	Csaba Kelen
Author:	Georgios Christou
File name:	O:\Projects\B3553F26 Chelmsford Modelling\1.Project Management\Deliverables\!Final Delivery 04042017\Cycling Model Final.docx

Jacobs U.K. Limited

New City Court
20 St Thomas Street
London SE1 9RS
United Kingdom
T +44 (0)20 7939 6100
F +44 (0)20 7939 6103
www.jacobs.com

Document history and status

Revision	Date	Description	By	Review	Approved
Draft	19/12/2016	Cycling Model Technical Note	Georgios Christou	Csaba Kelen	Csaba Kelen
Revised Draft	26/01/2017	Cycling Model Technical Note	Georgios Christou	Csaba Kelen	Csaba Kelen
Revised Draft	22/02/2017	Cycling Model Technical Note	Georgios Christou	Csaba Kelen	Csaba Kelen
Final	04/04/2017	Cycling Model Technical Note	Georgios Christou	Csaba Kelen	Csaba Kelen

Contents

Figures

Tables

Executive Summary

This technical note summarises the development and performance of the cycling component of the Chelmsford Strategic Model. Standard technical reports about the model have been issued previously, such as the Model Specification Report (MSR), the Local Model Validation Report (LMVR) and the Travel Forecast Report (TFR). Due to the timing of the development of this Cycling Model component, this note has been issued separately. Since there is not an established methodology in WebTAG for modelling cycling, the model development, calibration and validation, has followed established principles from the highway modelling.

The cycling model was developed on the basis of data collection via revealed preference (RP) and mobile app-based surveys, carried out as part of the project. The RP data provided information about cycling trips to the railway station and the city centre. The app survey data provided socioeconomic information about the cyclists as well as information about the cycling trips recorded by the users. The cycling model made a direct use of the following survey information: (1) origin-destination data (2) trip routeing (3) trip purpose (4) average speed (5) average trip length distribution data. The surveys are described in Chapter 2.

Chapter 3 summarises the cycling supply model, which consists of the highway, cycling, and walking network components. The network was adjusted to facilitate type-specific speed and capacity for cyclists.

Chapter 4 provides a detailed description of the cycling demand model development, which was based on a semi-synthetic approach. For trip generation survey data were used to establish daily trip ends for key destinations, such as the station, the city centre and the university. For other locations, a regression model was used to obtain trip-ends, which, in turn, were informed by the surveys. The trip distribution model used a standard gravity model approach, which was informed by trip length distribution data from the surveys. The resulting daily cycling trip matrix was converted to matrices by time period using area type and direction-specific time of day factors. The cycling model outputs morning peak hour, average inter-peak hour and afternoon peak hour cycle trip matrices.

An equilibrium methodology was used for the cycling assignment. The cycling assignment generalised cost function used perceived travel time only, as a measure of both cycling cost and convenience. The key feature of the volume-delay function is that combines deterrence caused by motorised traffic, as well as deterrence caused by cycling congestion. The cycling assignment methodology and results for the base year (2014) are summarised in Chapter 5.

The forecast methodology and results for the year 2021 and 2036 are shown in Chapter 6.

1. Introduction

The purpose of this document is to outline the scope and process of developing the cycling model component of the Strategic Multimodal Transport Model for the city of Chelmsford.

Chelmsford City is facing the challenge of meeting increasing travel demands while actively encouraging economic growth. Jacobs was commissioned to build a multi-modal transport model for the city of Chelmsford to understand the current and future transport issues in Chelmsford and to help bid for funding that will be made available via the Local Enterprise Partnership (LEP) and national funding sources.

Further background to the study is provided by the County Council's "Essex County Growth Deal", which forms part of the South East Local Enterprise Partnership's (SELEP) £1.2 Billion bid to Government to leverage £10 Billion of investment into the South East. The Essex County Growth Deal identifies a number of transport schemes and initiatives to help realise and promote the growth planned for the city of Chelmsford.

The scale of the potential proposals is such that the funding approval process requires the development of WebTAG compliant transport models. To this end, a strategic multi-modal model was developed to assess the strategic transport impacts of the various transport schemes in the city. The model was needed to evaluate the following infrastructure and policy interventions, to be implemented in Chelmsford:

- Residential, industrial and commercial land use developments,
- Road infrastructure improvements (roadways, junctions),
- Public transport service improvements (stations/stops, routes, timetables),
- Public transport policy (fares, information),
- Parking infrastructure and policy (car parks, parking costs),
- Cycling infrastructure and policy (bicycle lanes, parking).

The cycling infrastructure and policy impacts have not been traditionally modelled or assessed. Essex County Council (ECC) recognised the need for robust cycling model, and consequently the cycling component has been added to the Chelmsford Strategic Model suite for time horizons 2014, 2021 and 2036.

The PTV VISUM14 software package has been used for modelling cyclists, to be consistent with the rest of the Chelmsford Strategic Model. The model provides detailed spatial and network coverage of the whole Chelmsford Administrative and Urban Area, but also extend beyond its boundaries to ensure detailed representation of the key adjacent areas.

2. Cycling Data Collection

2.1 Revealed Preference Demand Data

A revealed preference survey was carried out in June 2014 by Jacobs at the train station and city centre to collect information about car drivers, train passengers, bus passengers, and cyclists. The results of this survey were analysed to gain insights into cycle trips in Chelmsford. Considering both sites, a total of 583 were distributed and 97 questionnaires were returned. Using this data, trip purpose, and trip origin/destination data have been analysed. This information has informed the cycling model development for the base year. Cycling trip purposes and desire lines for trips to Chelmsford station and the city centre are shown in the following figures 1 and 2, respectively.

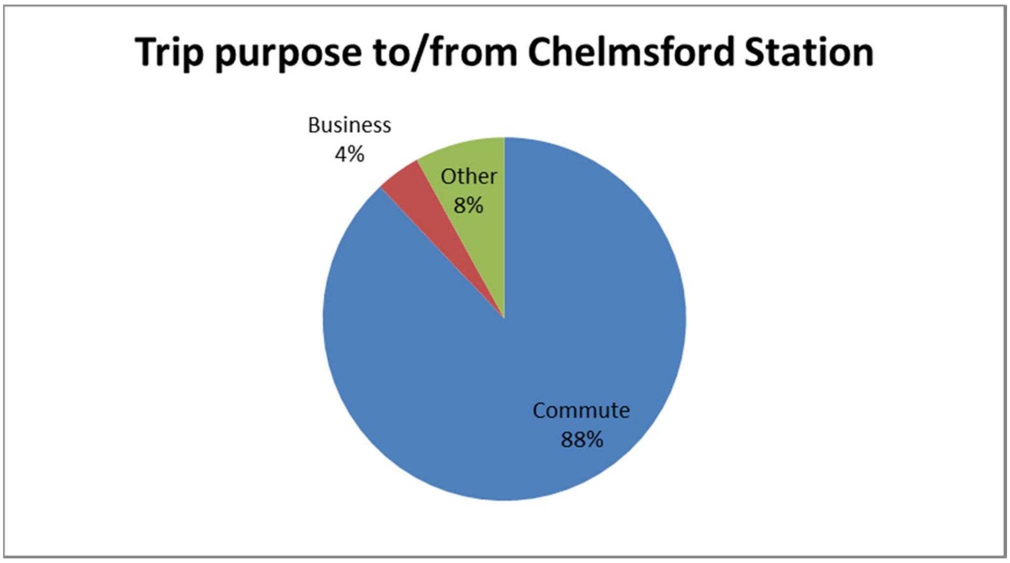


Figure 1 Cycling trip purpose to/from Chelmsford station

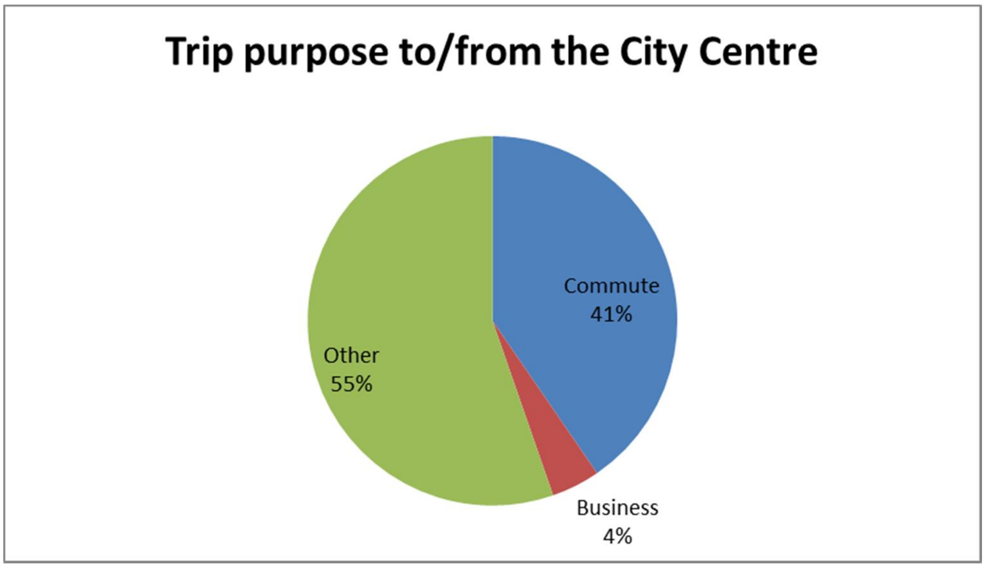


Figure 2 Cycling trip purpose to/from the city centre

As shown in the figures, cycling trips to/from Chelmsford station are dominated by commute trips, while cycle trips to/from the city centre are dominated by commute and other trips.

Figure 3: Train Station cycle trip desire lines (Left) and City Centre cycle trip desire lines (Right)

As shown in Figure 3, cycling trips, to Chelmsford station and the city centre, come mainly from Chelmsford. Trips to Chelmsford station tend to have longer trips length, than trips to the city centre. The survey reveals that the average trip length is 1.8km to the city centre and 2.2km to the station. This is because station-bound trips are predominantly commuting trips, which tend to have longer average trip length than other trip types.

2.2 Volumetric Data

To improve and understand how well the model replicates observed cycle traffic, it was necessary to use cycle counts to compare modelled flows against cycle counts. To this end, existing cycle counts within the study area have been obtained, and new cycling data was collected as part of this project.

Available cycling counts from the Department for Transport (DfT) and ECC were obtained and processed. After reviewing all the available sources of information, 11 locations were identified where additional data were needed. The data for 10 of the locations were collected in June 2016 and the remaining one was collected in October 2016. See Figure 4 for further detail on the location of each count site and its source.

The DfT AADF database[1] () contains the average number of vehicles that pass a site in the network for 10 vehicle classes for the years between 2000 and 2014. DfT also maintains an automatic count database as well, which contains 12 hours hourly data for 10 vehicle classes on a specific day. The

[1] http://www.dft.gov.uk/traffic-counts/cp.php

data was analysed to estimate the average volumes in each time period (AM peak hour, average inter-peak hour, PM peak hour).

2014 counts were collected for the whole Chelmsford Administrative Area. This data was used for the model calibration and validation.

Essex Highways provided Jacobs with the most recent cycling count data from the Chelmsford Administrative Area. This included 13 site locations with fixed cycling counts. From each site hourly data were collected from June 2014.

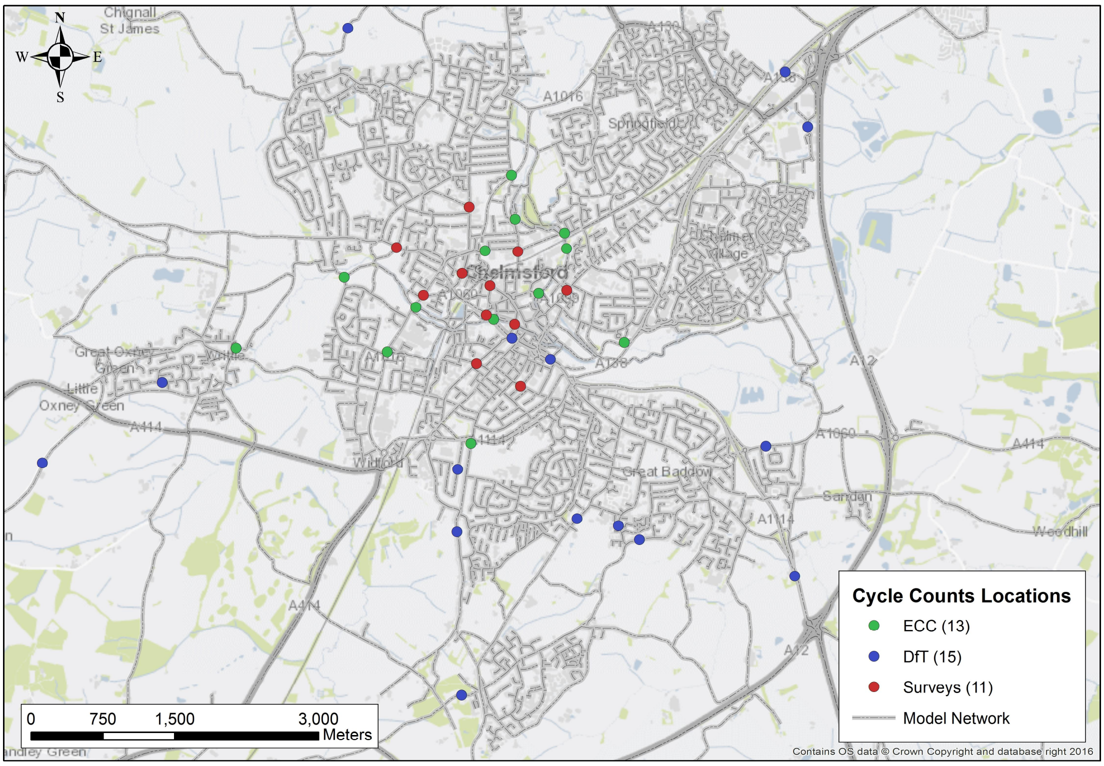


Figure 4 Cycling count sites locations in Chelmsford

2.3 App-based Demand Data

2.3.1 App Purpose

Due to the special characteristics and travelling patterns that characterise cyclists and their movements, a specific mobile phone app was developed with the intention of adequately capturing cyclists' data: origins, destinations, trip purpose, routeing, etc., to inform the model and any future decision on cycling infrastructure development.

ITS Planners and Engineers were commissioned by Jacobs to develop the mobile phone app, available in both Android and iOS mobile phone stores. During development the purpose of the app was extended to not only capture details from individual trips, but also a series of other socio-demographic information such as:

- Date of birth,
- Gender,
- Education,
- Annual income,

- Vehicle ownership,
- Employment sector.

See screenshots of the cycling app functionality in Figure 5.

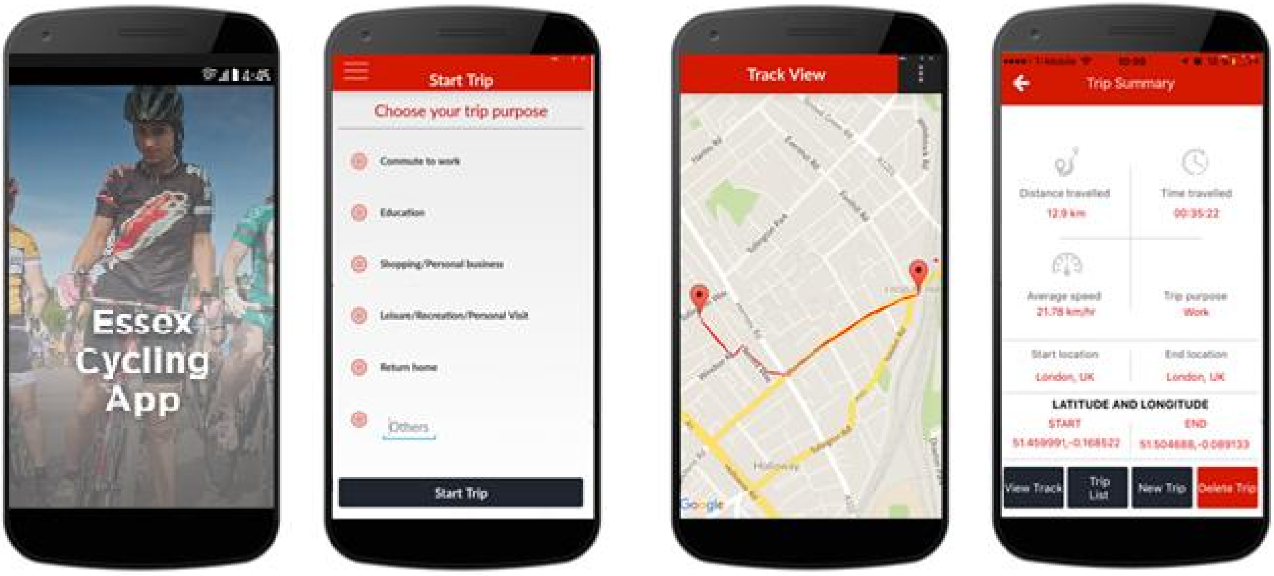


Figure 5 Essex Cycling app main screens

2.3.2 App Interface and Functionality

As a first step and once the app has been correctly downloaded and installed onto the terminal, the user is asked to create an account by introducing a personal email account and a password. Once registered, the user is requested to respond to a series of personal socio-demographic related questions. See Figure 6 for screenshots of the registration process.

