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Citation: Namdeo, Anil, Tiwary, Abhishek and Dziurla, R. (2014) Spatial planning of public charging points using multi-dimensional analysis of early adopters of electric vehicles for a city region. *Technological Forecasting and Social Change*, 89. pp. 188-200. ISSN 0040-1625

Published by: Elsevier

URL: <http://dx.doi.org/10.1016/j.techfore.2013.08.032>  
<<http://dx.doi.org/10.1016/j.techfore.2013.08.032>>

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# **Spatial planning of public charging points using multi-dimensional analysis of early adopters of electric vehicles for a city region**

A. Namdeo<sup>a</sup>, A Tiwary<sup>b,\*</sup>, R. Dziurla<sup>a</sup>

<sup>a</sup> *School of Civil Engineering and Geosciences, Newcastle University, Newcastle, NE1 7RU, UK.*

<sup>b</sup> *Faculty of Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK.*

\*Corresponding author: Dr Abhishek Tiwary

Email: a.tiwary@soton.ac.uk

Fax: +44 191 2380 667519

## **Abstract**

The success of a mass roll out of Plug-in electric vehicles (PEVs) is largely underpinned by establishment of suitable charging infrastructure. This paper presents a geospatial modelling approach, exploring the potentials for deployment of publicly accessible charging opportunities for consumers based on two traits – one, trip characteristics (journey purpose and destinations); two, PEV adoption intensity. Its applicability is demonstrated through a case study, which combines census statistics indicating lifestyle trends, family size, age group and affordability with travel patterns for an administrative region in the North-East England. Three categories of potential PEV users have been identified – ‘New Urban Colonists’, ‘City Adventurers’ and ‘Corporate Chieftains’. Analyses results indicate that Corporate Chieftains, primarily residing in peri-urban locations, with multi-car ownership and availability of onsite overnight charging facilities form the strongest group of early adopters, irrespective of public charging provision. On the other hand, New Urban Colonists and City Adventurers, primarily residing in the inner-city regions, show potentials of forming a relatively bigger cohort of early PEV adopters but their uptake is found to be dependent largely on public charging facilities. Our study suggests that effective PEV diffusion in city-regions globally would require catering mainly to the demands of the latter group, focussing on development of a purpose-built public charging infrastructure, both for provision of on-street overnight charging facilities in residential locations and for fast charging at parking hubs (park and ride, amenities and commercial centres).

*Keywords: charging infrastructure; electric vehicle; GIS; public charging; socio-demographic*

## 1 **1. Introduction**

2 Alternative fuelled vehicles (AFVs) are expected to play a major role in decoupling transport's ~93%  
3 dependence on liquid fossil fuels, through diffused adoption of both Plug-in electric vehicles (PEVs)  
4 and hydrogen fuel cell vehicles [1]. PEVs in particular, including both plug-in hybrid electric vehicles  
5 (PHEVs) and battery electric vehicles (BEVs), have the potential to improve the energy and  
6 environmental landscape of personal transportation over the next decade. However, absence of a  
7 proactive plan and schedule for charging infrastructure is a major impediment to mass market  
8 adoption, particularly pertinent to BEVs due to their sole dependency on electricity, range limits, and  
9 long recharging time [2]. In this context development of a coherent policy in the area of electric  
10 mobility (i.e. E-mobility) is being increasingly considered as a viable investment in offsetting  
11 transport-related climate change effects associated with conventional vehicles over near-term [3]. An  
12 analysis of developments in electric vehicles before and after 2005 suggests the diffusion of E-  
13 mobility configuration in recent years to be largely dependent on infrastructural investments [4].  
14 Consumer surveys from across different global markets indicate that lack of refuelling infrastructure  
15 is going to be a major deterrent for adoption of AFVs [5,6]. The UK Department for Transport (DfT)  
16 has set up an Office for Low Emission Vehicles (OLEV), committed to development of an ultra-low  
17 emission vehicle market – facilitating better energy security while addressing issues related to CO<sub>2</sub>  
18 emissions and air quality in cities [7]. However, the current drive for securing the future of mobility  
19 through electrification, at least over the short to medium term, is faced with technological,  
20 infrastructural and behavioural hurdles that need to be overcome in order to enable mass market  
21 penetration [8].

22

23 Development of adequate public charging opportunity has been proposed as a viable compromise in  
24 effectively mitigating the range anxiety rather than focussing on the development of longer-range  
25 vehicle capabilities [3,9]. Interesting findings, based on optimal charging algorithm for locating the  
26 service points while minimising the charging costs, reveal distinct charging infrastructure strategies  
27 for PHEVs and BEVs. While PHEVs tend to have lower returns from ‘non-home’ i.e. public charging

28 infrastructure (in terms of efficiency savings and operating costs reductions), BEVs on the other hand  
29 show increased feasibility from such investments [2]. The demand for optimal public charging point  
30 locations has led to consortiums of companies in the transport, energy and power electronic sectors  
31 working together on projects connected with the initiation of commercial charging terminals for  
32 BEVs, as well as fast charging public stations [10]. The C40 Electric Vehicle Network (C40 EVN),  
33 based on policy analysis exercise on the deployment of PEV charging infrastructures in C40 cities (a  
34 group of the world's largest cities) has facilitated the successful introduction of PEVs through  
35 collective municipal actions, including planning and deployment of charging infrastructure,  
36 streamlining permitting processes associated with new installations, providing monetary and non-  
37 monetary incentives and mobilising demand for PEVs in city fleets [11]. The C40 study assessed the  
38 potential barriers (policy, technological, economic, etc.) to the deployment of electric vehicle  
39 charging point infrastructure.

40

41 Currently the debate on the best set up for the provision of public charging point (PCP) infrastructure  
42 is wide open, given the technology and its implementation plan are still in their infancy. Better  
43 understanding of present and future PEV users through numerous market deployment scenarios, both  
44 at the European level [12,13,14] and globally [5,6,15,16], have been developed through dedicated  
45 literature surveys, focus groups and expert elicitations to assist in informed political decisions towards  
46 adequate policy interventions for supporting the PEVs (both PHEVs and BEVs) markets. Charging  
47 demand of an early PEV market in Beijing has been estimated using an assignment model on the basis  
48 of the number of local refuelling stations (conventional vehicles) and communal/public parking  
49 spaces [15]. A system dynamics model of the UK take-up of PEVs has provided modest market share  
50 forecasts, expected to evolve over the next 40 years [17]. A diffusion model, utilising multi-criteria  
51 analysis and choice modelling, has been applied to estimate the adoption of PEV technologies  
52 spatially across heterogeneous mix of Australian consumers through to 2030 [16]. Overall, it is  
53 envisaged the uptake of PEVs will largely depend on two crucial factors – a. oil price fluctuation; and  
54 b. consumer acceptance. In the UK, a London-wide PEV charging network is being set up as part of  
55 the 'Source London' initiative, with an aspiration for establishing London as the PEV capital of

56 Europe (with a target of installing 25,000 charging points by 2015, including 500 on-street charging  
57 points and 2,000 charging points in off-street public car parks and Tube/ Over ground rail station car  
58 parks) [18]. Based on the UK government projection, there will be acceleration in the uptake of PEVs  
59 nationwide from 2015-2020 [19], henceforth increasing the demand for a more spatially optimised  
60 charging point infrastructure over this period. The market will then have the opportunity to expand as  
61 the acceptance of the new technology grows and its range anxiety issues decline. In the short term at  
62 least, the majority of recharging in the UK is expected to occur at home, with further recharging  
63 opportunities provided in public charging bays, piloted through government schemes such as ‘Plugged  
64 in Places’ under the Carbon Plan or at work if the employers join these schemes [19]. Similar trends  
65 are reflected in global studies, suggesting a steady rate of growth in PEV uptake, with most users  
66 commuting short distances from suburban locations [5,6,15].

