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

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## 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. Introduction

Alternative fuelled vehicles (AFVs) are expected to play a major role in decoupling transport's ~93% dependence on liquid fossil fuels, through diffused adoption of both Plug-in electric vehicles (PEVs) and hydrogen fuel cell vehicles [1]. PEVs in particular, including both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), have the potential to improve the energy and environmental landscape of personal transportation over the next decade. However, absence of a proactive plan and schedule for charging infrastructure is a major impediment to mass market adoption, particularly pertinent to BEVs due to their sole dependency on electricity, range limits, and long recharging time [2]. In this context development of a coherent policy in the area of electric mobility (i.e. E-mobility) is being increasingly considered as a viable investment in offsetting transport-related climate change effects associated with conventional vehicles over near-term [3]. An analysis of developments in electric vehicles before and after 2005 suggests the diffusion of E-mobility configuration in recent years to be largely dependent on infrastructural investments [4]. Consumer surveys from across different global markets indicate that lack of refuelling infrastructure is going to be a major deterrent for adoption of AFVs [5,6]. The UK Department for Transport (DfT) has set up an Office for Low Emission Vehicles (OLEV), committed to development of an ultra-low emission vehicle market – facilitating better energy security while addressing issues related to $CO_2$ emissions and air quality in cities [7]. However, the current drive for securing the future of mobility through electrification, at least over the short to medium term, is faced with technological, infrastructural and behavioural hurdles that need to be overcome in order to enable mass market penetration [8].

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

2

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'

4

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,

10

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

former two groups suggested to be relying heavily on deployment of PCPs [33] while the latter group was assumed to only use PCPs, especially those located at workplace, for top-up and emergency charging. The outcome of this analysis informed zoning of suitable charging point locations, both within the residential areas, and the earmarked parking hubs and commercial centres. The feasibility assessment followed the recently published UK National Planning Policy Framework guidance for green transport (i.e. potential for reducing environmental impact, mainly $CO_2$ emissions compared to equivalent standard vehicles depending on the embodied energy of the vehicle and the source of the electricity) on encouraging local authorities in incorporating PEV charging infrastructure at suitable sites as well as developing policies for embedding recharging infrastructure within new workplace developments [35].

*2.3.3 Weighted overlay analysis*

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

The layers of spatial information were overlaid to assess the favourable hotspots for PCP infrastructure. In order to reduce the investment costs it was considered necessary to first filter out the 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

13

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**

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