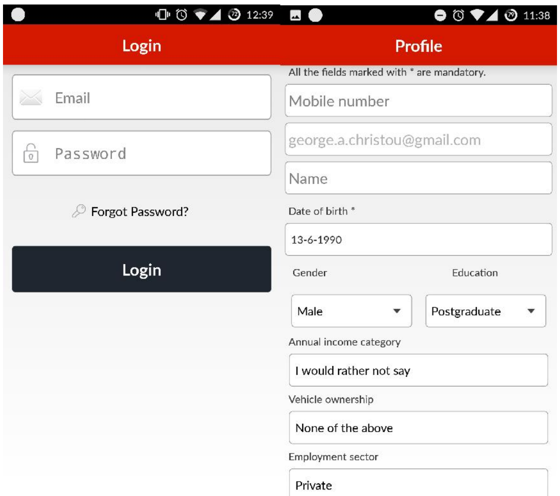


Figure 6: Login (left) and Personal profile screens (right)

Once the registration process has been completed (this only needs to be done for the first use), a trip purpose selection screen appears. After the purpose has been selected and the "Start Trip" button has been triggered, a 10-second countdown begins and the app starts recording. The Start Trip screen is shown in the figure below.

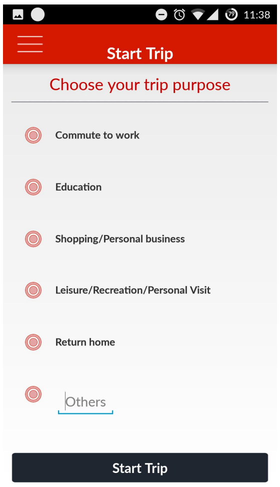


Figure 7 Purpose trip selection screen

Once the user has reached his/her destination, the user has to end the trip and a trip summary screen is displayed on his/her device allowing access to the following information: distance and time travelled, average speed, details on the start and end location, calories burned and the route followed.

Also, every trip is collected into the “History Trip List”, allowing each user to access information from past trips. The Track review, Trip Summary and Trip List screens are shown in the following figure.

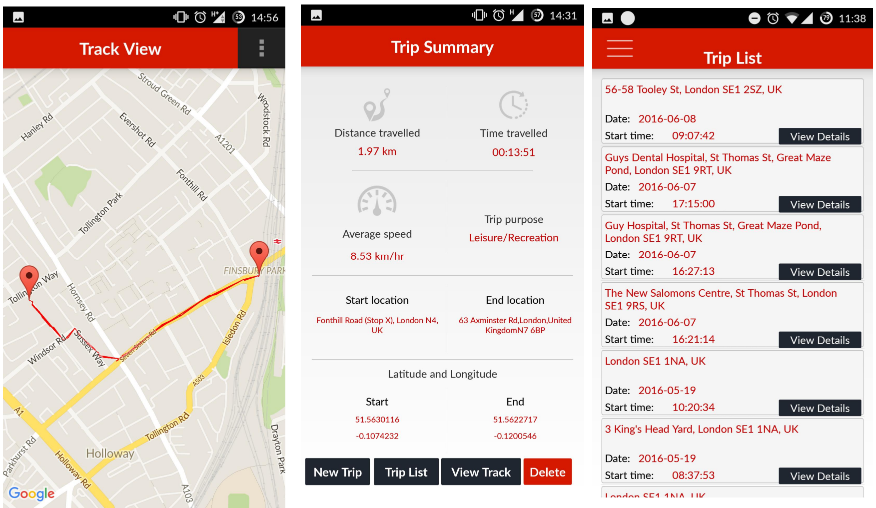


Figure 8: Track view (left), Trip Summary (middle) and Trip history list (right)

From the backend and data storage point of view, all the data collected from each cyclist is stored in a cloud database. In order to guarantee anonymity and privacy, random user IDs have been generated and associated with the user data. The collected data can be accessed using a web-based platform through any browser, using administrator credentials.

2.3.3 App Data Collection and Analyses

The data was collected from 20th of July to 24th October 2016. At the end of the data collection period, 671 trips had been recorded from around 100 users. However, after data cleaning, only 83 unique trips were considered as valid journeys, undertaken by 27 cyclists. The main reasons for reducing the sample were as follows:

- Trips were repeated between the same origin and destination by the same cyclist every day,
- Trips with journey time or average speed outside of the thresholds of cyclist trips,
- Trips with incomplete records.

Although this is a relatively small sample, it provided useful insights about Chelmsford's cyclists' behaviour and characteristics. After the data cleaning, the characteristics of the cyclists, and the trips they made, were analysed. The characteristics are summarised in the following figures showing their gender, age, education, employment status.

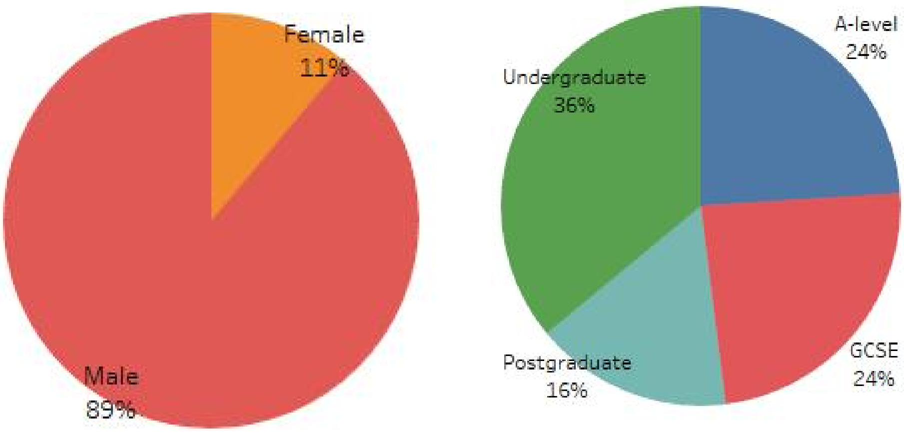


Figure 9: Cyclists gender and education

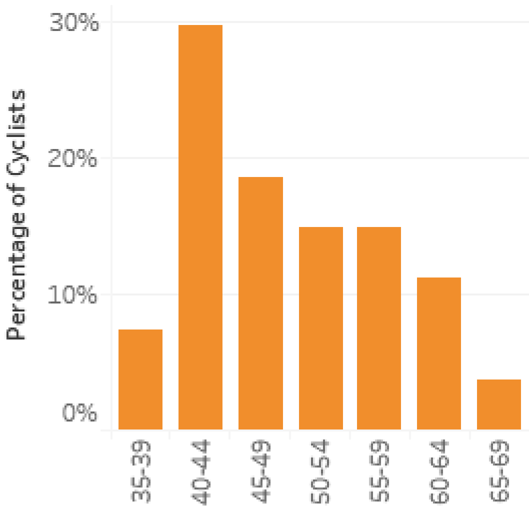


Figure 10: Cyclist's age distribution (years)

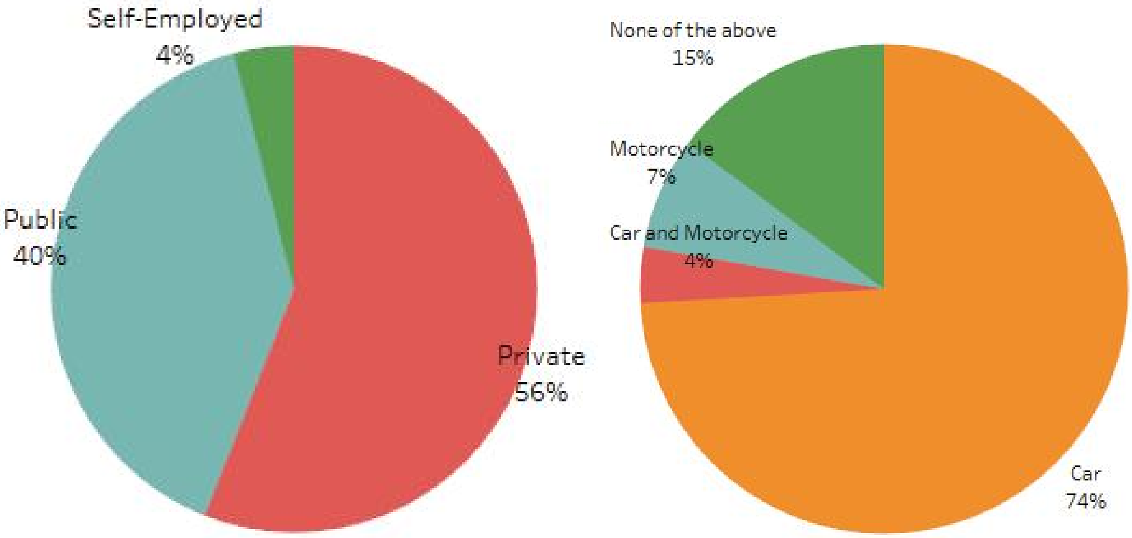


Figure 11: Cyclist's employment and vehicle ownership

In summary, the cyclists were predominantly car-owning males between the ages of 40 and 65. Cyclists varied regarding their educational background and employment. The results are comparable with the National Travel Survey (NTS 2015), which shows that 80% of the cyclists are males. Furthermore, according to DfT[2], 80% of the cyclists hold a driving licence, which again is similar to the app data where 78% of the cyclists are car owners. In terms of their age distribution, the NTS data reveals a more even representation of the various age groups between 17-70 years of age.

The trips characteristics are summarised in the following figures regarding trip purpose, average speed, departure time and trip duration. The return home trips are expected to be shopping, commute or leisure trips in proportion to the purposes of the rest of the cycling trips.

[2] https://www.gov.uk/government/news/drivers-and-cyclists-agree-lets-look-out-for-each-other

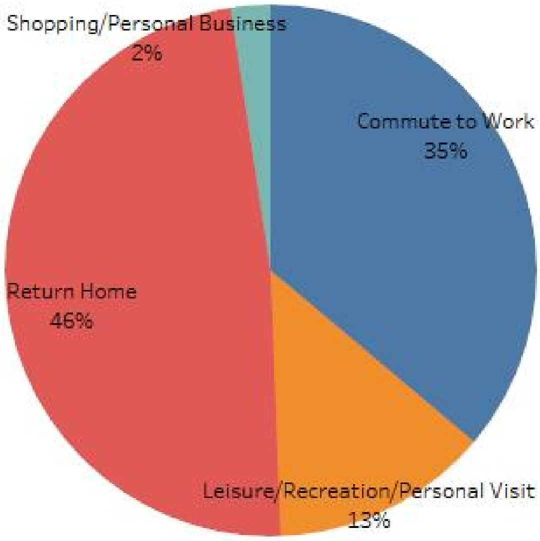


Figure 12: Trip purpose

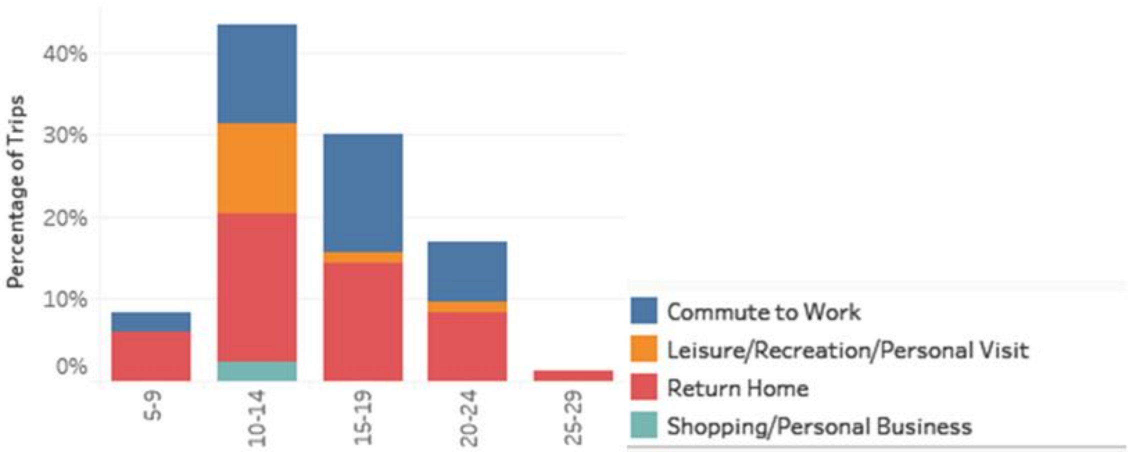


Figure 13: Average speed by trip purpose (km/h)

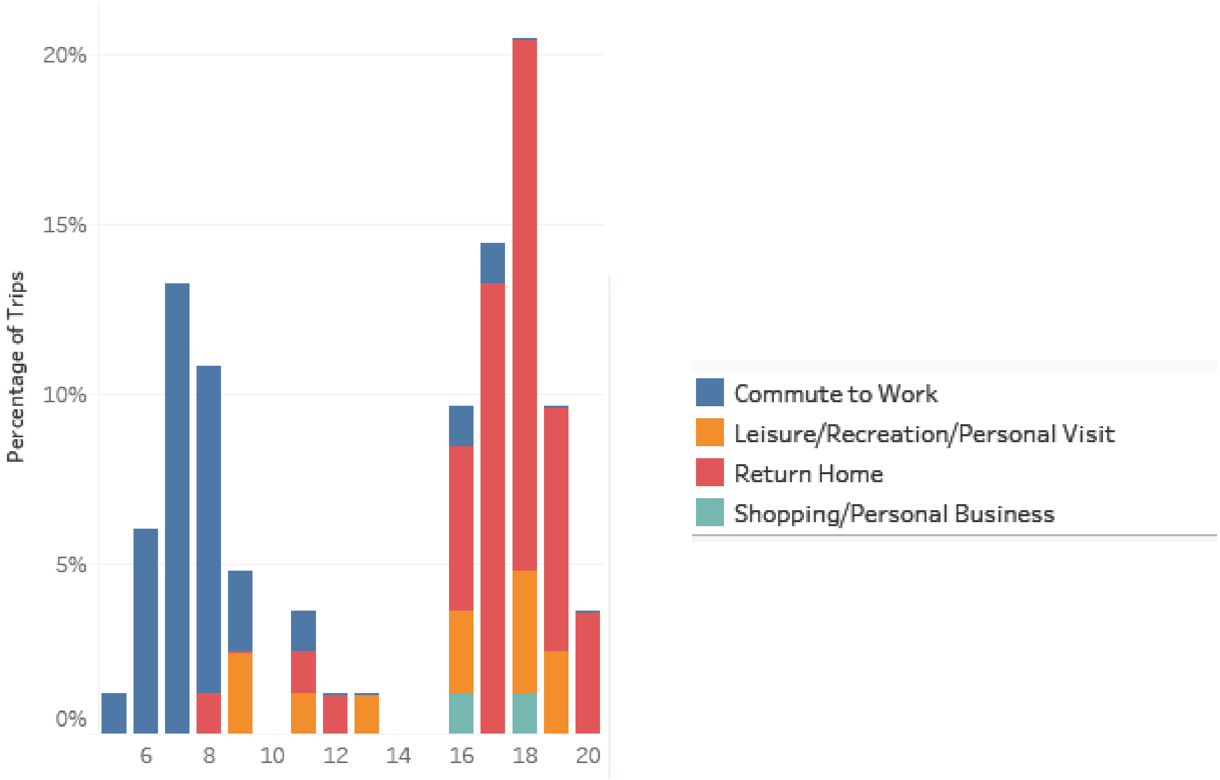


Figure 14 Departure time by trip purpose (hour of day)

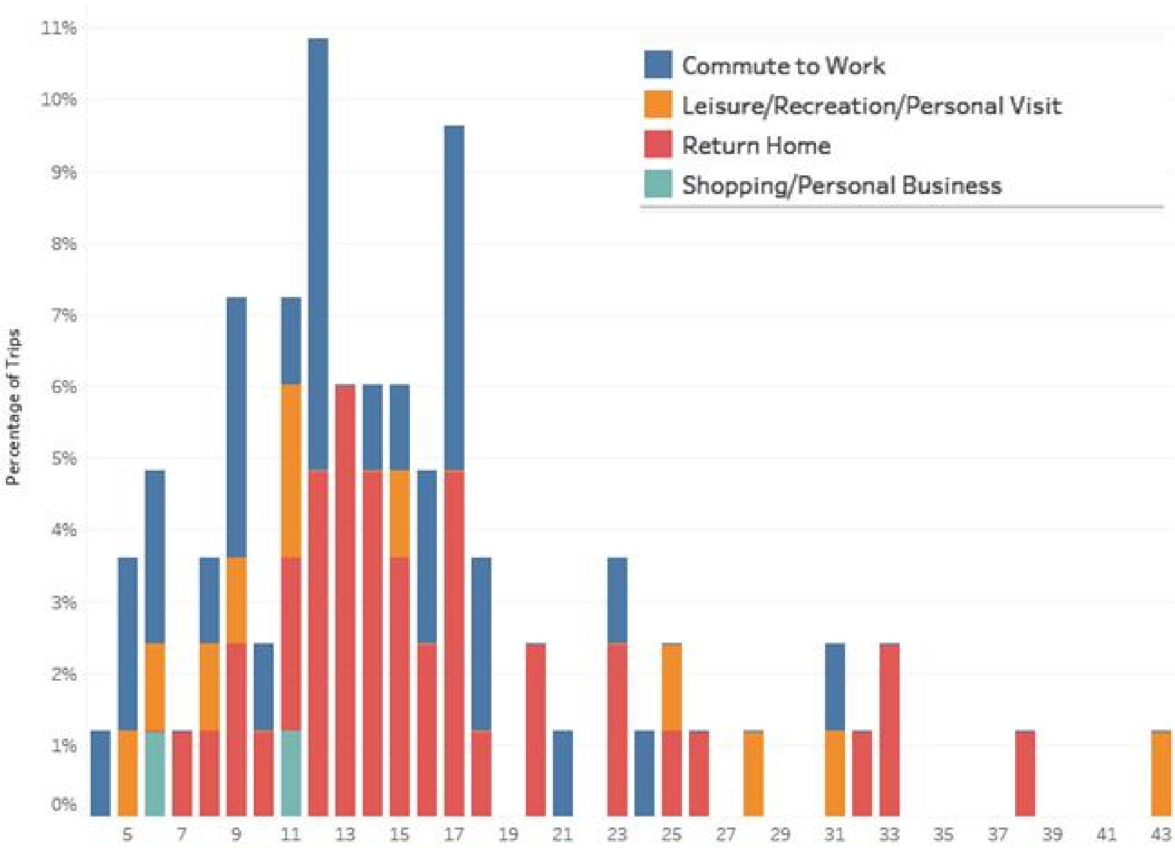


Figure 15: Trip duration by trip purpose (min)

In summary, trip purposes are dominated by commuters which made up 87% of the total trips. Most trips' average speed was between 10-20 km/h, while trip duration was between 5-18 minutes. The morning period was dominated by trips to work, while the afternoon period was dominated by trips to home.