67

68 Limiting the scope for developing an implementation strategy for PCPs is the fact that till date there is  
69 little information on profiling of early PEV adopters. A recent survey in the US has identified  
70 potential socio-technical barriers to consumer adoption of PEVs, particularly highlighting the  
71 perceptions and preferences of technology enthusiasts as potentials early adopters [3]. In the UK, a  
72 statistical methodology based on hierarchical cluster analysis to census data, characterising the age,  
73 income, car ownership, home ownership and socio-economic status, has been applied to identify  
74 potential early adopters of a range of AFVs (predominantly for the uptake of PEVs) using a case study  
75 for the city of Birmingham [8]. Over the years public charging points are expected to generate greater  
76 awareness and marketing potential for the roll out of PEVs [18]. However, recent insight into the  
77 business case of public fast chargers for PEVs indicate the current market outlook to be uncertain for  
78 triggering a large scale roll out, unless investment costs can be severely lowered [20]. During the  
79 current phase of austerity in public spending by governments this however requires well-informed  
80 decision making on the choice of strategic locations upfront for installation of cost-effective charging  
81 points, especially with regard to targeting areas of potential PEV uptake. This is vital to creation of a  
82 region-wide charging network independent of individual/ household charging facilities. In this regard  
83 a GIS-based multi-criteria decision support approach - combining several ‘expert-weighted’

84 economic, social, environmental and transport-related traits for European cities (scoped at cities level  
85 within EU27) – has been applied recently to assess the PEV market penetration up to 2030 [21].  
86 However, the importance of range anxiety in consumer decision making, involving neighbourhood  
87 level spatial infrastructural data (e.g. accounting for multiple-parking capacity for specific dwelling  
88 location) alongside geographically-enabled travel pattern data (e.g. distance, journey purpose, etc.),  
89 has not been investigated spatially in any previous studies [13].

90

91 The aim of this paper is to develop a methodological approach for multi-dimensional spatial analysis  
92 addressing the aforesaid knowledge gap, combining the underlying socio-economic traits and trip  
93 characteristics (journey types and origin-destination) for prioritising the demand-based public  
94 charging hotspots. Keeping the scope of the assessment essentially as urban its applicability is  
95 demonstrated through a case study for a city-region in the North-East England. The multi-criteria  
96 spatial analysis considers both residential premises and commercial centres spanning across the inner-  
97 city and out-of-town locations in the case study region. The spatial model predicts suitable sites/  
98 zones for installing purpose-built PCPs within the existing built-infrastructure on the basis of socio-  
99 economic traits and trip characteristics. In the subsequent section, viable recommendations have been  
100 made based on our results, supporting mass uptake of transport innovation through adequate  
101 infrastructure planning, specifically catering to the demands of early adopters lacking overnight, off-  
102 street residential parking facilities.

103

## 104 **2. Methods**

### 105 *2.1 Data analysis and assumptions*

106 As a first step, a hierarchical data structure for multi-dimensional spatial analysis was developed  
107 based on a number of criteria to ascertain the most appropriate location of PCPs. A shortlist of key  
108 determinants of PEV adopters was generated utilising recent literature [8,6,22,23,24,25], combining  
109 the underpinning household demographic and macroeconomic traits. The main features included –  
110 gender, age, occupation, level of household income, number of vehicles owned, environmental

111 awareness, interest in new technologies, sensitivity to government incentives, and knowledge about  
112 fuel economy. This led to acquisition of required data from a range of census information statistics as  
113 detailed below.

114

115 Table 1 lists the key variables applied to this analysis, the rationale for including them is based on the  
116 literature reference along with their information source. As can be noted, the majority of spatial  
117 information on socio-demographics, accessible as digitised map layers with boundary information in  
118 GIS format, was obtained from the UK Census Dissemination Unit (Casweb) [26]. However, the trip  
119 origin-destination data could not be collated within the Casweb system and was alternatively accessed  
120 from the Centre for Interaction Data Estimation and Research (CIDER) [27], mainly covering  
121 information on traffic flows pertaining to commuting patterns. The latter dataset enabled generation of  
122 intra-regional origin-destination statistics used in the spatial analysis (Section 2.3.1). The following  
123 four constraints were applied to identify the potential for setting up PCPs which duly accounted for  
124 the emerging trends in potentials for early adopters charging privately at home. Adequate assumptions  
125 were made while interpreting census information from a particular selection of data sets, as described  
126 later where applicable. This was deemed essential due to the limitation of available information in  
127 projecting the PEV uptake potential directly.

128

### 129 *2.1.1 Off-Street Parking*

130 As common to several European and global cities, the majority of UK cities have less than 40 percent  
131 of urban households with off-street parking availability though around 70 percent of suburban  
132 residential households have off-street parking availability [28]. For households that do not have off-  
133 street (garage) parking, and those who park on the street or in public garages, PCPs are going to be  
134 key to early uptake [6,29]. Although off-street home charging, utilising a 240 V/13 A (or 16 A)  
135 connection with a switchable socket and surge protection device, has been considered as common  
136 route for charging by majority of first generation PEV users [30], a more recent study in the UK  
137 suggests that current planning policies often limit the number of off-street parking places, and in



138 many rented properties, installing charging sockets with required specification could be complicated  
139 [31]. These issues are going to be reverberated in cities in other parts of the world as well. We have  
140 therefore taken a conservative estimate in locating the PEV charging infrastructure - for PHEVs,  
141 assuming 50% of consumers would charge off-street at home; for shorter range BEVs, assuming 90%  
142 of consumers would charge on-street, i.e. dependent mainly on PCP availability [13]. While  
143 populating the neighbourhood level infrastructural data in the spatial model we assumed that only  
144 detached and semi-detached households have off-street parking while remaining residents park their  
145 vehicles on-street.

146

### 147 *2.1.2 PEV User Demographics*

148 The UK Office of National Statistics has generated 14 categories of occupations, ranging from  
149 employers in large organisations to those who have never worked and long-term unemployed [26]. A  
150 recent study derived the representative socio-economic status of early adopters for a UK city  
151 (assuming direct association with higher income levels) by combining two occupation groups –  
152 ‘Higher professionals’ and ‘Lower managerial and professionals’ [8]. Extending this approach further,  
153 the potential PEV adopters in our study were assumed to be representing the top 3 rankings of these  
154 socio-economic categories, including ‘Employers in large organisations’, ‘Higher managerial  
155 occupation’ and ‘Higher professional occupations’. It was assumed that these cohorts in turn would  
156 lead the way to mass market adoption of PEVs.