Further analysis of the collected data was undertaken in order to maximise the usage of the developed mobile phone app. As an example, an exhaustive analysis of the reported routes was undertaken to enhance the model behaviour and its reliability. The following figures show the observed cycling routes in wider Chelmsford and the city centre.

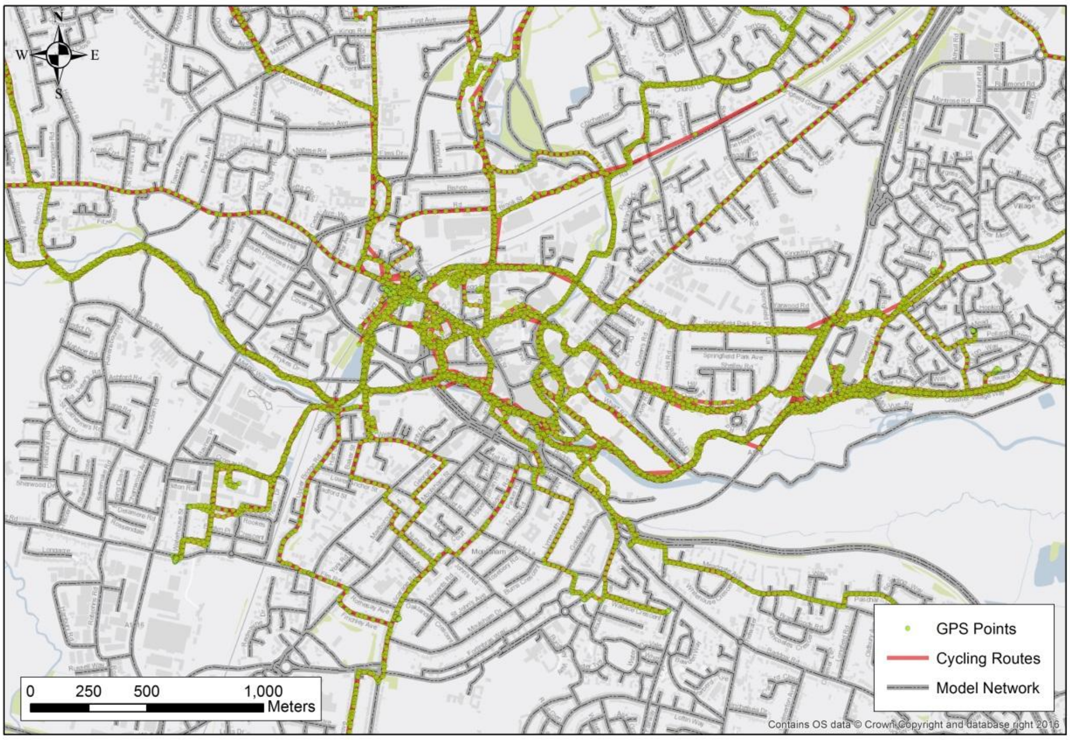


Figure 16: Cycling routes in Chelmsford with GPS points

Figure 17: Cycling routes in Chelmsford city centre with GPS points

Cycle routes were mapped in ArcGIS using GPS location data along the cycle routes. The data allowed for the identification of network coding deficiencies (missing links etc.), the refinement of cycling count survey locations, and the identification of major origins/destinations, as illustrated in the following figures.

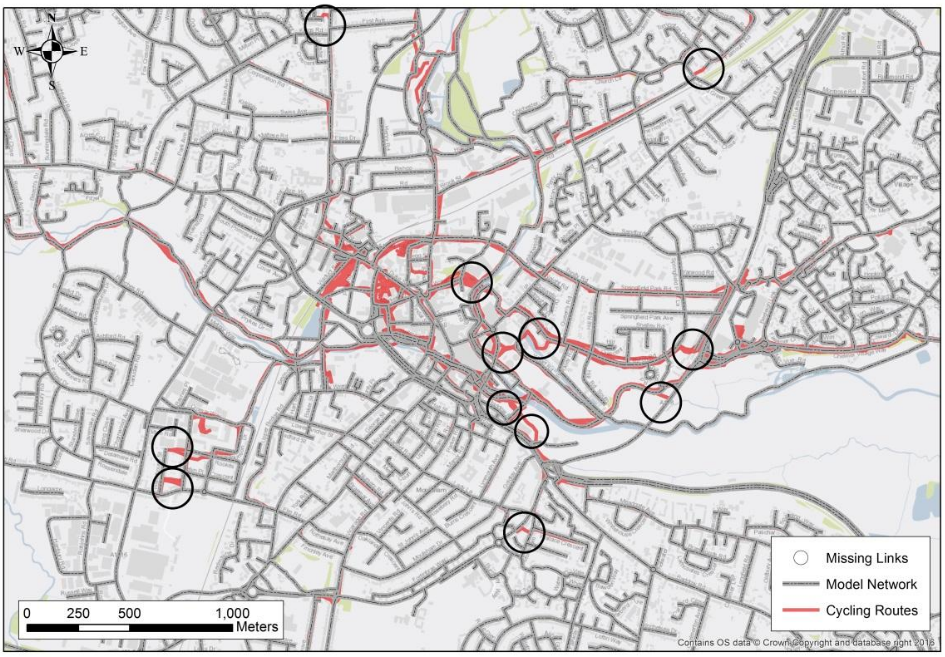


Figure 18: Identification of network coding deficiencies via mapped cycle routes

Figure 19: Heat map of Cycle origins and destinations in Chelmsford city centre[3]

[3] Heat map show high cycling activity at the Chelmsford Railway Station and at Essex County Council

In addition, the cycling trip desire lines were analysed. As shown in the figure below, the majority of cycling trips were made within Chelmsford, most of which was directed to/from the Cycling Point near Chelmsford railway station.

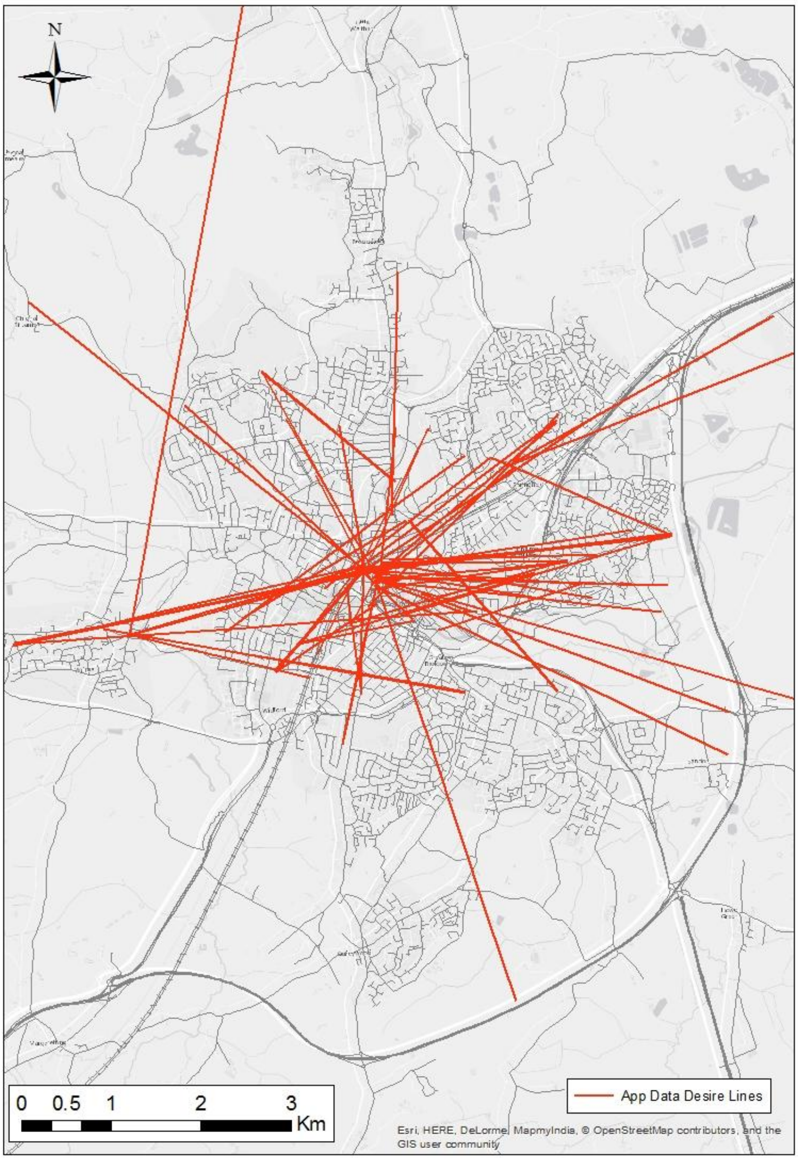


Figure 20: App-based cycling trip desire lines

3. Transportation Supply Model

3.1 Highway Transport Network

The existing highway transport network (as described in the LMVR) was used as the starting point for the supply side of the cycling model.

The purpose of the supply model is to represent the network topology and the physical properties of the highway network that provides accessibility to the city of Chelmsford.

A modelled network consists of sections of roads (known as links) connected by junctions (known as nodes). Links are formed by creating connections between node points. For further analysis of model outputs to inform noise, air quality and other outputs, it is important that all junctions are coded with the correct local coordinate reference system.

The highway network inside the Chelmsford Urban Area includes all streets and roads that are to be used by motor vehicles. The Chelmsford Administrative Area also includes all major and minor roads with proportional treatment of local roads. Outside of the Chelmsford Administrative Area major and minor roads were coded while the model gradually reduces its resolution as we move further away from the Essex County boundaries, Figure 21 contains a schematic map of the different areas.

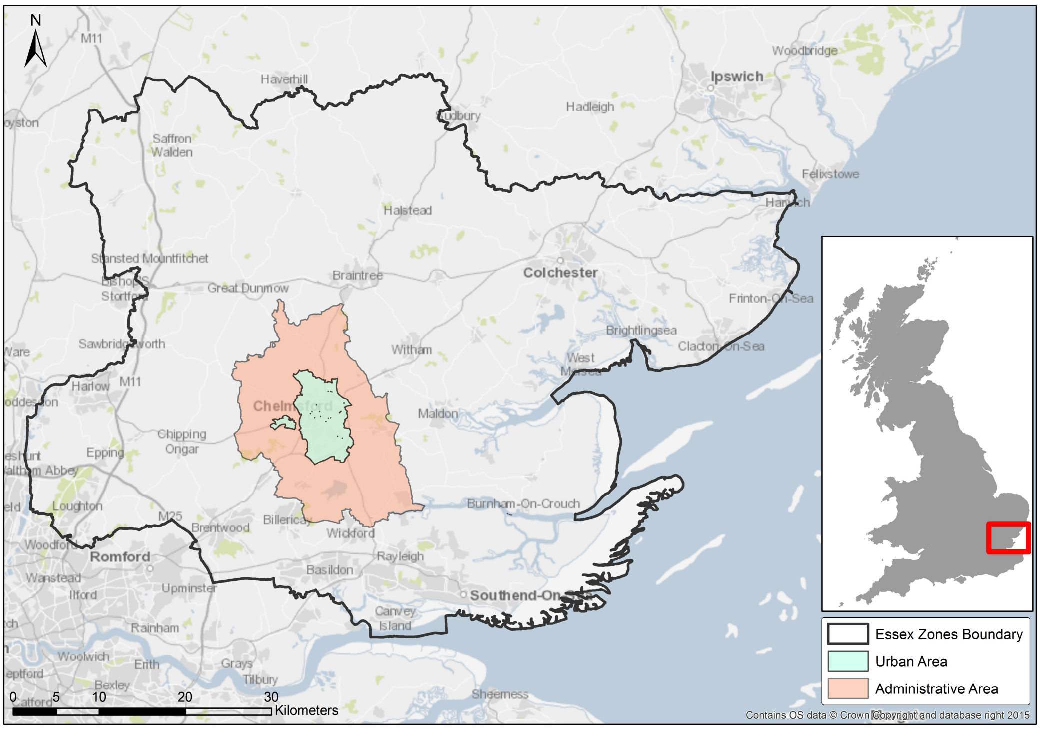


Figure 21 Administrative and Urban Areas

A total of 96 different highways classes or types were coded in VISUM software, classifying roads based characteristics such as: road class, number of lanes, speeds, and modes allowed, etc. a full list of all the defined link types can be found in the Local Model Validation Report (LMVR).

3.2 Walk and Cycling Network

The highway links and connectors were coded for the different transportation systems allowing for cycles and pedestrians to access the road where appropriate, making sure that no redundancy and duplication of objects occured.

In addition, the walking and cycling network were carefully coded and reviewed to guarantee that all cycling paths and most of the walking links, to provide a realistic representation of inter-zonal walking trips, were included inside the Chelmsford Administrative Area. Outside this area, the model provides sufficient walk/cycling connectivity to access the highway and the public transport network.

The following map contains the multi-modal network for Chelmsford city centre, as an example.

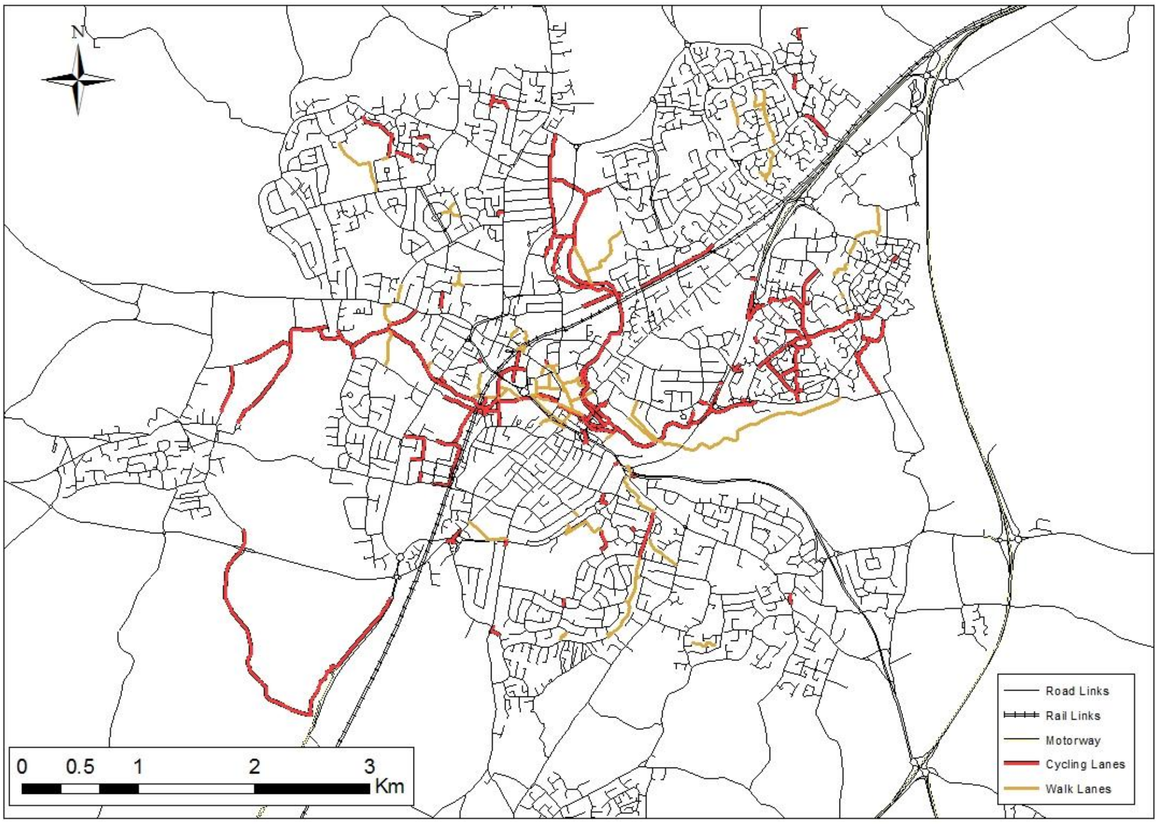


Figure 22 Coded network by mode, Chelmsford Administrative Area

In addition, the coded network was enhanced with the aid of the mobile phone app, as described in section 2.3.3. GPS analysis of the reported routes was undertaken and routes compared against the coded network. Gaps in the network were fixed accordingly where required.

4. Transport Demand Model

4.1 Model Characteristics

4.1.1 Zonal Structure

The model uses geographic zones to represent locations of trip origins and destinations. The level of zonal detail of the model varies as follows:

- Chelmsford Administrative Area and Urban Area used Lower Level Super Output Area (LSOA) and Middle Level Super Output Area (MSOA) to define the zonal system. Infrastructure topology and land use were taken into account and further divisions added on these basis,
- Middle Level Super Output Area (MSOA) were used to define the zonal system immediately surrounding Chelmsford Administrative Area,
- District or unitary authority level for the counties surrounding the county of Essex,
- County or regional level for the rest of mainland United Kingdom, with the exception of London, where zones were aggregated at borough level.