157

### 158 *2.1.3 Young Professionals*

159 Recent industry surveys for the EU and the US suggest that early adopters of BEVs will generally be  
160 male, between 18 and 34 years of age [6]. Further, young professionals are viewed as being strongly  
161 attached to technology and the media, and are known to have early adoption traits [8]. Although  
162 recent studies have highlighted the extension of this age-group to include both early- and middle-aged  
163 professionals (20-55 years) [8,23] the latter, relatively older age group of professionals, has been

164 considered as more affluent (and owning semi-detached or detached houses with off-street parking)  
165 and thus having lower demand for PCPs. In the data selection process of census area statistics  
166 provided by Casweb, data sets categorised by age groups can be matched to economic demographics.  
167 However, the age groups concerned are particularly large (e.g. 20-24, 25-34, 35-54). Therefore, the  
168 age band of the demographic group representing young and professional (or young urban  
169 professional), referring to members of the upper middle class in their 20s and 30s were considered.  
170 Along these lines, the age boundaries of 20-24 and 25-34 were chosen to symbolise young urban  
171 professionals.

172

#### 173 *2.1.4 Socio-economic Classification*

174 A recent study for the UK HEV adopters (1263 participants) has reported 39 percent with household  
175 income over £48,000 net per year (~\$78,000 USD, 2011), and 58 percent possessing an extra car [24].  
176 Although a PCP infrastructure framework has already been developed in the UK for London as part of  
177 the London Strategy [32] similar guidelines are still not available for other regions. We therefore  
178 adopted the London Strategy with slight amendment to the socio-economic characteristics of the  
179 region (for example the ‘global connection’ category was omitted to develop a more generalised  
180 classification since this was considered specific to the most affluent features of areas in central  
181 London). On this basis, the resident population was divided into the following three cohorts,  
182 essentially reflecting their distinct characteristics – New Urban Colonists; City Adventurers;  
183 Corporate Chieftains. These three cohorts were synthesised from the mosaic types of current PEV  
184 (both PHEVs and BEVs) users in London [32] and is considered representative of the majority of  
185 European cities with similarly short driving ranges and densely populated urban areas. These  
186 population groups were geographically combined with the local socio-demographic information,  
187 utilising already established set of criteria for early adopters as identified in recent literature from  
188 cluster analysis [8]. ‘New Urban Colonists’ were assumed to include small households (with either  
189 single or couple with no children) as well as other households (implying multi occupancy  
190 households). The emphasis on ‘single or couples’ was assumed to provide a distinct classification.

191 ‘City Adventurers’ were considered as young professionals and ‘Corporate Chieftains’ were  
192 represented by senior management professions with detached houses.

193

194 The spatial location of these cohorts in a specific study location could be established through selection  
195 of appropriate household composition from published national statistics, for example in the UK this  
196 information can be acquired from the National Statistic Socio-economic Classifications (NS-SeC)  
197 [33]. It was anticipated that some of the traits between the three cohorts would be overlapping. To  
198 account for this anomaly, census data with high ranking NS-SeC classifications and the age groups of  
199 20-24 and 25-34 were chosen as representative of all three cohorts. Further, the data on Corporate  
200 Chieftains was collected by gathering separate information from ward totals of detached housing and  
201 the assumption that managers belonged to the classification for the highest NS-SeC category ranking.  
202 This is along the lines of an earlier study [8] who also used socio-economic status as an indicator of  
203 income by assuming occupation group ‘professionals and managers’ to be representing those expected  
204 to have a higher income than other occupation groups. In previous studies education has been  
205 considered as an important factor in determining AFV uptake potentials [23,34]. However, a recent  
206 study from Birmingham (UK) reported some wards with high student population, having higher  
207 education levels but not affluent home-owners, yet possessing multiple cars in the household [8].  
208 Such contradictory results demonstrate the need for extra caution in applying specific demographic  
209 characteristics to a given area while assessing the PEV adoption trends, in particular for determining  
210 locations of PCPs. Based on this argument education level was not considered a reliable trait while  
211 evaluating early adopter potentials and hence omitted from subsequent spatial analysis in profiling of  
212 early adopters of PEVs in this study.

213

## 214 **2.2 Case study**

215 This section demonstrates the applicability of the spatial modelling framework described in Section  
216 2.1 through a case study based in the Tyne and Wear County of the North-East England. The study  
217 region comprises of five local authorities (South Tyneside, North Tyneside, Newcastle, Gateshead and

218 Sunderland) with a total population of over 1 million [33]. It has been considered appropriate on its  
219 merits of being a suitable test bed for evaluation of the regional spread of early adopters of PEVs,  
220 relying on both private and public charging points. Pertinent to this, the region is currently witnessing  
221 a huge push from the UK government funded ‘Plugged in Places’ scheme on promotion of low-  
222 emission vehicles [7,19]. In addition, crucial to the scope of this study in promoting public charging  
223 infrastructure at workplaces and publically available charging locations, the proportion of travel to  
224 work by car in the Tyne and Wear region is reported as 58.7 percent, well-within a comparable range  
225 of national average of 61 percent reported for the UK [26].

226

### 227 *2.3 Spatial Analysis*

228 While Section 2.1 enabled assignment of neighbourhood level spatial infrastructural data (dwelling  
229 sizes, PEV early adoption traits, Off-street charging etc.) this section concentrates on populating  
230 geographically-enabled travel pattern data for locating the PCP hotspots for the case study site.  
231 Essentially this is based on the following two metrics – one, trip destination; two, PEV adoption  
232 intensity. This selection was based on recent findings suggesting geographical differences in PEV  
233 uptake to be primarily influenced by driving distances and socio-economic characteristics of  
234 households [8,16]. Further, the two metrics enabled a representative mechanism for spatially  
235 analysing the impact of PEV driving patterns for the purpose of locating the potential hotspots for  
236 PCPs. This follows similar methodology adopted in recent studies [8,27] to overcome the anomalies  
237 in previous studies where PEV vehicle flows were estimated as a subset of the conventional vehicle  
238 flows, assuming homogenous PEV adoption rates within a region, ignoring the underlying traits of  
239 PEV users. A dedicated spatial software tool (ArcGIS v10) was used to integrate the GIS-enabled  
240 demographic and travel datasets acquired at the Super Output Area Level (SOA). The SOAs in the  
241 UK represent the smallest geographic units for disseminating robust census statistics while the  
242 confidentiality of individual census returns remains preserved [22]. Various spatial layers were  
243 computed from census statistics and compared between different areas of the Tyne and Wear region  
244 through application of geoprocessing tools to establish the favourable traits, including distribution of  
245 affluent households (characterised by detached houses, multi-car ownership), park and ride facilities,

246 and regional centres. The latter comprising of large industrial facilities, large retails and business  
247 parks, amenities and prominent transport hubs (including the regional airport) (Figure 1). This  
248 allowed for deriving relationships in the data that could not have been readily apparent in databases or  
249 spread sheets. GIS outputs with graduated colour ramps highlighting key areas of interest (i.e.  
250 hotspots) were generated for evaluation and interpretation of the spatially varying totals between  
251 wards across the study domain.