These four levels of spatial detail were applied according to the illustration below:

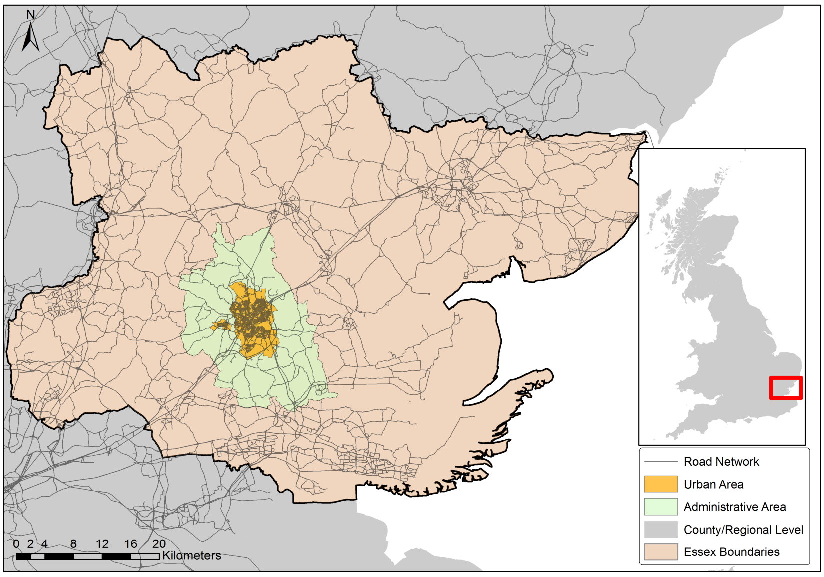


Figure 23 Zonal structure level of detail

The intermediate model area contains the remaining region of the county of Essex outside of the Chelmsford Administrative area. Different parts of this intermediate model area were coded at a different level of resolution, such as MSOAs were used for zones immediately surrounding Chelmsford Administrative area, while areas further away used district or unitary authority definitions. The zone structure by geographic area is summarised in the table below.

Geographic Area	Zone ID	Number of Zones
Chelmsford Admin Area	1-146 (excluding 115)	143
Essex Area	147-269 (including 115)	122
Rest of mainland UK	301-321	21
Total		**286**

Table 1 Zone structure summary table

4.1.2 Journey purpose, vehicle class and user class segmentation

The journey purpose, vehicle class and user class segmentation of the model have been specified in detail in the LMVR of the Chelmsford model. The cycling model made it necessary to append to the list of motorised trip purposes, user classes, and vehicle types.

The relationships between purpose, vehicle class and user class, including non-motorised (cycling) trips, are summarised in the table below:

Purpose	User Class (UC)	Vehicle Class (VC)
Home Based Work (HBW)	UC1: Commute	VC1:Car
Home Based Employer's Business (HBEB)	UC2: Business	
Non-Home Based Employer's Business (NHBEB)		
Home Based Other (HBO)	UC3: Other	
Non-Home Based Other (NHBO)		
LGV (All Trips)	UC4: LGV	VC2: LGV
HGV (All Trips)	UC5: HGV	VC3: HGV
Cycles (All Purposes)	UC6: Cycle	VC4: Cycle

Table 2 Purpose, User Class and Vehicle Class Correspondence

In line with WebTAG Unit 2.6, user classes are defined to differentiate between travellers with various perceptions of travel cost, such as commute, business and other trips.

Cycle assignment is performed separately from the rest of the user groups, where the capacity available for cyclists is informed by the assignment of the motorised user groups. The detailed treatment of different cyclist types and trip purposes in the assignment was beyond the scope of this work. In addition, cycle travel demand is not included in WebTAG for appraisal calculations, therefore, it was sufficient to use a single purpose cycling user class.

Buses are loaded onto the network as fixed pre-loads, based on their coded timetables, and therefore they do not form part of a discrete assignment user class.

4.1.3 Modelled Time Periods

In line with the highway and public transport models, the cycling demand model was also developed for the AM peak period (07:0010:00), inter-peak period (10:00-16:00), and the PM peak period (16:00 to 19:00).

The assignment models were developed for the peak hours in order model the most critical traffic conditions. In line with the highway and public transport models, the following standard time periods were used:

- Morning peak hour (08:00-09:00),
- Average inter-peak hour (average hour),
- Evening peak hour (17:00-18:00).

4.1.4 Modelled time horizons

The year 2014 was selected as the base year time horizon for the Chelmsford Strategic Model, which includes the cycling model.

ECC requested that the travel forecast year model is developed for the years 2021 and 2036 to be consistent with the council planning horizon. Local and national planning data was used to inform the forecast year demand models.

The cycle demand model was developed for the base year (2014) and the forecast years of 2021 and 2036.

4.2 Trip Generation Model

The combined number of trips, recorded in the revealed preference surveys and the cycle app-was not sufficient to generate robust cycling trip ends. Therefore, the collected data was used to inform a regression analysis between the number of origins and population (workplace plus residential population).

The methodology behind the trip generation model consisted of a series of steps as follows.

First, daily matrices were created by generating OD trips for each recorded route. This was followed by data cleaning, where ODs with less than one trip were removed to avoid double-counting in the second stage of the trip generation process. Zones with special characteristics were identified and treated separately. These zones include the train station, city centre and Anglia Ruskin University.

In the second stage, a regression model was implemented to estimate final origins and destinations at regular model zones (residential and industrial land uses). The estimated trip ends were factored up after comparing trip totals against TEMPro values. The above methodology was necessary in order to infill matrix trip ends synthetically due to the low sample size.

The following regression formula was used to generate trip ends for all regular zones within the administrative area:

$$y_{Trip\ ends} = (Workplace\ population + Residential\ Population) * 0.00417$$

4.3 Trip Distribution Model

Once trip generation was complete, a distribution component was introduced to generate the final set of matrices with the use of a gravity model. Skimmed cost matrices, reported trip length distributions

(Figure 24) and the previously calculated trip ends were used to estimate the gravitation parameter and calculate a demand matrix. The process was done using the VISUM's Kalibri process which allow to calibrate a utility function (determine parameters a, b and c) for the gravity model used for trip distribution. The utility function used for this process follows:

$$f(U_{ij}) = a * U_{ij}{}^{b} * e^{c*U_{ij}}$$

Where:
U_{ij} - Value of the utility (for example distance or travel time) between zone i and zone j
a, b, c - Parameters to be estimated

The result of the trip distribution model was a daily matrix. Further adjustments, as listed below, were applied to the resulting matrix to reflect reality. The matrix estimation distorted the matrix and increased residential to residential and commercial to commercial trips. Thus, a suppression mask was created, which consists of a flat factor applied to trips between those OD pairs to reduce their size prior to the furnessing. Further improvements included:

- the removal of trips outside the Administrative Area since they were very small in quantity and had no relevance for the Chelmsford model; and
- the removal of short trips from/to the special zones (train station, university, and city centre) since, based on the trip length distribution statistics (Figure 24), cycling trips tend to be at least a kilometre long.

After the above adjustments, the matrix trip ends no longer met the expected trip ends from the trip generation model; hence a Furness distribution model was used to meet the desirable trip ends.

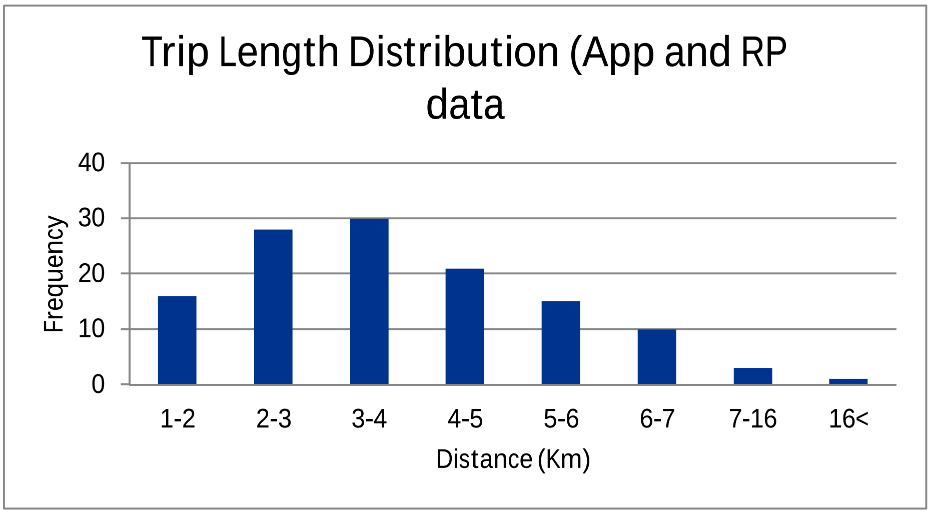


Figure 24: Combined trip length distribution (App and RP data)

4.4 Peak Hour Matrix Development

Once the daily matrix was developed, a series of proportions were used to split the matrix into the appropriate time periods. The time of day factors were developed based on time of day traffic patterns observed in Chelmsford.

First, a set of factors was used for the zones which included the train station, the university and the city centre. Then a different set of factors was used for the rest of the model zones. The factors are shown in the following tables.

Special Zones	AM		IP		PM	
	Origins	Destinations	Origins	Destinations	Origins	Destinations
City Centre	0.1	0.6	0.1	0.1	0.8	0.3
Train Station	0.1	0.8	0.1	0.1	0.8	0.1
University	0.1	0.6	0.4	0.3	0.5	0.1

Table 3 Time of day factors of the special zones

Other Zones	AM		IP		PM	
	Origins	Destinations	Origins	Destinations	Origins	Destinations
Commercial	0.4	0.5	0.1	0.1	0.5	0.4
Residential	0.6	0.1	0.1	0.1	0.3	0.8
Zones near city centre	0.4	0.2	0.3	0.2	0.3	0.6

Table 4 Time of day factors of the regular zones

The resulting base year matrix totals are shown in the following table.

	AM peak hour (trips)	IP peak hour (trips)	PM peak hour (trips)
2014	957	607	1157

Table 5 Base year trip matrix totals

5. Base Year Assignment

5.1 Cycle Assignment Methodology

Cycle route choice depends on numerous factors, such as trip characteristics, roadway facility type and road attributes, as well as cyclist characteristics. Variables that are typically considered in building cost functions include trip time, road type (including segregated cycle lanes, cycle superhighways), gradient, road surface, motorised traffic volume, presence of bus/HGV traffic, availability of cycling provision in mixed traffic (shared bus lane, non-segregated cycle lane), number/type of junctions, and agility/aggressiveness of cyclist etc.

In this work, due to data and software limitations, a cost function was adopted that is suitable for the equilibrium assignment approach. However, the treatment of different roadway facility types and road attributes was achieved. First, the following generalised cost function was formulated:

$$G_{cycle} = perceived\ time_{cycle}$$

As it was assumed that cyclists incur only negligible cycle operating costs, only the ‘perceive time’ variable was used in the generalised cost function. Cycle maintenance costs, similar to cars for most trip purposes, have no impact on route choice and were therefore ignored.

Perceived times by link type were borrowed from the logit choice utility function, developed for Transport for London’s London Cyclist’s Route Choice Model[4]. Perceived time reflects the cyclists’ perception of speed, which is a combination of physical and psychological factors. By using the estimated parameters of various roadway facilities, as a proportion of the route, the equivalent perceived distance for each road type was derived. For example, riding 1000 metres on “A” roads was equivalent to riding 646 metres on minor roads, or 220 metres of pedestrian facilities. These values were converted to free flow speeds and pivoted off the maximum sustained average speed of 18 km/h on “A” roads. The study road types were combined and converted to model road types, as summarised in the following table.

[4] TfL Cycle Route Choice Study, Report 6 – Modelling Report, May 2016, Transport for London, Mott MacDonald

Road use	Model Road Type	Cycling Speed (km/h)
Motorised	Motorways	NA
Mixed	A roads	18
Mixed	B roads	18
Mixed	Other main roads	18
Mixed	Residential streets - signposted	18
Mixed	Residential streets - other	13
Mixed	Residential streets - contraflow	13
Mixed	Single track lanes	4
Pedestrian	Pedestrian streets (cycle dismount)	4
Pedestrian	Footpath (cycle dismount)	4
Cycle	Segregated cycle lanes	19
Cycle	Cycle superhighways	19

Table 6: Cycle free flow speed by road type

A volume-delay function developed by A. Subhani et al.[5] was used for the cycle impedance function. The formula is built to capture delay imposed on a cyclist by motorised traffic (first part of the formula) and delay imposed on cyclists by a cyclist (second part of the formula).

The formulation, shown below, was modified to include a cycling capacity variable and to represent the observed cycle behaviour patterns in Chelmsford using app data on reported routeing.

$$perceived\ time_{cycle} = t_0 * \left(1 + \mu\left(\frac{V_{car}}{C_{cycle}}\right)^{v}\right) * \left(1 + \rho\left(\frac{V_{cycle}}{\min(max\{C_{car} - V_{car}, \alpha * C_{car}\}, C_{cycle})}\right)^{max\left\{\gamma, min\left\{\left(\frac{C}{V_{car}+\epsilon}\right)^{\theta}, \beta\right\}\right\}}\right),$$

where:

- $\text{perceived time}_{\text{cycle}}$ – Cyclist's perceived time
- t_0 – Free flow speed
- Vcar – Motorised traffic volume in PCU (veh/hour)
- Vcycle – Cycle volume (cycle/hour)
- C – Road capacity in PCU (PCU/hour)
- Parameters: $\propto = 0.1$, $\beta = 4$, $\gamma = 1$, $\epsilon = 100$, $\theta = 2$, $\mu = 0.3$, $v = 4$, $\rho = 0.6$

5.2 Model Calibration and Validation

The process of calibrating and validating the highway assignment consisted of a series of checks on the model's representation of traffic flows.

Volumetric cycle counts, as mentioned before in this report, were obtained from the following data sources:

- Department for Transport,

[5] Incorporating Cycling in Ottawa-Gatineau Travel Forecasting Model, A Subhani, D Stephens, R Kumar and P Vovsha, 2013, Conference of the Transportation Association of Canada

- Essex County Council,
- Jacobs - surveys performed in this project (see Figure 4).

In order to improve the overall fit of the calibration/validation sites, iterative matrix estimation was performed in each time period. Due to the limited number of cycle count sites, 76% of the sites were used for calibration and 24% of the sites were used for validation. The total number of sites is summarised in the following table.

Number of Link Counts		
Calibration	**Validation**	**Total**
106	33	139

Table 7 Link calibration and validation sites

The adequacy of the Chelmsford multimodal model was established by using WebTAG unit M3.1 “Highway Assignment Modelling” and WebTAG unit M3.2 “PT Assignment Modelling”. WebTAG sets out a series of measures to compare the base year model against observed independent data to quantify the level of fit. However, there is no guidance for cycling models yet so similar guidance to the highway assignment model was used for the cycling model. The calibration and validation of the cycling assignment has been quantified using the assigned flows and counts on individual links at junctions as a check on the quality of the assignment.

In addition to validation of total flows, the GEH is a statistic, measuring the difference between modelled and observed flows, was employed. The GEH statistic is of the form:

$$GEH = \sqrt{\frac{(M - C)^2}{(M + C)/2}}$$

Criteria		Description of Criteria	Acceptability Guideline
1	A	Individual flows within 100 veh/hr of counts for flows less than 700 veh/hr	> 85% of cases
	B	Individual flows within 15% of counts for flows from 700 veh/hr to 2,700 veh/hr	> 85% of cases
	C	Individual flows within 400 veh/hr of counts for flows more than 2,700 veh/hr	> 85% of cases
2	B	GEH < 5 for individual flows	> 85% of cases

Table 8: Link flow validation criteria and acceptability guidelines (Highways)

In the case of the cycling assignment the criteria 1.A and 2.B were used since the cycling volumes in individual links does not exceed 100. A few counts which meet the GEH criterion they have a high discrepancy on the flow criterion, and this is due to the low overall cycling volumes which make it difficult to meet. However, most of the links that do not pass the flow criterion pass because the GEH is below 5.

The results of calibration validation process can be found in Appendix A and B respectively. The table below summarises the results.

Pass	AM	IP	PM
Calibration	96%	100%	96%
Validation	96%	100%	92%

Table 9: Percentage of counts passing at least one of the two calibration/validation criterions

As the tables show, cycling calibration is above 96% in the AM peak and PM peak, while it is 100% in the inter-peak. Validation results are the same, except PM peak where it is slightly lower at 92%. Overall, these values reflect a well-calibrated model. In addition, to assess the impact of matrix estimation, the model volumes were plot against link counts, which can be seen Appendix C.

5.3 Base Year Assignment

Cycling assignments were created for the base year scenario of 2014 for AM peak, interpeak, and PM peak hours and can be seen in the following plots.

In general, the model demonstrates how important the Chelmsford train station is for attracting trips during the AM peak and generating them during the PM. During the IP average hour, cyclists have a more dispersed distribution for the origins and destinations of their trips.

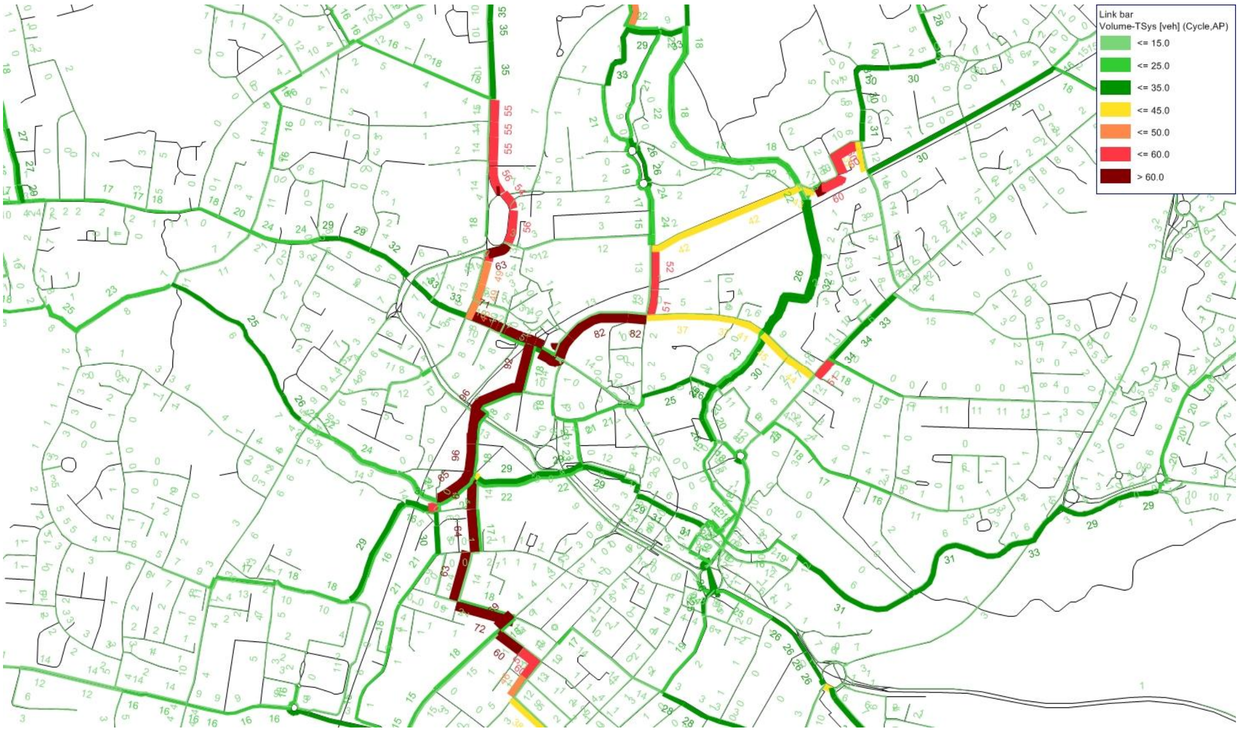


Figure 25: AM Cycling Assignment (2014)

Figure 26: IP Cycling Assignment (2014)

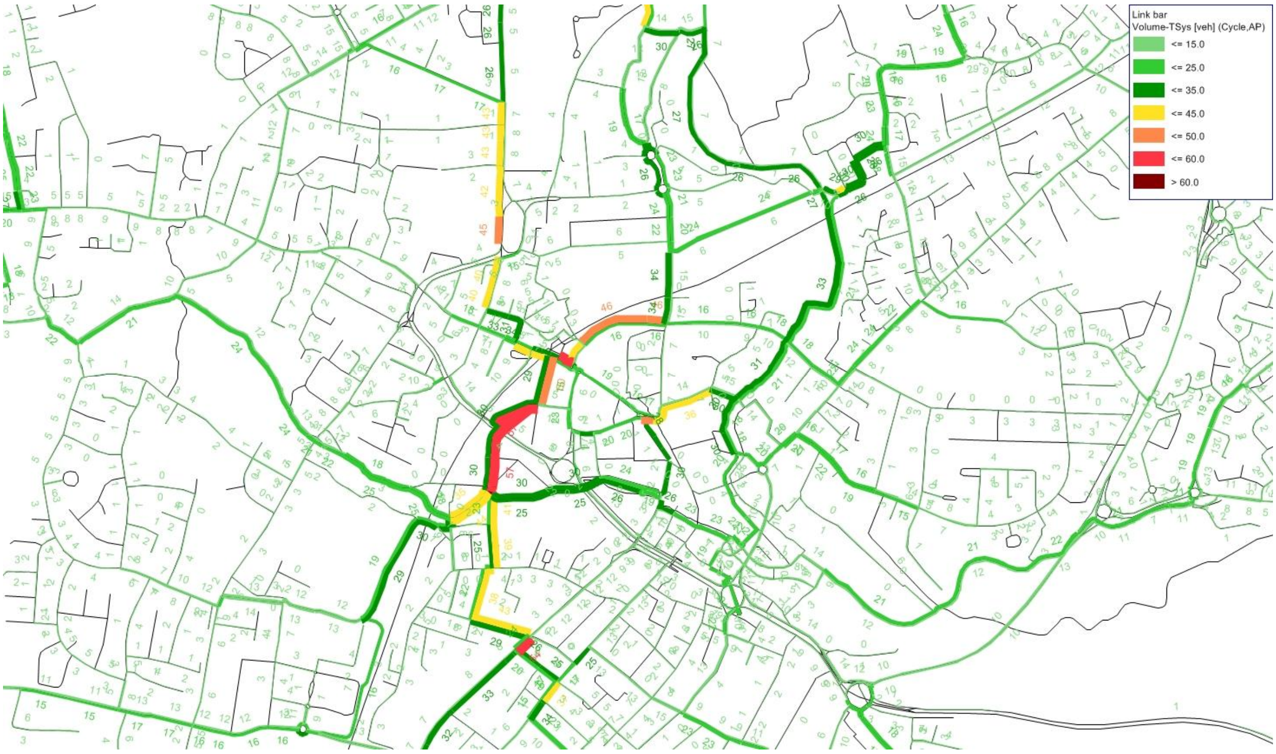


Figure 27: PM Cycling Assignment (2014)

The results of the assignments show that in the AM and PM peak hour, cycling traffic is dominated by trips to and from Chelmsford station, respectively. Key routes to the station include Duke Street, Victoria Road the cycle lane through Central Park. In the IP cycling traffic is significantly smaller than in the AM and PM peaks. Inter-peak cycling shows a more balanced trip pattern, where cycling lanes along the parks and River Chelmer are used relatively more, than main roads.

6. Forecast Model (2021, 2036)

6.1 Forecast Methodology

The primary input to the cycling trip generation formula is the forecast population for the new developments, which was estimated using the same methodology as the one used in the highway model. To calculate the new forecast trip ends for 2021, the regression-based cycling trip generation formula was used (described in Chapter 3.3) in combination with the DfT's National Trip End Model (NTEM) forecasts. The detailed description of the methodology can be found in the (TFR (Chapter 4).

TEMPro version 6.2 was used to produce national forecast growth factors from NTEM which were used to estimate the cycling growth from 2014 to 2021 and from 2021 to 2036. The 2021 TEMPro based total trip ends and the 2021 planning based matrix were combined to generate the final forecast matrix. 2021 planning based matrix forecast trips were adjusted to keep the control totals at the 2021 TEMPro forecast trip-end level.

The forecast for 2036 was based exclusively on TEMPro growth between 2021 and 2036.

6.2 Forecast Matrices

Forecast matrices were developed based on the methodology explained in the previous section. The following tables summarise the forecast cycling trip ends and growth factors in 2021 and 2036.

	AM peak hour (trips)	IP peak hour (trips)	PM peak hour (trips)
2014	957	607	1157
2021	1119	904	1467
2036	1192	979	1568

Table 10: Trip ends forecasts by time horizon and time period (trips)

	AM peak hour	IP hour	PM peak hour
2021	17%	49%	27%
2036	25%	61%	36%

Table 11: Trip end growth between 2014 and the time horizons

As shown in the previous tables, cycle trip growth is about 3% a year in the AM peak, 7% a year in the Inter-peak and 4% per year in the PM peak up to 2021. The rate of growth is significantly slower between 2021 and 2036. However, it is noteworthy that the cycling forecasts have a high level of uncertainty since TEMPro forecasts are also based on people choosing healthier lifestyles and changing the overall perception of cycling. In addition there is no guidance from WebTag for cycling forecasts.

6.3 Forecast Assignments

Cycling assignments were created for the future network for the year 2021 and 2036 for AM, IP, PM peak hours for the highway. The following figures show future year traffic assignments for both, 2021 and 2036 scenarios.

The assignments plots show that the highest cycling volumes are found on cycling lanes and especially cycle lanes which are connecting parts of the city to the Chelmsford station. There is also significant cycling traffic along the main leisure route by the River Chelmer.

Figure 28: AM Cycling Assignment (2021)

Figure 29: IP Cycling Assignment (2021)

Figure 30: PM Cycling Assignment (2021)

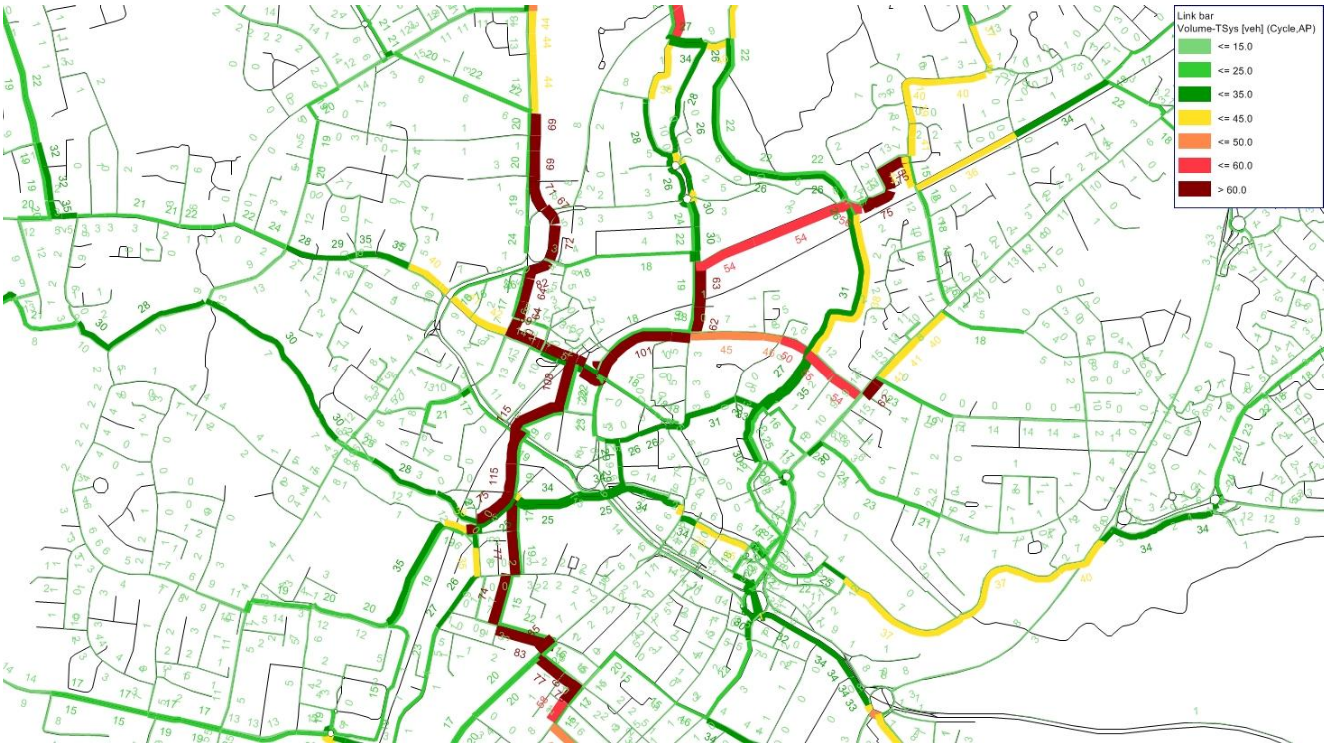


Figure 31: AM Cycling Assignment (2036)

Figure 32: IP Cycling Assignment (2036)

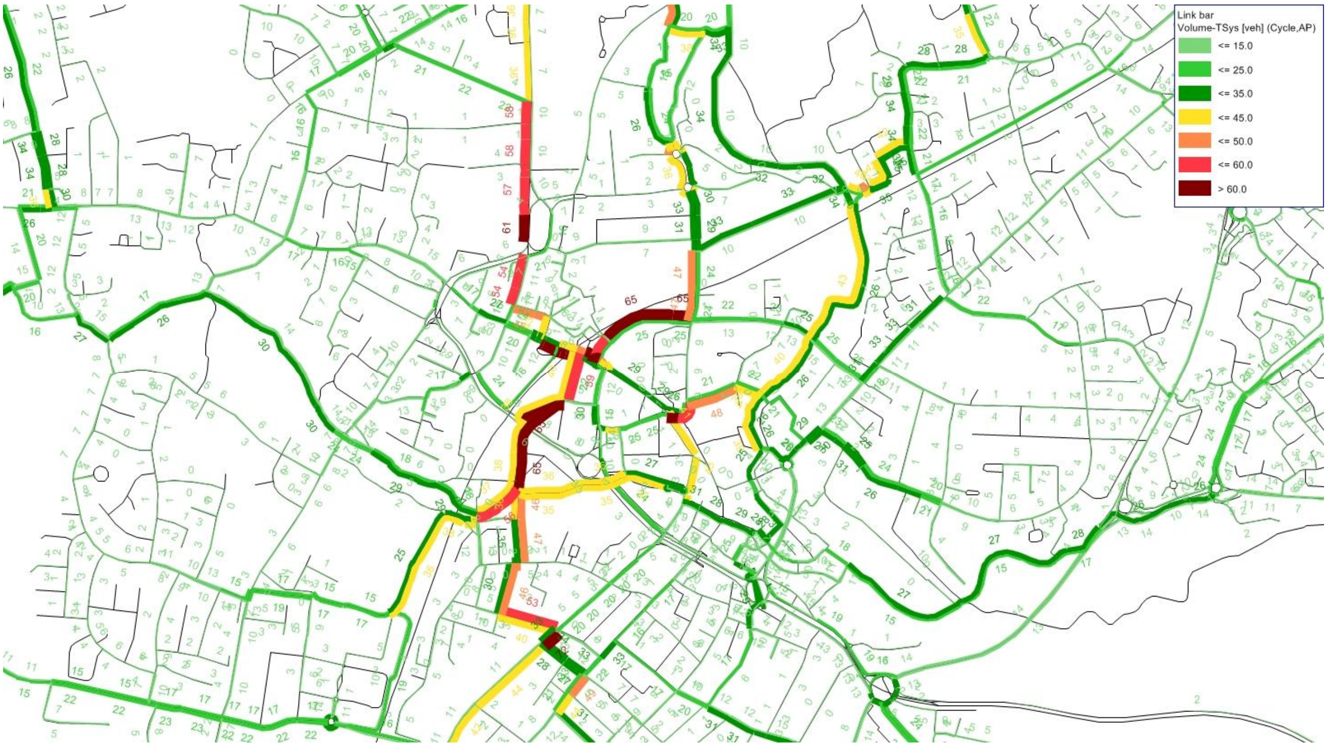


Figure 33: PM Cycling Assignment (2036)

The results of the 2021 and 2036 assignments show slightly higher volumes than in 2014. In the AM and PM peak hour, cycling traffic is dominated by trips to and from Chelmsford station, respectively. In the IP cycling traffic is significantly lower than in the AM and PM peaks. Inter-peak cycling has a more balanced trip pattern, where cycling lanes through the parks and along the River Chelmer are used relatively more than main roads.

7. Interaction between the cycling and the multi-modal model

The cycling model has been developed by using non-motorised trip data (RP surveys, app data), cycling behaviour information (app data), and cycling traffic counts (DfT, ECC, Jacobs). The model is set up separately from the multi-modal transport model, without any direct input-output relationship in between. Since the highway network model is used for cycling assignment it needs to be updated along with the multi-modal transport model, including infrastructure and traffic attributes. Due to VISUM software limitations, it is not possible to use different volume-delay-functions in the assignment module for different vehicle types (such as car and cycling). Therefore, a fully integrated model is currently not feasible in the chosen software environment.

If cycling exceeds current forecasts in the future due to currently unforeseen future changes in lifestyle choices, combining the cycling and the multi-modal models might become necessary. This might be feasible by that time if the VISUM software is updated.

8. Conclusions

The objective of the cycling model is to provide cycling forecasts across the roadway and cycling network of Chelmsford. The model was developed using different data sources including data collected from revealed preference surveys and a mobile application, developed specifically for the purposes of this project. Although the amount of the data collected was not sufficient to develop a fully observed travel matrix, the data was sufficient to create a model by combining observed and synthetic techniques.

With regard to the overall methodology, the cycling model followed the traditional four step model, without an explicit mode choice component. Since there is not an established methodology in WebTAG for modelling cycling, the model development followed a simplified version of the established principles of the highway modelling. The forecasts were estimated using both planning data and TEMPro data.

A limitation of the cycling model is that, due software limitations, the cycling model is a standalone tool that is not integrated to the multi-modal transport model. If cycling exceeds current forecasts in the future, combining the cycling and the multi-modal model might become necessary. Another limitation is that the current cycling forecasts contain inherent uncertainties, especially when considering the impact of future trends in lifestyle choices.

The model may be used to estimate current and future cycling volumes in Chelmsford, including the impact of future changes in population or employment on cycling, or the impact infrastructure schemes on route choice. The model is not capable of estimating the number of new cycling trips due to better cycling infrastructure, signage, storage etc. The impact of these interventions will first need to be estimated via a cycling demand elasticity calculation, which can be done as part of any future cycling scheme travel forecast work.

An advantage of the app-based data collection is that it provided an opportunity not only to study the cyclist’s trip patterns and route choice, but also the socioeconomic characteristics of the cyclists, which could potentially help targeting future developments. Furthermore, the model can be developed further in the future, when data will be collected in higher quantity and quality.