252 <Place Fig 1 here>

253 The following sections describe the steps involved in trip characterisation for early EV adopters.

254

### 255 *2.3.1 Intra-regional origin-destination mapping*

256 Commuting and other major trip purpose journeys were identified for the study region using the ward  
257 census data. While analysing commuting patterns the focus was mainly on car trips and not on overall  
258 commuting patterns from all modal forms. This was done to assess the implementation of charging  
259 infrastructure for personal transport users (mainly cars). The origins and destinations of all  
260 commuting journeys were only calculated within the case study region. For commuting trips  
261 originating outside the study domain only the portion of the trip falling within the study boundary  
262 were considered for consistency in finding suitable charging point locations. Following the  
263 recommendations of a recent study [9], the spatial analysis coupled vehicle range and trip length as a  
264 function of trip journey purpose to locate PCPs. Constraining the origin-destination mapping by BEV  
265 range requirements was considered relevant for ensuring the commuters' concern on non-reliability of  
266 BEVs for essential trips. On this basis mappable information of the most likely destinations for BEVs  
267 were generated, thus facilitating the derivation of viable PCP installations in areas with high  
268 proportions of car commuting trips.

269

### 270 *2.3.2 Electric vehicle adoption intensity*

271 This step utilised the socio-economic demographics, acquired following the criteria described in  
272 Section 2.1.4, to determine the spatial distribution of New Urban Colonists, City Adventurers and  
273 Corporate Chieftains in the case study region. These were considered as early uptake 'hotspots'; the

274 former two groups suggested to be relying heavily on deployment of PCPs [33] while the latter group  
275 was assumed to only use PCPs, especially those located at workplace, for top-up and emergency  
276 charging. The outcome of this analysis informed zoning of suitable charging point locations, both  
277 within the residential areas, and the earmarked parking hubs and commercial centres. The feasibility  
278 assessment followed the recently published UK National Planning Policy Framework guidance for  
279 green transport (i.e. potential for reducing environmental impact, mainly CO<sub>2</sub> emissions compared to  
280 equivalent standard vehicles depending on the embodied energy of the vehicle and the source of the  
281 electricity) on encouraging local authorities in incorporating PEV charging infrastructure at suitable  
282 sites as well as developing policies for embedding recharging infrastructure within new workplace  
283 developments [35].

284

### 285 *2.3.3 Weighted overlay analysis*

286 This step assessed the strategic locations for PCP installations, taking into consideration the multi-  
287 criteria assessment underpinning successful deployment and usage of these facilities. The key  
288 constraint was in making the choice of public charging infrastructure (fast or trickle charging) that  
289 would allow PEV users to recharge their batteries at varying rates, depending on trip purpose and  
290 parking duration. A recent study for the US, utilising a simulation-optimisation model to evaluate the  
291 PCP deployment strategies, considered location of trickle charging (typically rated at 220V and  
292 between 15 and 30A) to be ideal for parking lots and less effective at dedicated charging points since  
293 unlike conventional refuelling stations the availability of fast charging (DC high-voltage ~ 400–500V)  
294 at such sites becomes paramount for avoiding excessive waiting time. To compensate for the latter,  
295 previous studies [27,36] have recognised the need for multiple charging stations at a single location to  
296 capture a large flow of PEVs.

297

298 The layers of spatial information were overlaid to assess the favourable hotspots for PCP  
299 infrastructure. In order to reduce the investment costs it was considered necessary to first filter out the  
300 zones with majority of charging occurring privately on off-street premises; eliminating the cohort with

301 least dependence on public charging consumer share. For this purpose, multi-criteria evaluation  
302 parameters were established for both public and private charging categories through combination of  
303 data layers generated in Sections 2.3.1 and 2.3.2 (Table 2). An integrated analysis was performed  
304 using the weighted-overlay technique in ArcGIS Spatial Analyst toolbox [37]. It is important to note  
305 that the Weighted Overlay tool accepts only discrete raster (integer values) as inputs. This makes it  
306 possible to perform arithmetic operations on the raster that originally held dissimilar types of values.  
307 For this purpose all the spatial information was first converted into classified datasets using raster pre-  
308 processing tools. The input raster were weighted by importance and added together to produce an  
309 output raster. A discretised evaluation scale from 1 to 10 (with 10 being the most favourable) was  
310 applied to represent the level of suitability of the locations for both private charging users and for  
311 installing PCPs.

312

#### 313 *2.3.4 Ground validation of multi criteria assessment*

314 A series of consumer surveys were conducted as part of ground validation exercise to ascertain the  
315 reliability of the predictions made through weighted overlay analysis. This involved interviewing a  
316 sample population by splitting the case study area into four sub regions based on PEV adoption  
317 intensity following a recent approach applied to consumer testing of PEV technology diffusion [16].  
318 The interview questionnaire involved acquiring relevant information for validating some of the  
319 outputs from the GIS mapping, typically asking the consumers' education level, gender, age, interest  
320 in green technologies, number and age of vehicles owned, average travel distance and time,  
321 willingness to install charging socket at home, availability of off-street charging facility.

322

323

## 324 3. Results and Discussions

### 325 3.1 Spatial analysis of potential PEV users

#### 326 3.1.1 Origin-destination dependence

327 Outputs from the first step analysis of commuting patterns of car users in the region provided a clear  
328 indication of possible destination areas for potential PEV users. This enabled an assessment of the  
329 feasible zones for locating the PCPs. For this purpose ward-level commuting totals were split up into  
330 five class intervals to cover the bulk of the commuting trips into each ward (Figure 2). These were  
331 then used to symbolise the varying levels of commuting destination levels across the region. This was  
332 generated by dividing the maximum car commuting ward totals by the number of classifications  
333 necessary to show clear results. Car commuting hotspots (darker tone in Figure 2) were found to have  
334 over 78 percent car use as compared to a mean of 55 percent noted across the case study area. This  
335 indicates the potentials for PCPs installed in these locations in encouraging early PEV uptake due to  
336 the high proportion of car commuting dependence in the ward area.

337

338 The largest frequency came from smaller total commuting destination totals which were normally  
339 under 2000 car commuters. These wards symbolise residential areas, to which fewer people commute.  
340 At the far end of the scale four wards having very large car commuting totals were noted, representing  
341 central workplace areas to which a large majority of the region's working population commute to.  
342 Apart from this the major car commuting totals on the periphery of the two town centres (Sunderland  
343 and Gateshead) were mainly attractors of employees commuting to a large car manufacturing plant  
344 and several out-of-town shopping malls. This large total of car commuting destination trips to these  
345 remote locations is further augmented by the lack of availability of public transport. This pattern is  
346 typical of the majority of global cities with limited access to public transport availability to out-of-  
347 town commercial hubs and industrial parks. From our analysis it appears developing a work-based  
348 charging infrastructure would encourage employees working in this zone to be early PEV adopters.  
349 This is along the lines of current focus in promoting workplaces as the second main pillar of the UK



350 plug-in vehicle recharging infrastructure [35]. It has been considered more applicable to Plug-in  
351 Hybrid Electric Vehicles (PHEVs) or Extended-Range Electric Vehicles (E-REVs), as these may need  
352 a different pattern of charging to deliver their maximum environmental and financial benefits, making  
353 the benefits of workplace top-up recharging potentially significant [7].