Appendix A. Calibration Site Statistics

Cycling Count ID	Observed			Model			Flow Difference (%)			GEH			Pass/Fail Test		
	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM
2-EntranceA	37	8	6	35	8	5	-5%	0%	-17%	0	0	0	Pass	Pass	Pass
2-Exit A	10	6	25	10	6	26	0%	0%	4%	0	0	0	Pass	Pass	Pass
2-Exit B	53	12	6	55	13	7	4%	8%	17%	0	0	0	Pass	Pass	Pass
2-Entrance B	13	8	41	15	8	43	15%	0%	5%	1	0	0	Pass	Pass	Pass
4-Exit B	3	4	25	2	4	24	-33%	0%	-4%	1	0	0	Pass	Pass	Pass
4-Entrance B	37	6	4	42	6	6	14%	0%	50%	1	0	1	Pass	Pass	Pass
4-Exit A	22	11	21	23	12	21	5%	9%	0%	0	0	0	Pass	Pass	Pass
4-EntranceA	23	11	22	22	10	19	-4%	-9%	-14%	0	0	1	Pass	Pass	Pass
1-Exit D	5	7	14	5	3	7	0%	-57%	-50%	0	2	2	Pass	Pass	Pass
1-Entrance D	30	11	12	33	13	18	10%	18%	50%	1	1	2	Pass	Pass	Pass
1-Exit A	7	5	28	6	4	11	-14%	-20%	-61%	0	0	4	Pass	Pass	Pass
1-Entrance A	47	12	9	46	11	7	-2%	-8%	-22%	0	0	1	Pass	Pass	Pass
1-Exit B	70	20	19	71	20	17	1%	0%	-11%	0	0	0	Pass	Pass	Pass
1-Entrance B	11	10	35	10	6	11	-9%	-40%	-69%	0	1	5	Pass	Pass	Fail
8-Exit A	11	6	22	10	6	22	-9%	0%	0%	0	0	0	Pass	Pass	Pass
8-EntranceA	53	11	13	51	12	14	-4%	9%	8%	0	0	0	Pass	Pass	Pass
8-Exit B	1	0	0	0	0	0	-100%	0%	0%	1	0	0	Pass	Pass	Pass
8-Entrance B	2	0	0	1	0	0	-50%	0%	0%	1	0	0	Pass	Pass	Pass
5-Exit C	5	4	16	3	3	13	-40%	-25%	-19%	1	1	1	Pass	Pass	Pass
46690-EB	6	5	11	6	6	10	0%	20%	-9%	0	0	0	Pass	Pass	Pass
9-Entrance D	2	2	7	18	9	43	800%	350%	514%	5	3	7	Fail	Pass	Fail
9-Exit D	37	4	3	72	14	29	95%	250%	867%	5	3	7	Pass	Pass	Fail
9-Entrance B	7	2	4	7	3	9	0%	50%	125%	0	1	2	Pass	Pass	Pass

	Observed			Model			Flow Difference (%)			GEH			Pass/Fail Test		
Cycling Count ID	**AM**	**IP**	**PM**	**AM**	**IP**	**PM**	**AM**	**IP**	**PM**	**AM**	**IP**	**PM**	**AM**	**IP**	**PM**
9-Exit B	2	2	4	0	0	0	-100%	-100%	-100%	2	2	3	Pass	Pass	Pass
9-Entrance C	43	7	4	69	14	24	60%	100%	500%	3	2	5	Pass	Pass	Fail
9-Exit C	2	4	17	18	11	54	800%	175%	218%	5	3	6	Fail	Pass	Fail
7-Entrance D	22	7	5	20	6	4	-9%	-14%	-20%	0	0	0	Pass	Pass	Pass
7-Exit D	2	3	10	1	3	9	-50%	0%	-10%	1	0	0	Pass	Pass	Pass
7-Exit B	24	8	4	24	7	5	0%	-13%	25%	0	0	0	Pass	Pass	Pass
7-Entrance B	1	3	11	2	4	12	100%	33%	9%	1	1	0	Pass	Pass	Pass
6-Entrance C	9	5	8	9	4	8	0%	-20%	0%	0	0	0	Pass	Pass	Pass
6-Exit C	9	5	8	6	4	7	-33%	-20%	-13%	1	0	0	Pass	Pass	Pass
07000015-NB	19	10	15	17	10	14	-11%	0%	-7%	0	0	0	Pass	Pass	Pass
07000015-SB	13	10	19	11	10	17	-15%	0%	-11%	1	0	0	Pass	Pass	Pass
8-Exit C	11	8	7	12	7	7	9%	-13%	0%	0	0	0	Pass	Pass	Pass
8-Entrance C	7	4	9	7	4	10	0%	0%	11%	0	0	0	Pass	Pass	Pass
8-Exit D	47	7	11	44	8	12	-6%	14%	9%	0	0	0	Pass	Pass	Pass
8-Entrance D	8	5	18	8	5	17	0%	0%	-6%	0	0	0	Pass	Pass	Pass
7-Exit A	6	4	11	4	3	11	-33%	-25%	0%	1	1	0	Pass	Pass	Pass
7-Entrance A	13	5	6	11	4	5	-15%	-20%	-17%	1	0	0	Pass	Pass	Pass
6-Exit B	7	2	3	8	3	4	14%	50%	33%	0	1	1	Pass	Pass	Pass
6-Entrance B	4	2	5	5	2	6	25%	0%	20%	0	0	0	Pass	Pass	Pass
941304-SB	1	1	3	1	1	2	0%	0%	-33%	0	0	1	Pass	Pass	Pass
941304-NB	2	1	2	2	1	2	0%	0%	0%	0	0	0	Pass	Pass	Pass
4-Entrance C	15	10	34	13	11	34	-13%	10%	0%	1	0	0	Pass	Pass	Pass
4-Exit C	50	11	13	52	12	15	4%	9%	15%	0	0	1	Pass	Pass	Pass
07000014-EB	7	3	13	3	2	6	-57%	-33%	-54%	2	1	2	Pass	Pass	Pass
07000014-WB	16	4	7	12	3	5	-25%	-25%	-29%	1	1	1	Pass	Pass	Pass

Cycling Count ID	Observed AM	Observed IP	Observed PM	Model AM	Model IP	Model PM	Flow Difference (%) AM	Flow Difference (%) IP	Flow Difference (%) PM
46690-WB	23	7	7	25	8	8	9%	14%	14%
07000009-WB	7	8	20	8	9	22	14%	13%	10%
07000009-EB	23	10	12	25	10	12	9%	0%	0%
13-Entrance D	69	13	29	64	9	23	-7%	-31%	-21%
13-Exit D	20	11	39	14	7	41	-30%	-36%	5%
5-Exit B	5	2	3	0	0	0	-100%	-100%	-100%
5-Entrance B	9	4	2	0	0	0	-100%	-100%	-100%
10-Entrance A	6	10	29	7	12	32	17%	20%	10%
10-Exit A	27	7	7	30	10	7	11%	43%	0%
07000006-NB	28	18	36	26	16	33	-7%	-11%	-8%
07000006-SB	35	17	19	32	18	21	-9%	6%	11%
07000004-SB	5	1	1	5	9	1	0%	800%	0%
07000004-NB	1	1	4	1	9	4	0%	800%	0%
07000007-NB	31	7	10	34	7	10	10%	0%	0%
07000007-SB	8	6	21	8	6	20	0%	0%	-5%
13-Exit C	37	31	56	29	16	30	-22%	-48%	-46%
13-Entrance C	37	23	46	22	8	25	-41%	-65%	-46%
13-Exit B	1	0	2	0	0	0	-100%	0%	-100%
7-Exit C	10	4	5	11	5	5	10%	25%	0%
7-Entrance C	5	4	8	7	4	10	40%	0%	25%
07000001-WB	33	11	13	31	10	12	-6%	-9%	-8%
07000001-EB	7	8	24	6	8	21	-14%	0%	-13%
48473-NB	0	0	2	0	0	2	0%	0%	0%

Cycling Count ID	GEH AM	GEH IP	GEH PM	Pass/Fail Test AM	Pass/Fail Test IP	Pass/Fail Test PM
46690-WB	0	0	0	Pass	Pass	Pass
07000009-WB	0	0	0	Pass	Pass	Pass
07000009-EB	0	0	0	Pass	Pass	Pass
13-Entrance D	1	1	1	Pass	Pass	Pass
13-Exit D	1	1	0	Pass	Pass	Pass
5-Exit B	3	2	2	Pass	Pass	Pass
5-Entrance B	4	3	2	Pass	Pass	Pass
10-Entrance A	0	1	1	Pass	Pass	Pass
10-Exit A	1	1	0	Pass	Pass	Pass
07000006-NB	0	0	1	Pass	Pass	Pass
07000006-SB	1	0	0	Pass	Pass	Pass
07000004-SB	0	4	0	Pass	Pass	Pass
07000004-NB	0	4	0	Pass	Pass	Pass
07000007-NB	1	0	0	Pass	Pass	Pass
07000007-SB	0	0	0	Pass	Pass	Pass
13-Exit C	1	3	4	Pass	Pass	Pass
13-Entrance C	3	4	4	Pass	Pass	Pass
13-Exit B	1	0	2	Pass	Pass	Pass
7-Exit C	0	0	0	Pass	Pass	Pass
7-Entrance C	1	0	1	Pass	Pass	Pass
07000001-WB	0	0	0	Pass	Pass	Pass
07000001-EB	0	0	1	Pass	Pass	Pass
48473-NB	0	0	0	Pass	Pass	Pass

	Observed			Model			Flow Difference (%)			GEH			Pass/Fail Test		
Cycling Count ID	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM
07000003-SB	15	8	13	13	7	14	-13%	-13%	8%	1	0	0	Pass	Pass	Pass
07000003-NB	13	7	14	17	7	13	31%	0%	-7%	1	0	0	Pass	Pass	Pass
13-Exit A	99	9	21	96	14	30	-3%	56%	43%	0	1	2	Pass	Pass	Pass
13-Entrance A	14	9	53	18	12	57	29%	33%	8%	1	1	1	Pass	Pass	Pass
10-Exit C	4	6	20	6	9	26	50%	50%	30%	1	1	1	Pass	Pass	Pass
10-Entrance C	24	6	5	29	9	7	21%	50%	40%	1	1	1	Pass	Pass	Pass
07000012-EB	24	18	33	23	17	31	-4%	-6%	-6%	0	0	0	Pass	Pass	Pass
07000012-WB	29	20	21	30	17	21	3%	-15%	0%	0	1	0	Pass	Pass	Pass
18390-WB	11	2	3	9	1	2	-18%	-50%	-33%	1	1	1	Pass	Pass	Pass
18390-EB	3	2	7	3	3	8	0%	50%	14%	0	1	0	Pass	Pass	Pass
3-Entrance D	25	24	63	22	21	56	-12%	-13%	-11%	1	1	1	Pass	Pass	Pass
3-Exit D	77	15	24	77	12	20	0%	-20%	-17%	0	1	1	Pass	Pass	Pass
3-Entrance B	4	3	10	0	0	0	-100%	-100%	-100%	3	2	4	Pass	Pass	Pass
5-Exit D	4	1	2	4	0	2	0%	-100%	0%	0	1	0	Pass	Pass	Pass
5-Entrance C	15	3	4	0	0	0	-100%	-100%	-100%	5	2	3	Fail	Pass	Pass
5-Exit A	14	4	3	0	0	0	-100%	-100%	-100%	5	3	2	Fail	Pass	Pass
3-EntranceA	66	7	8	67	9	13	2%	29%	63%	0	1	2	Pass	Pass	Pass
3-Exit A	9	6	35	11	7	41	22%	17%	17%	1	0	1	Pass	Pass	Pass
1-Exit C	8	2	3	8	3	4	0%	50%	33%	0	1	1	Pass	Pass	Pass
1-Entrance C	2	1	7	1	1	3	-50%	0%	-57%	1	0	2	Pass	Pass	Pass
10-Entrance D	3	2	3	3	2	3	0%	0%	0%	0	0	0	Pass	Pass	Pass
10-Exit D	2	5	11	3	4	10	50%	-20%	-9%	1	0	0	Pass	Pass	Pass

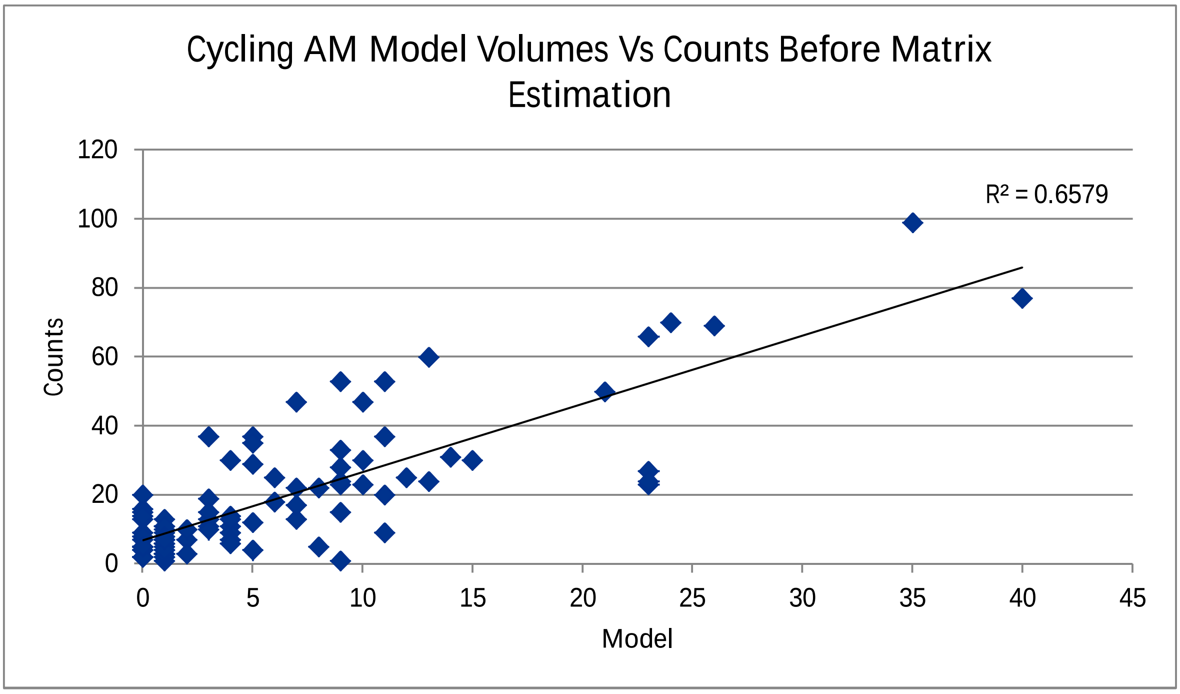
Cycling Count ID	Observed			Model			Flow Difference (%)			GEH			Pass/Fail Test		
	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM
941218-EB	0	0	2	0	0	2	0%	0%	0%	0	0	0	Pass	Pass	Pass
941218-WB	2	0	3	2	0	3	0%	0%	0%	0	0	0	Pass	Pass	Pass
6-Exit A	3	2	5	4	2	6	33%	0%	20%	1	0	0	Pass	Pass	Pass
6-Entrance A	6	3	3	4	3	2	-33%	0%	-33%	1	0	1	Pass	Pass	Pass
2-Exit C	5	3	17	4	3	17	-20%	0%	0%	0	0	0	Pass	Pass	Pass
2-Entrance C	18	5	1	18	5	3	0%	0%	200%	0	0	1	Pass	Pass	Pass
77249-EB	3	0	2	3	0	2	0%	0%	0%	0	0	0	Pass	Pass	Pass
77249-WB	4	1	3	4	2	3	0%	100%	0%	0	1	0	Pass	Pass	Pass
Control Count WB	0	6	10	0	6	10	0%	0%	0%	0	0	0	Pass	Pass	Pass
Control Count EB	0	6	8	0	6	8	0%	0%	0%	0	0	0	Pass	Pass	Pass
5-EntranceA	5	4	17	1	1	7	-80%	-75%	-59%	2	2	3	Pass	Pass	Pass
9-Exit A	12	4	3	4	3	3	-67%	-25%	0%	3	1	0	Pass	Pass	Pass
9-Entrance A	1	3	11	1	2	12	0%	-33%	9%	0	1	0	Pass	Pass	Pass
941157-SB	1	2	1	0	0	0	-100%	-100%	-100%	1	2	1	Pass	Pass	Pass
941157-NB	1	1	2	0	0	0	-100%	-100%	-100%	1	1	2	Pass	Pass	Pass
48473-SB	1	1	0	0	0	0	-100%	-100%	0%	1	1	0	Pass	Pass	Pass
5-Entrance D	1	1	1	3	2	5	200%	100%	400%	1	1	2	Pass	Pass	Pass
13-Exit E	25	19	49	24	14	44	-4%	-26%	-10%	0	1	1	Pass	Pass	Pass
13-Entrance E	60	24	34	65	20	35	8%	-17%	3%	1	1	0	Pass	Pass	Pass