354 *<Place Figure 2 here>*

355 It is noteworthy that some city centre areas (in particular for Newcastle) show low percentages of car  
356 commuting trips compared to other modal choices. This is in agreement with finding from the  
357 Birmingham study [8] which also reported higher use of public transport while travelling to work in  
358 the inner-city wards. However, we note that this area is also attractor to car trips with a number of  
359 regional centres (see star shapes in top-centre locations in Figure 1), primarily leisure and shopping  
360 activities within the city centre. Locating PCPs at these sites would encourage car users to use these  
361 facilities, specifically if they are subsidised over the weekends. On the other hand, supermarkets and  
362 large retail outlets can become popular charging points as they can be incentivised through their  
363 promotional offers during twilight shopping hours.

364

### 365 *3.1.2 Socio-economic dependence*

366 Analysis of the socio-demographic GIS layers, generated from census data, enabled locating our three  
367 earmarked cohorts of residents in the region spatially. This analysis was conducted in several stages.  
368 The first step involved locating the specific areas where New Urban Colonists were most  
369 concentrated.

370 *<Place Figure 3 here>*

371 From Figure 3 it can be noted that the highest density of New Urban Colonists is located mainly in the  
372 North of the region, typically representing small families in the suburbs of Newcastle. Further, two  
373 areas that stand out from the trend of early uptake groups were found to be located in North Tyneside  
374 (middle-east zone on the map). Evidently, this reflects the fact that greater part of the resident  
375 population living in a household either singly or as a couple without children, prefer to live in the  
376 inner suburbs of the major city centre i.e. Newcastle, compared to other areas in the region. Therefore,

377 the likelihood of early adoption of PEVs in this socio-economic category would strengthen the case  
378 for installing more charging points in this zone compared to other metropolitan districts in the region.  
379 This characteristic has spatial resemblance to the Birmingham study, suggesting majority of the wards  
380 (almost 60 percent) favouring the uptake to be located furthest from the city centre [8]. A general  
381 pattern emerging from these studies, that can be extended to other cities across the globe, suggest  
382 hotspots of early PEV adoption intensity to be dominant in the inner suburban pockets, closer to a  
383 major city (i.e. <15 minutes of travel time).

384 <Place Figure 4 here>

385 The next step analysis involved classification of City Adventurers mosaic type in the Tyne and Wear  
386 region. Due to the high NS-SeC rating when collecting the census data, the largest concentrations of  
387 the City Adventurers were mostly located in similar areas to the New Urban Colonists in Newcastle  
388 and on the mid-eastern flanks, albeit representing greater population densities (Figure 4). The  
389 neighbouring districts were again noted to make only a minor contribution to the target demographics  
390 for early PEV uptake. However, the corridor of a motorway (the A19 situated on the borders of  
391 Holystone and Valley) showed significantly high levels of City Adventurers compared to the rest of  
392 the Tyne and Wear region (93 City Adventurers compared to a regional mean of 14 per census output  
393 area). This essentially reflects the dominant influence of young professionals residing in such  
394 locations closer to motorway for convenience of commuting to workplaces in satellite towns and  
395 neighbouring business districts, using link routes.

396 < Place Figure.5 here>

397 Mapping Corporate Chieftains through census data set was particularly challenging, mainly owing to  
398 unavailability of data sets that could co-determine spatial distribution of detached houses as well as  
399 location of population with the highest NS-SeC rating. This was overcome by combining two separate  
400 data sets in a GIS layer, symbolising the most likely locations of this mosaic type. The outputs suggest  
401 this resident group to be predominantly occupying peri-urban locations, marked with lower population  
402 densities compared to New Urban Colonists and City Adventurers cohorts (and in some wards with  
403 nil values) (Figure 5). This is in agreement with the number of detached housing in the census output  
404 areas being moderately correlated with the highest ward totals of NS-SeC category 1 rankings. This

405 category was considered as the strongest cohort for early PEV adoption, independent of PCP  
406 infrastructures. Nevertheless, this information was deemed essential for developing a cost-effective  
407 installation plan, diverting resources to alternative locations instead of reinforcing PCPs in such areas  
408 with lower demand for on-street PCPs.

409

### 410 ***3.2 Charging Infrastructure Development***

411

412 Having established the spread of potential early PEV users into the three earmarked cohorts in the  
413 study region on the basis of the adopted methodological framework, the next step of the analysis  
414 involved ascertaining the share of those users who would be directly benefitted from setting up of  
415 PCPs. An elimination approach was applied, first establishing the spatial distributions of users with  
416 private charging facility on their premises, followed by a detailed analysis of potential locations for  
417 PCPs through weighted-overlay spatial statistics, using a combination of criteria listed in Table 2  
418 (Section 2.3.3).

419

420 The private charging hotspots (Figure 6) seem to map quite closely onto the spatial distribution of  
421 Corporate Chieftains, as this cohort was characterised jointly by the ownership of detached houses  
422 and possession of multiple vehicles (see Figure 1). The output zones were mapped alongside the  
423 major road network, the location of park and ride facilities (large circles) and the regional centres of  
424 commercial interest (stars; as defined in Section 2.3) in the case study area. As discussed in Section  
425 3.1.2, it can be clearly noted that private PEV charging potentials are higher in peripheral residential  
426 locations, close to the main city centre but away from the park and ride and regional centres.  
427 Interestingly, the potential zones for locating PCPs, output from the weighted-overlay spatial  
428 statistics, show complete contrast (Figure 7) and somewhat complementary to the spatial distribution  
429 of private charging locations.

430 *<Place Figure 6 here>*

431

432 Based on the spatial assessment in Figure 7, two categories of potential PCP locations, of particular  
433 relevance to both the New Urban Colonists and the City Adventurers, were noted: one, inner-city  
434 residential locations; two, out-of-town parking lots and commercial centres. The ground validation  
435 exercise, utilising the interview questionnaire (Section 2.3.4), indicated a good agreement with our  
436 spatial mapping from multi-dimensional analysis. Out of the total sample population (N=37) the  
437 majority of respondents were Corporate Chieftains (i.e. owning detached houses) who expressed their  
438 willingness to buy either a second car operating on BEV technology alongside their main vehicle  
439 operating on conventional fossil technology or investing in PHEV technology. In both cases this  
440 group of respondents were interested in using off-street trickle charging facilities on their own  
441 premises. On the other hand, the respondents with no ‘home-charging’ facilities were relatively  
442 smaller in number (N=11) and clearly expressed the limitation of parking space for more than one car  
443 and their unwillingness to install charging socket at home despite their interest in adoption of PEV  
444 technology. This was inferred as their motive of getting PEV as their main car with sole reliance on  
445 PCPs (either on-street in public bays or in work places) for their charging needs. The following  
446 sections describe the design recommendations for these two categories of PCPs and their potential  
447 usage. Apart from serving the users with restricted off-street charging facilities (identified above) it is  
448 envisaged they would be useful for Corporate Chieftains as either ‘top-up’ charging or as ‘visible  
449 comfort for curbing the range anxiety’ issues and would also offer charging provisions to long-  
450 distance car users travelling to the region from other parts of the country.