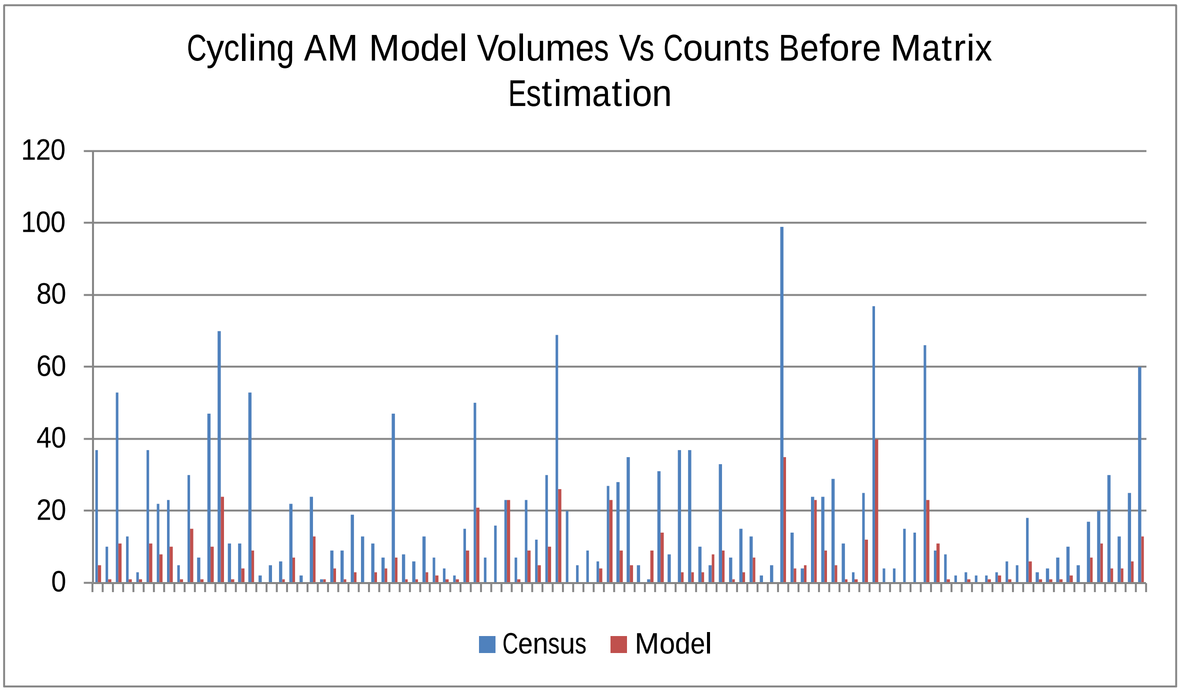
Appendix B. Validation Site Statistics

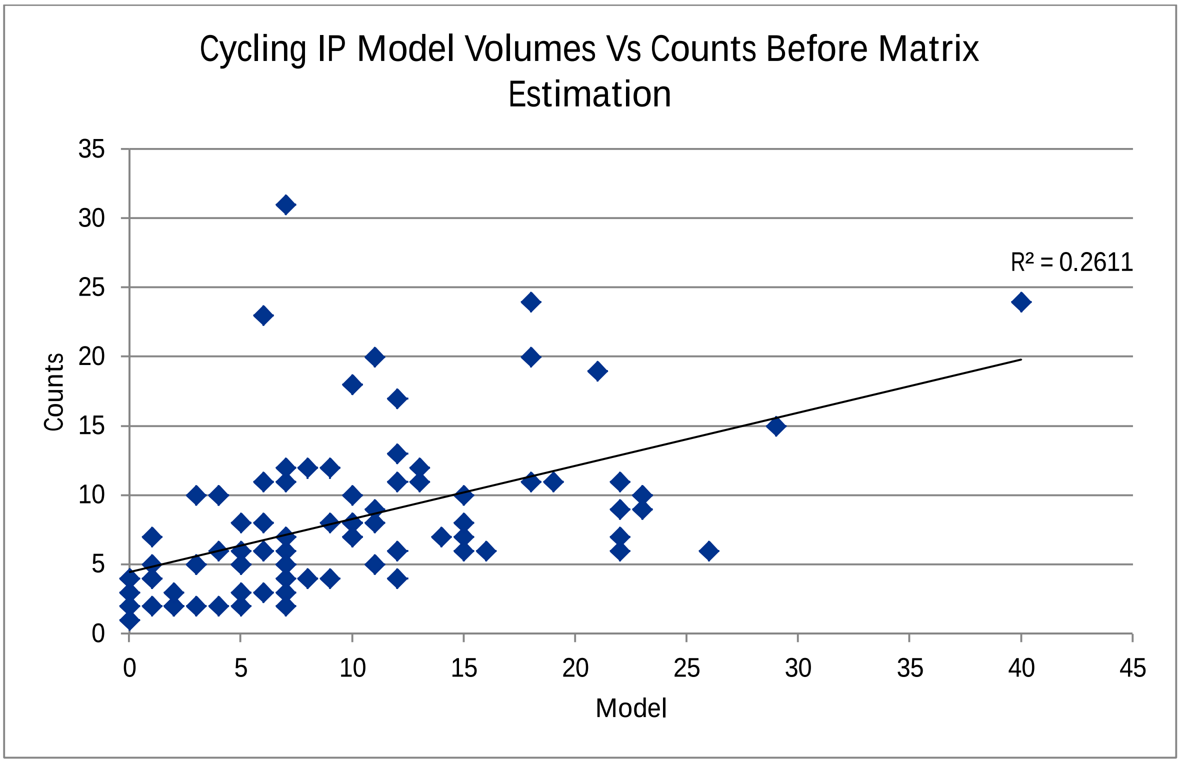
	Observed			Model			Flow Difference (%)			GEH			Pass/Fail Test		
Cycling Count ID	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM
07000005-NB	4	4	27	15	11	35	275%	175%	30%	4	3	1	Pass	Pass	Pass
07000005-SB	48	6	6	62	17	27	29%	183%	350%	2	3	5	Pass	Pass	Fail
12-Entrance D	4	2	6	4	4	8	0%	100%	33%	0	1	1	Pass	Pass	Pass
12-Exit D	7	2	2	14	7	15	100%	250%	650%	2	2	4	Pass	Pass	Pass
12-Exit A	7	2	2	19	8	13	171%	300%	550%	3	3	4	Pass	Pass	Pass
12-Entrance A	4	1	6	2	6	4	-50%	500%	-33%	1	3	1	Pass	Pass	Pass
12-Exit B	3	3	7	3	7	9	0%	133%	29%	0	2	1	Pass	Pass	Pass
12-Entrance B	9	3	3	28	12	23	211%	300%	667%	4	3	6	Pass	Pass	Fail
12-Entrance C	4	1	1	3	2	3	-25%	100%	200%	1	1	1	Pass	Pass	Pass
12-Exit C	3	1	5	1	2	1	-67%	100%	-80%	1	1	2	Pass	Pass	Pass
941148-NB	4	1	0	4	5	0	0%	400%	0%	0	2	0	Pass	Pass	Pass
941148-SB	4	1	0	3	5	0	-25%	400%	0%	1	2	0	Pass	Pass	Pass
941436-SB	3	1	6	2	4	6	-33%	300%	0%	1	2	0	Pass	Pass	Pass
941436-NB	5	2	3	6	5	6	20%	150%	100%	0	2	1	Pass	Pass	Pass
941176-NB	1	1	3	0	0	0	-100%	-100%	-100%	1	1	2	Pass	Pass	Pass
941176-SB	1	0	0	0	0	0	-100%	0%	0%	1	0	0	Pass	Pass	Pass
38471-EB	0	0	0	0	0	0	0%	0%	0%	0	0	0	Pass	Pass	Pass
38471-WB	0	0	0	0	0	0	0%	0%	0%	0	0	0	Pass	Pass	Pass

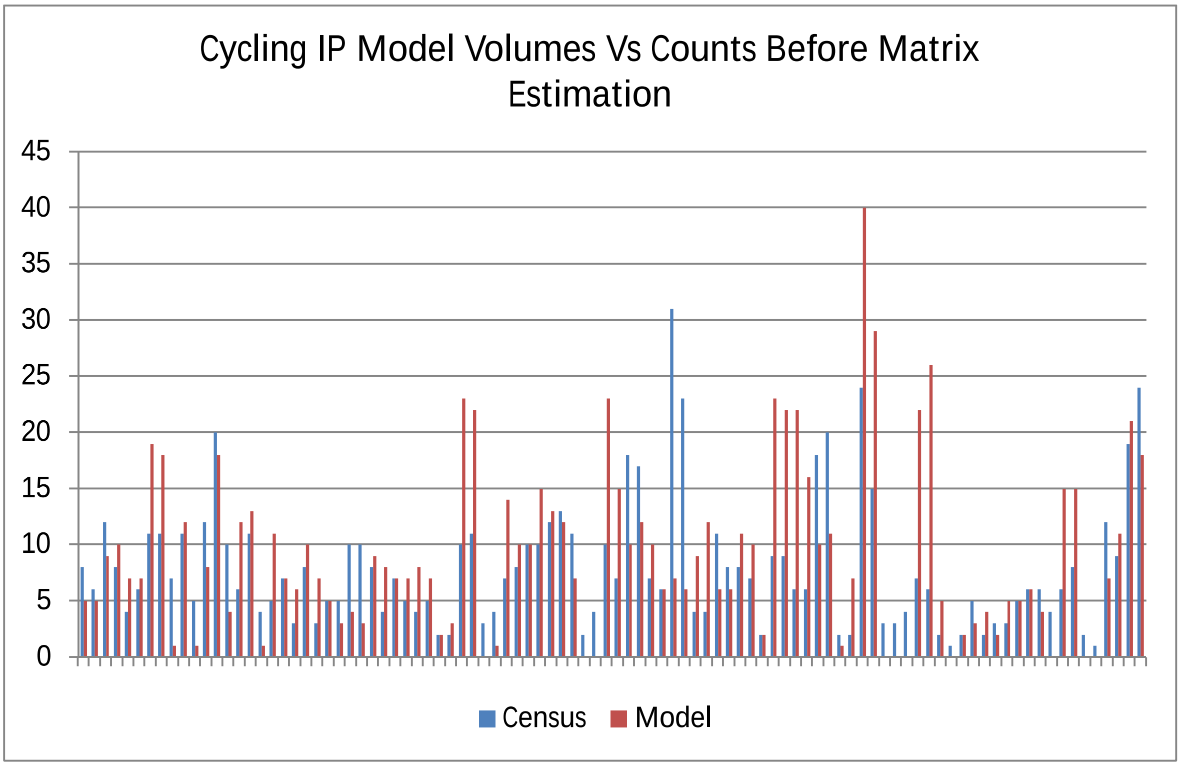
	Observed			Model			Flow Difference (%)			GEH			Pass/Fail Test		
Cycling Count ID	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM	AM	IP	PM
07000013-EB	30	8	8	45	15	19	50%	88%	138%	2	2	3	Pass	Pass	Pass
07000013-WB	6	7	17	19	18	36	217%	157%	112%	4	3	4	Pass	Pass	Pass
3-Exit B	19	17	28	14	18	19	-26%	6%	-32%	1	0	2	Pass	Pass	Pass
941136-NB	7	3	5	28	6	9	300%	100%	80%	5	1	2	Fail	Pass	Pass
941136-SB	5	3	6	4	8	21	-20%	167%	250%	0	2	4	Pass	Pass	Pass
3-EntranceC	17	10	17	14	7	15	-18%	-30%	-12%	1	1	1	Pass	Pass	Pass
3-Exit C	5	5	11	1	0	6	-80%	-100%	-45%	2	3	2	Pass	Pass	Pass

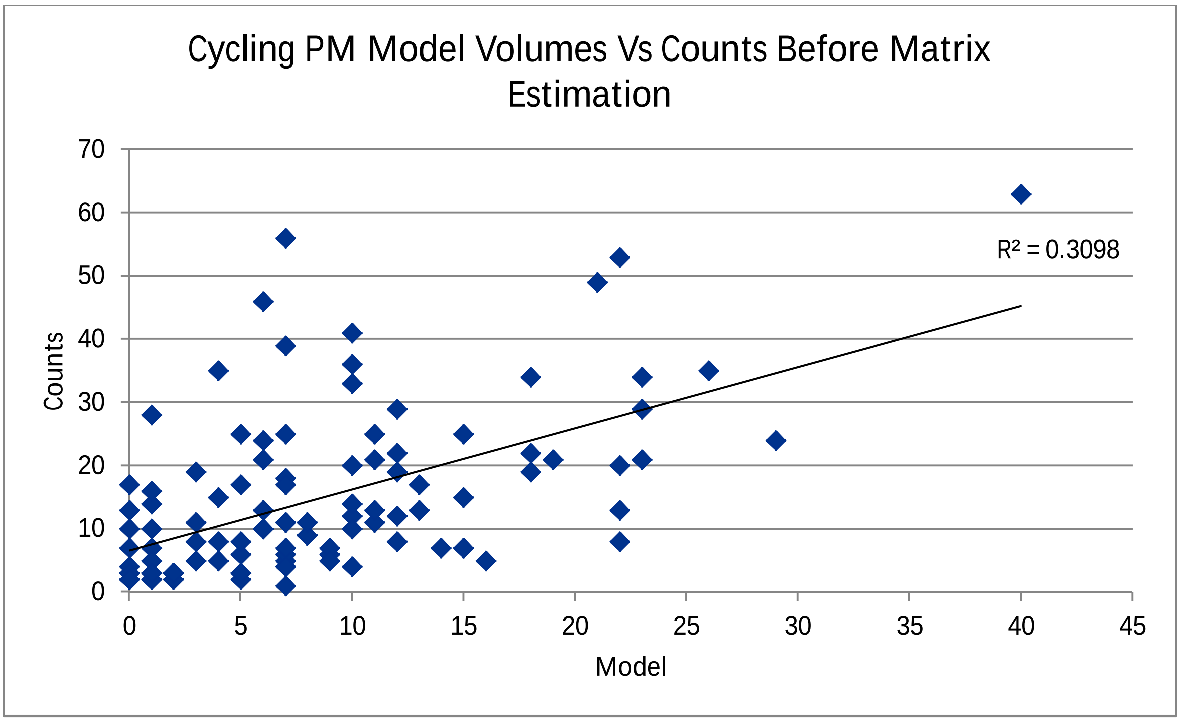
Appendix C. Volumes vs Counts before and after matrix Estimation

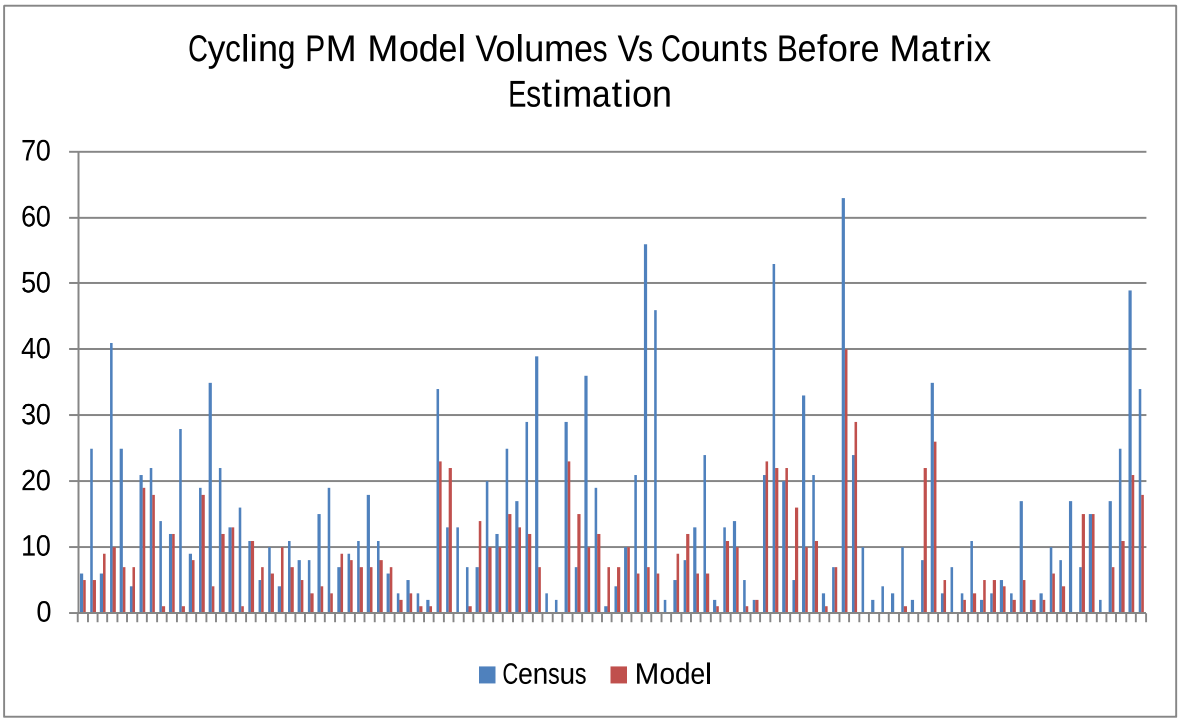


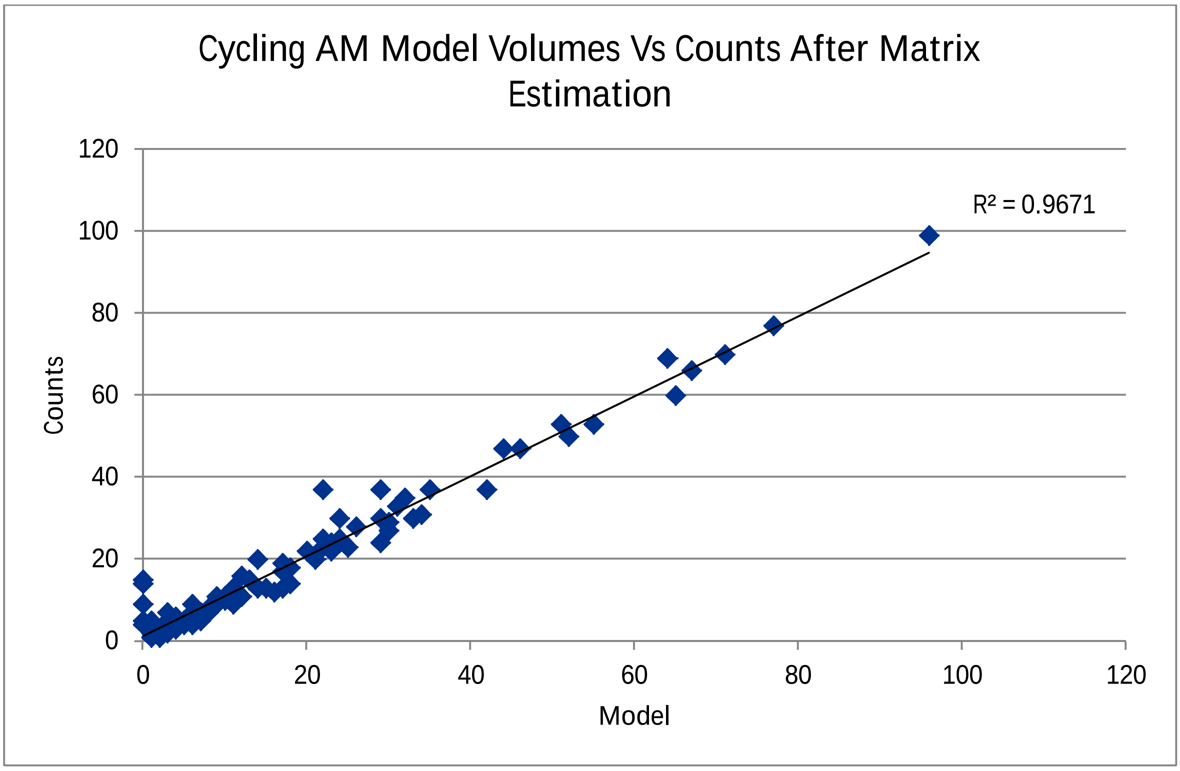


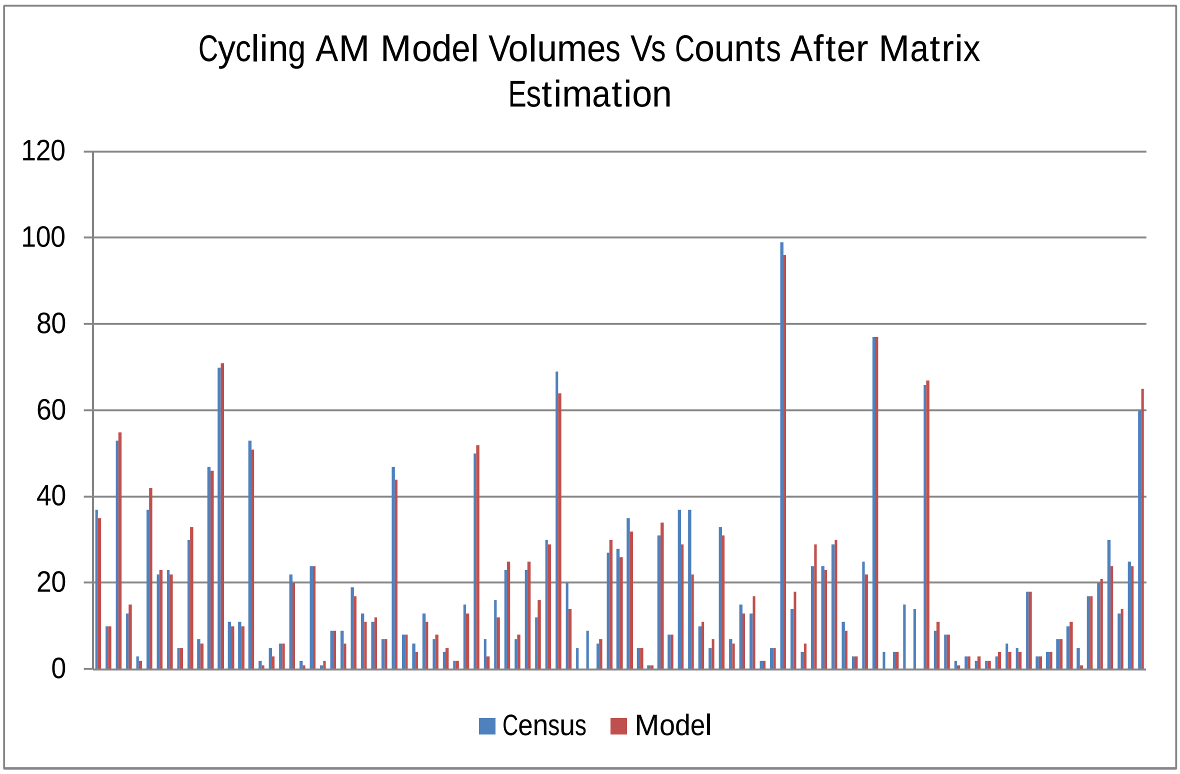

Cycling IP Model Volumes Vs Counts Before Matrix Estimation
Counts
Model
R² = 0.2611
0
5
10
15
20
25
30
35
40
45

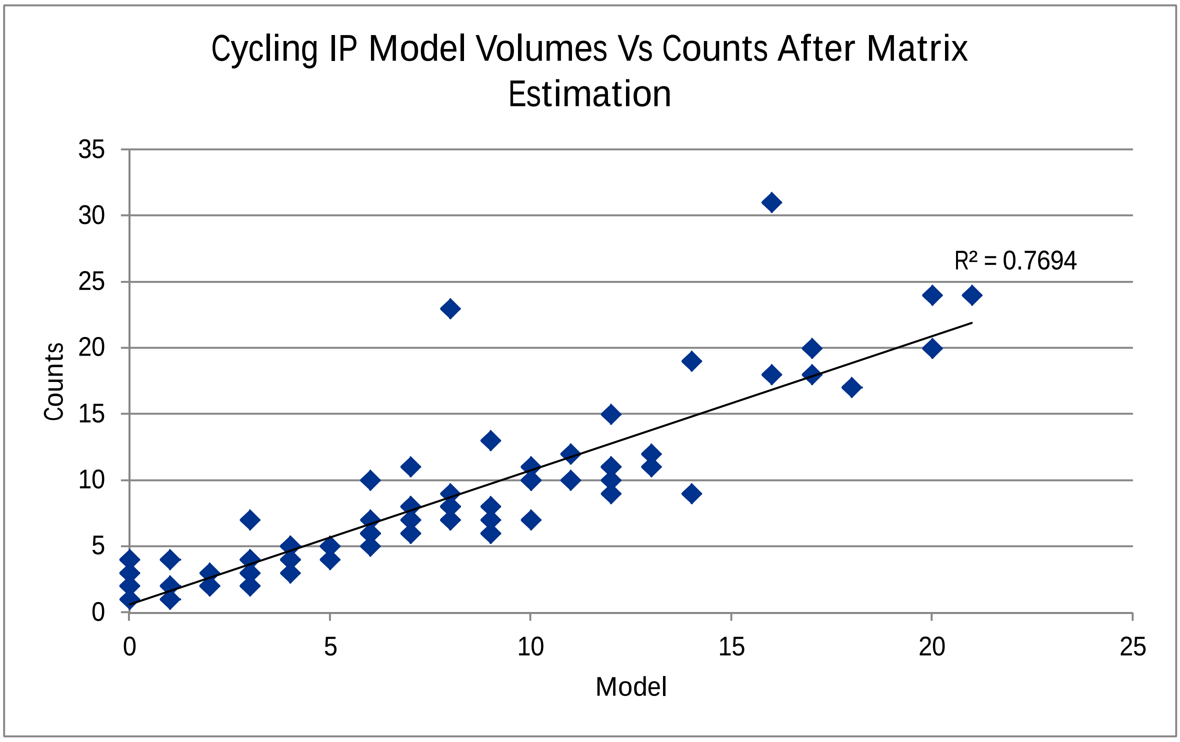

Cycling IP Model Volumes Vs Counts Before Matrix Estimation
0
5
10
15
20
25
30
35
40
45
Census
Model

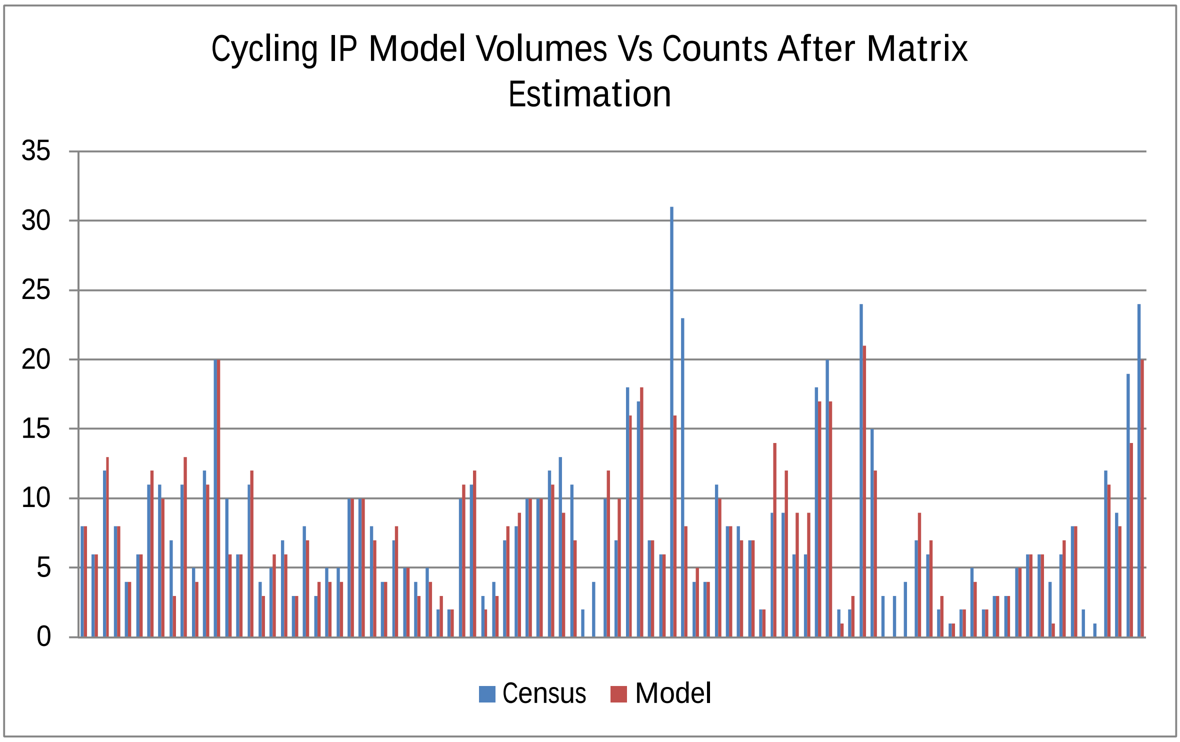

Cycling PM Model Volumes Vs Counts Before Matrix Estimation
70
60
50
40
30
20
10
0
Counts
0
5
10
15
20
25
30
35
40
45
Model
R² = 0.3098

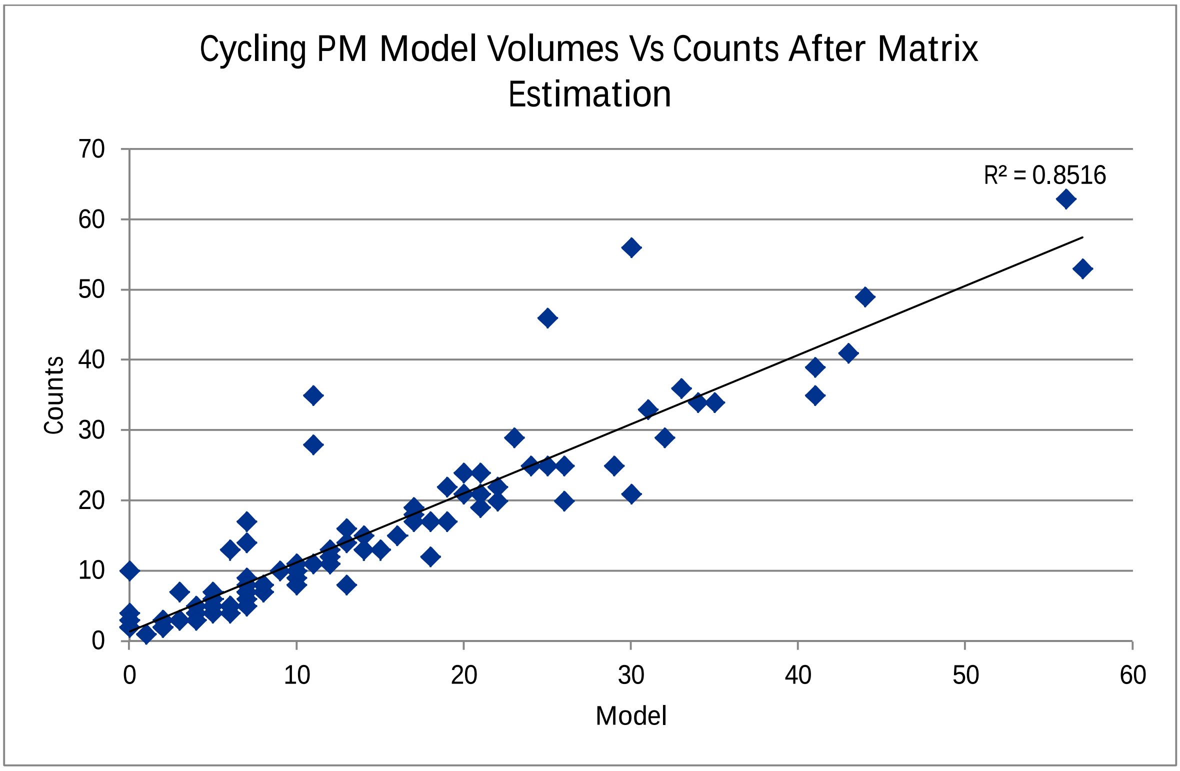

Cycling PM Model Volumes Vs Counts Before Matrix Estimation
70
60
50
40
30
20
10
0
Census
Model

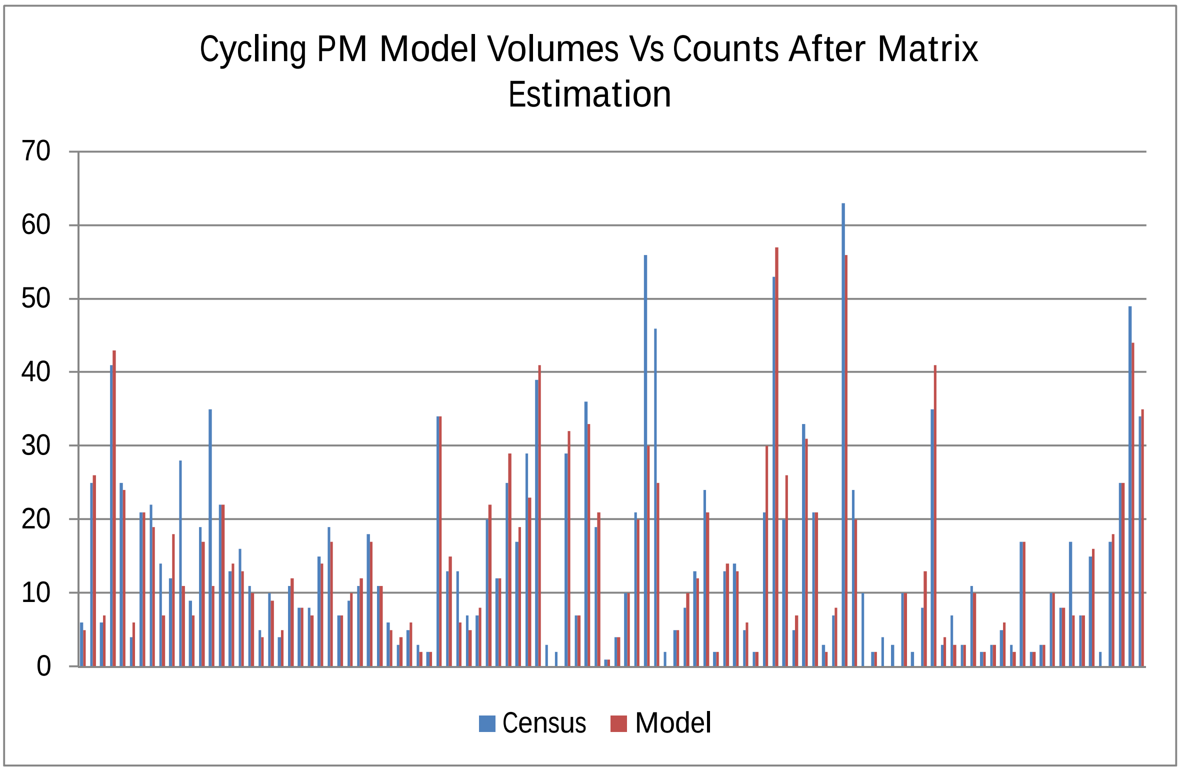

Cycling AM Model Volumes Vs Counts After Matrix Estimation
R² = 0.9671
Counts
Model
120
100
80
60
40
20
0
0
20
40
60
80
100
120


Cycling AM Model Volumes Vs Counts After Matrix Estimation
120
100
80
60
40
20
0
Census
Model


Cycling IP Model Volumes Vs Counts After Matrix Estimation
R² = 0.7694
Counts
Model
0
5
10
15
20
25
30
35


Cycling IP Model Volumes Vs Counts After Matrix Estimation
0
5
10
15
20
25
30
35
Census
Model


Cycling PM Model Volumes Vs Counts After Matrix Estimation
R² = 0.8516
Counts
Model
0
10
20
30
40
50
60
70


Cycling PM Model Volumes Vs Counts After Matrix Estimation
0
10
20
30
40
50
60
70
Census
Model