451 <Place Figure 7 here>

452

### 453 3.2.1 Inner-city locations

454 Depending on their locations, PCPs in inner-city regions are aimed to cater to the needs of the local  
455 residents as well as shoppers and employees. We have shown a high proportion of the early PEV  
456 users to be residing in inner-city regions, typically New Urban Colonists and City Adventurers with  
457 limited off-street parking. In these locations it would be crucial to provide access to on-street PCPs.  
458 Otherwise, although it has been concluded that early uptake of PEVs in such areas is likely, the lack

459 of overnight charging could become a significant deterrent for mass uptake. For effective  
460 implementation, ideally each residential street with high uptake potential would have to be installed  
461 with PCPs. This would serve two purposes - one, generate PEV awareness and best practice; two,  
462 provide a dedicated parking space for PEVs which would be highly beneficial for end users  
463 overcoming the insecurity issues in finding parking space in such areas [30]. It is envisaged, both  
464 these initiatives in turn would potentially induce further PEV uptake.

465

466 Implementation plans for developing dedicated PCPs, especially for on-street charging, are already  
467 well underway for inner London as part of ‘on-street parking location plan’ [32]. These designs have  
468 prioritised both good visibility and good access to the parking bay for promoting early uptake. Such  
469 PCPs are located at either end of terracing, primarily because the end bay offers good visibility and  
470 easy access for users. In addition, high footfall from any adjoining main road is also potential for  
471 developing highly visible PCPs, creating further awareness. Overall, such infrastructure design is  
472 aimed to raise awareness and create growth in the PEV market. For practical reasons the locations of  
473 such on-street PCPs in residential areas would be more appealing than those situated in isolated car  
474 parks. In addition, access to overnight charging would be also relevant to the economy of PEV users  
475 through provision of off-peak tariff.

476

### 477 *3.2.2 Peri-urban locations*

478 The consumers of public PCPs in peri-urban locations would be most benefitted from installations in  
479 public car parks, park and ride facilities and regional centres of amenities, business parks, and local  
480 supermarkets. This would potentially also instigate usage by local residents frequenting these  
481 locations, specifically combining with the shopping and leisure activities. As shown in Figures 3 and  
482 4, one of the most highly populated areas for New Urban Colonists and City Adventurers in the study  
483 area is located in the top-central part of the region, just on the outskirts of Newcastle. These areas  
484 have several park and ride facilities (Figure 1) which hold huge potentials for enhancing the PEV

485 uptake to the target groups living in these locations with shortage of off-street charging facilities.  
486 Typically, following the London guidelines on ‘public car park location plan’ [32], up to two PCPs  
487 are recommended as best practice for installation in public car parks (usually recommended to be  
488 close to entrances or exits). This is in agreement with earlier studies recommending installations of  
489 PCPs in workplace parking, park and ride sites, retail areas and leisure facilities [8,11]. However, it  
490 has been suggested that cities should only design PEV strategies suiting their individual  
491 circumstances, mainly socio-demographics and parking availability [11].

492

493 The abovementioned implementation plans for developing dedicated PCPs can be extended to other  
494 global cities with similar urban driving patterns as discussed in Section 3.1. Combining this initiative  
495 with adequate provision of local renewable energy supply in peri-urban regions (e.g. wind, biomass,  
496 tidal) would facilitate building of a ‘balanced system’ for charging PEVs, supported by local energy  
497 from renewable sources. Some sites in the region can be classed as high value commercial locations  
498 for installing PCPs, which apart from serving the requirements of the two earmarked cohorts relying  
499 on public charging, would also generate further awareness and appeal for rapid PEV uptake in the  
500 region. Further, as can be noted from Figure 1, a number of hotspot locations serve as major  
501 commercial hubs in the region, thus strengthening the awareness for potential early adopters by  
502 appropriate selection of installation sites within these car parks.

503

#### 504 **4. Conclusions and Future works**

505 Implementation of a well distributed PCP infrastructure is essential, both for supporting PEV drivers  
506 and for promoting a sustainable PEV market. In terms of public infrastructure development, especially  
507 borne out of the current austerity measures, strategic PCP locations would pave way for furthering the  
508 PEV agenda by reducing the range anxiety while facilitating on-street charging solutions. Crucial to  
509 the successful implementation of PCPs, however, is the availability of information on the projected  
510 spatial profiling of would-be PEV users who are lacking off-street charging.

511

512 This study adopted a multi-dimensional spatial modelling framework, utilising a combination of  
513 socio-demographic traits and travel patterns, to determine hotspots of PCP locations for a city-region.  
514 The applicability of this approach was demonstrated through a case study, utilising real datasets for  
515 the city-region of Tyne and Wear County in the North-East England. In the absence of any established  
516 metrics a combination of indicative census statistics were used to identify three categories of potential  
517 PEV users – New Urban Colonists, City Adventurers and Corporate Chieftains. These cohorts are  
518 considered as representative of typical city dwellers interested in adopting low-carbon transport  
519 measures.

520

521 Our study showed the capability of the modelling framework to predict the spatial distribution of  
522 private and public charging needs across a city-region, based on assumptions of early PEV adoption  
523 potentials. Locating zones with high private PEV charging potentials were helpful in demonstrating  
524 the non-urgency for installing PCPs in these locations, as it is anticipated such households will have  
525 access to overnight charging on their private premises. Specific to innovation in urban planning, our  
526 study showed two categories of potential PEV users utilising PCPs. First, a general uptake potential in  
527 the inner-city residential pockets with on-street parking, marked by New Urban Colonists and City  
528 Adventurers. These areas were identified as worthy of public infrastructure development in the  
529 targeted wards in the immediate future. Second, out-of-town public parking facilities, covering non-  
530 residential premises with opportunities for promoting PEV charging in parking bays or at park and  
531 ride facilities. We consider the multi-criteria assessment framework applied to this study equally  
532 extendable to other metropolitans and megacities across the globe with comparable socio-  
533 demographics and travel patterns (primarily commuting using personal transport). It is also felt that  
534 apart from serving the first generation of PEV users the extensive development of PCPs will also  
535 reduce range anxiety for those considering purchasing into the market. However, this study mainly  
536 demonstrated an integrated approach for linking the socio-demographics with forecasting of the  
537 hotspots of PEV uptake using geo-spatial analysis. The spatial analysis provides key insights into PCP  
538 allocations in the case study area. While extending this exercise to other cities it is recommended that  
539 the assessment framework is customised to utilise the publicly accessible statistics in a similar

540 hierarchical structure in order to retain the effectiveness of the multi-dimensional analysis. In  
541 addition, a detailed roll out plan warrants further assessment of the implementation costs of installing  
542 PCPs at preferred locations. This would involve decision on the distribution and the kind of PCPs to  
543 be located, applying the principles of spatial economics. For example, location theory could be  
544 utilised to address the following specific operational questions: How many and what type of PCPs  
545 would be required? What precise location and design would optimise the economy of scale and multi  
546 functionality? What would be the total cost of such a system? All this has to be targeted in potential  
547 PEV uptake areas serving the two cohorts - New Urban Colonists and City Adventurers - where  
548 public charging point installations is found to provide the most impact.

549

## 550 **5. Acknowledgements**

551 We would like to acknowledge the contributions from Transport for London for their guidance in  
552 implementation of public charging infrastructure. Acknowledgements are also due to the anonymous  
553 reviewers for their pertinent inputs towards enhancement of the manuscript and to David Alderson,  
554 Geomatics researcher at Newcastle University for his technical assistance in the spatial analysis. The  
555 UK EPSRC Sustainable Urban Environment – Self Conserving Urban Environment (SECURE)  
556 project (grant ref. EP/I002154/1) supported some part of this research.



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**Figure 2.** Car commuter destinations across the Tyne and Wear region (map source: UK Ordnance Survey, Crown copyright).

**Figure 3.** Location of New Urban Colonists mosaic class (map source: UK Ordnance Survey, Crown copyright).

**Figure 4.** Location of City Adventurers mosaic class (map source: UK Ordnance Survey, Crown copyright).

**Figure 5.** Factors predicting Corporate Chieftains location (map source: UK Ordnance Survey, Crown copyright).

**Figure 6.** Spatial plot showing the outputs from weighted overlay statistics for private charging locations [note: the favourable locations are shown alongside the road network, park & ride locations and region centres] (map source: UK Ordnance Survey, Crown copyright).

**Figure 7.** Spatial plot showing the outputs from weighted overlay statistics for public charging locations [note: the favourable locations are shown alongside the road network, park & ride locations and region centres] (map source: UK Ordnance Survey, Crown copyright).

Fig 1

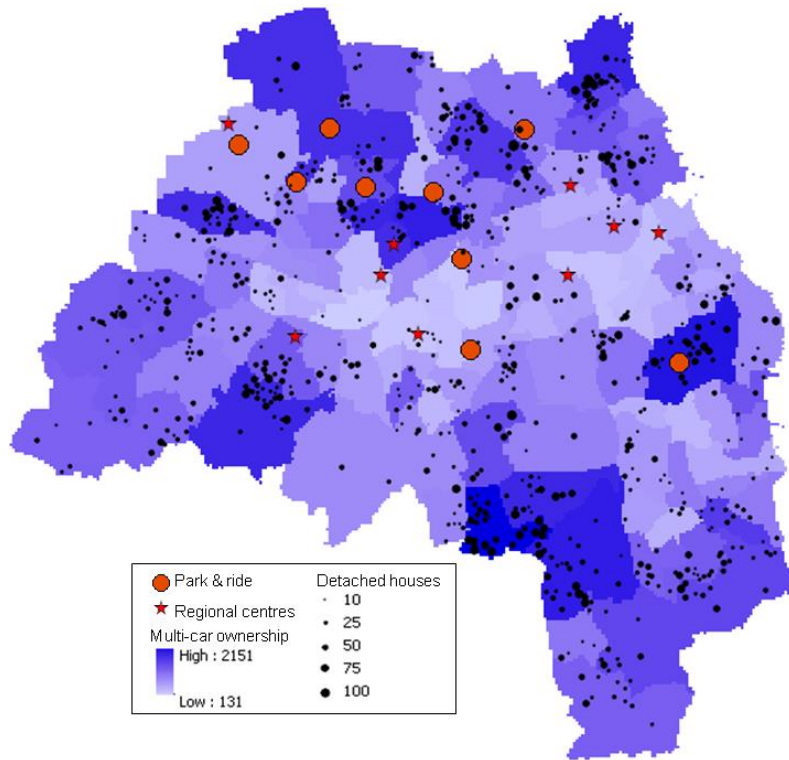


Fig 2

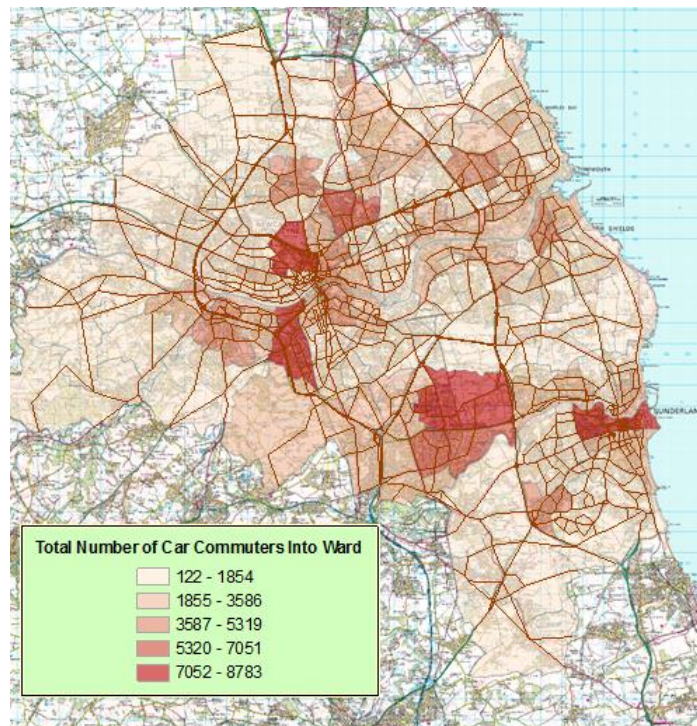


Fig 3

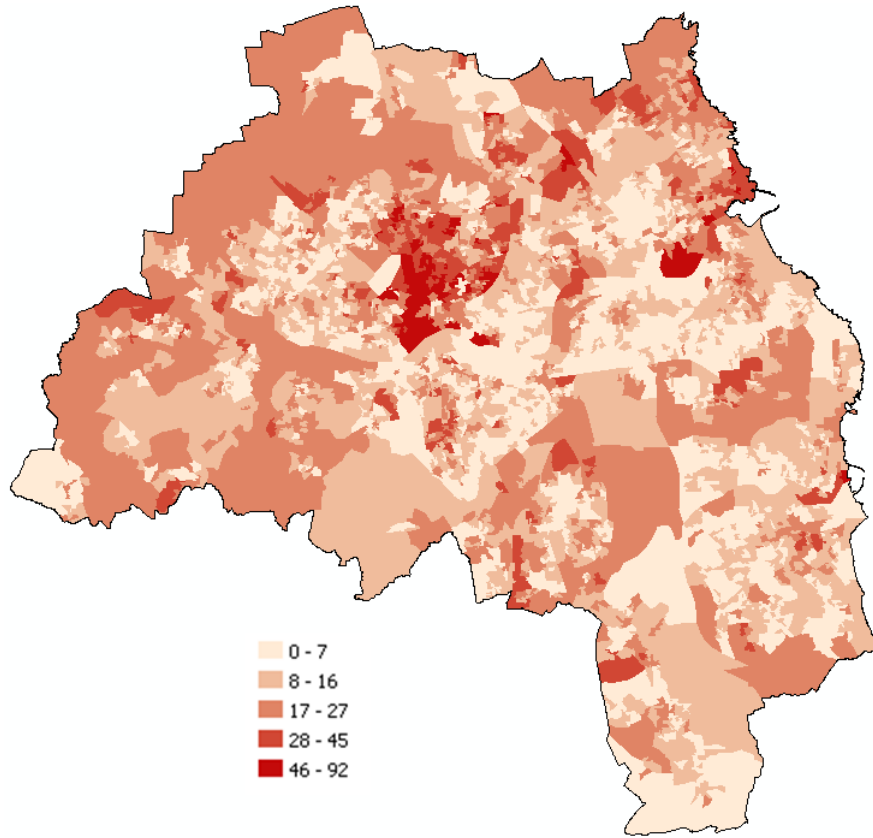


Fig 4

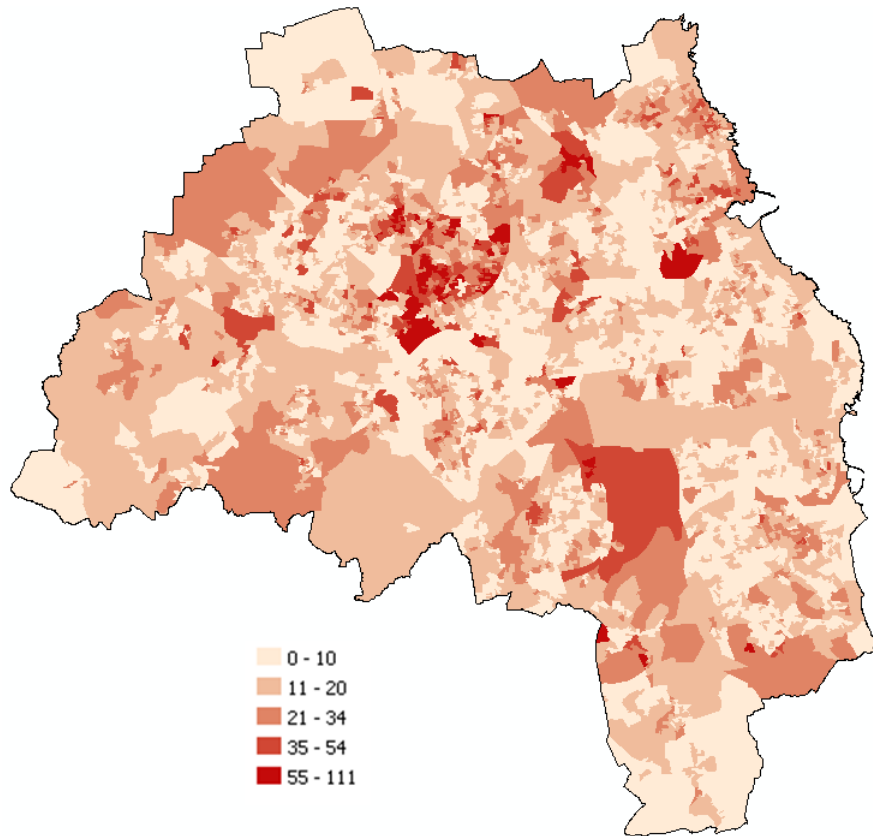


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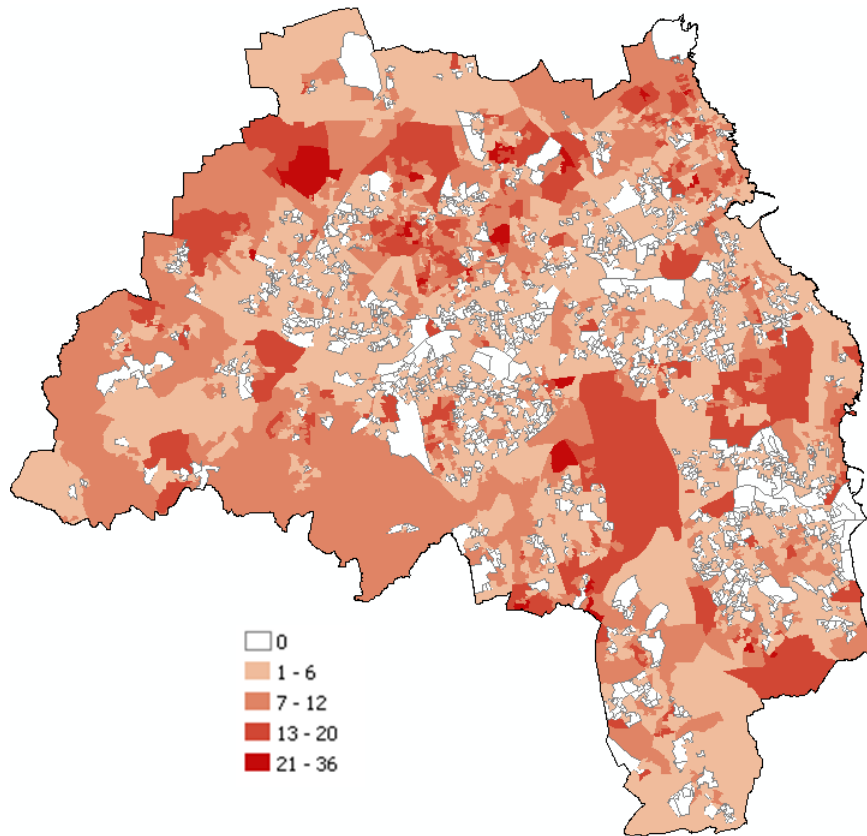


Fig 6

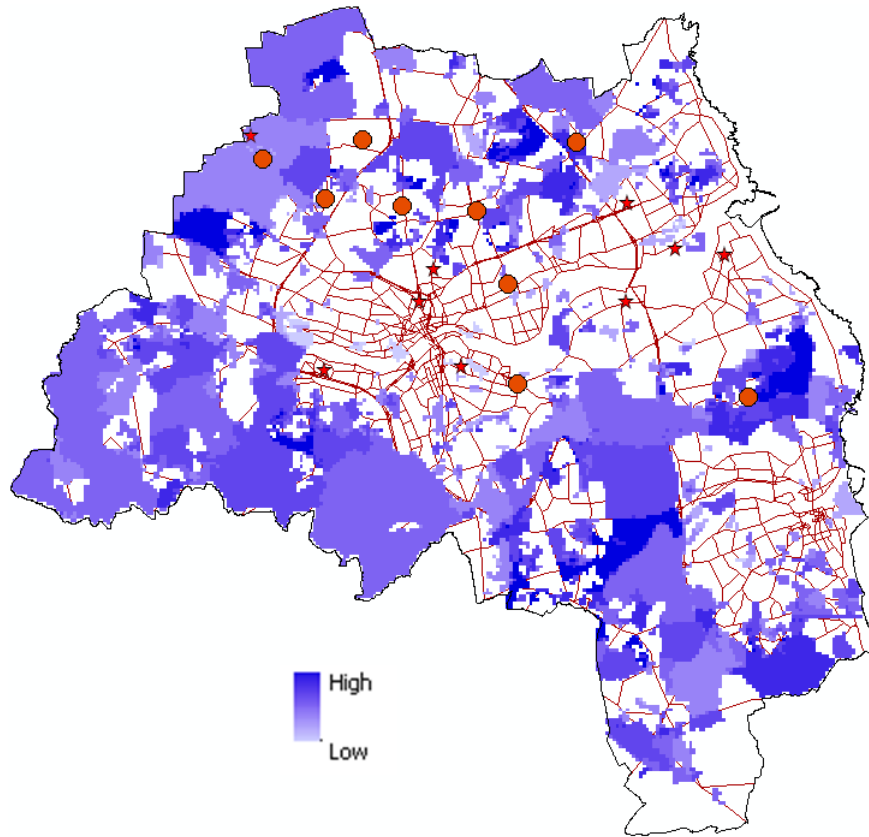


Fig 7

