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1 **Land-use, transport and vehicle technology futures:**
2 **An air pollution assessment of policy combinations for the**
3 **Cambridge Sub-Region of the UK**

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34

35 **Highlights**

- 36 • Impact on air quality of combinations of urban form and vehicle technology explored;
- 37 • Application of integrated model chain addressing land use-transport-interaction, traffic
- 38 emission and dispersion modelling;
- 39 • Urban compaction reduces regional GHG (13%) and local air quality emissions (up to
- 40 9%);
- 41 • Expansion and Market-led policies increase regional GHG (7%) and air quality emissions
- 42 (up to 7%);
- 43 • Air quality deterioration in urban centres under Compaction occurs but can be offset by
- 44 technology.
- 45

46 **Abstract**

47 This paper reports on an investigation of the impact on air-quality of combinations of urban
48 form development scenarios and vehicle fleet technology changes. The scenarios combine
49 policies affecting urban land-use plans within the Cambridge Sub-Region of the UK,
50 alongside technological changes within the projected vehicle fleet. Broadly, the scenarios
51 consist of the 'Trend' for urban form policy and vehicle technology and the urban form policy
52 options of 'Planned expansion', 'Market-led development' and 'Urban compaction', each
53 combined with form-appropriate technological scenarios addressing the uptake of current,
54 and future, technologies in the vehicle fleet. The framework developed for environmental
55 assessment is described, from land-use transport interaction, through traffic assignment and
56 emissions modelling, through to dispersion calculations.

57 The urban form-vehicle technology combinations have been assessed in terms of overall
58 vehicle kilometres travelled (VKT), greenhouse gas (CO₂) emissions, and local air quality
59 (NO_x, NO₂, PM, HC). Results are presented for 2021 and show that overall network
60 emissions change from -13% (Compaction) to +8% (Market-led) relative to the Trend, but
61 effects on emissions in individual districts (NO_x) may much greater, -40% to +50%. Annual
62 mean concentrations of NO₂ at the street level may vary by -7 to 8 µg/m³. The use of electric
63 vehicles in the 'Urban compaction' scenario aids mitigation of air quality issues in the city
64 centre. The results are discussed with respect to the feasibility of scenario implementation,
65 current approaches to planning, and trends in vehicle technology. Limitations of the
66 modelling framework are also identified, and future developments outlined.

67 **1. Introduction**

68 **1.1 Urban form and air quality**

69 There has been much debate in recent decades over how urban form can impact
70 transportation behaviour and environmental quality. It has been argued that dispersed
71 patterns of living and decentralised employment, enabled by ready access to private
72 transportation, increase vehicle kilometres travelled (VKT) (Newman and Kenworthy, 1989;
73 Glaeser and Kahn, 2001), resulting in exacerbation of negative externalities including air
74 pollution (Cervero and Kockelman, 1997; Pourahmad *et al.*, 2007; McCarthy and Kaza,
75 2015). Such reasoning has led to the conclusion that urban compaction offers a solution, by
76 promoting shorter trips and modal shift to public transport (Litman, 2007), reducing overall
77 emissions. For example, Stone *et al.*, (2007) suggested a 10% increase in urban population
78 density would lead to a 3.5% reduction in VKT and emissions. .

79 However, Melia *et al.* (2011) present a counter argument, known as the 'Paradox of
80 Intensification' that arises due to the relationship between population density and vehicle use
81 being rather inelastic, as confirmed by an extensive TRB (2010) review of this relationship

82 that finds a doubling of urban density reduces VKT, on average, by only 5%. The paradox
83 then arises that urban compaction reduces VKT and so is beneficial in terms of reduction in
84 global pollutant (CO₂) emission, but is detrimental in terms of local pollution (e.g. NO₂,
85 particulates) as traffic intensity increases on capacity-constrained networks in urban centres,
86 often accompanied by localised congestion, and elevated pollution levels that can offset any
87 form-achieved gains.

88 Understanding the nature of the intensification paradox clearly requires that assessment
89 goes beyond a consideration of emission to address pollutant concentration that is important
90 to exposure and health impact. This is complex to determine, having dependency on
91 specific, local factors such as on-street travel patterns, meteorological conditions and canyon
92 morphology (Borrego *et al.*, 2006; Martins, 2012; Yuan *et al.*, 2014; McCarty and Kaza,
93 2015). In addition, the paradox is sensitive to geography, as the most problematic pollutants
94 at local level vary (Chen *et al.*, 2011; Fan *et al.*, 2018). Cities in the UK and northern Europe
95 tend to have most issues with compliance to nitrogen dioxide (NO₂) standards (DEFRA,
96 2018; EEA, 2018), whereas those in Eastern Europe and Asia have greater problems with
97 particulate matter (Tasmin, 2019) due to differences in source types and mixes, fuels and
98 technologies. Furthermore, understanding how air quality varies across the city, where local
99 morphology and density varies is complicated by processes of transboundary pollution
100 movement (Ramaswami *et al.*, 2008), the photochemistry between oxides of nitrogen and
101 ozone (Borrego *et al.*, 2006; Stone, 2008), and formation of secondary particles from nitrates
102 and sulphates. Some of these factors can be addressed via a very dense network of
103 monitoring sites, but this is generally impractical, hence atmospheric dispersion modelling,
104 which is capable of addressing such complexities is required. However, to date such models
105 have been little used in the exploration of urban form effects on air quality.

106 **1.2 Urban form, air quality and technology**

107 Our prior work on sustainability appraisal of urban form within its regional context (Echenique
108 *et al.*, 2012), modelled emissions but not atmospheric concentrations, and revealed a
109 relatively weak influence of urban form on CO₂ emissions, given a context of strong growth
110 pressure and long run social and economic pressures, and hence we argued that:

111 “Smart growth principles should not unquestioningly promote increasing levels of
112 compaction on the basis of reducing energy consumption without also considering its
113 potential negative consequences”, and that “CO₂ reductions may be better pursued
114 through technological improvements.” Echenique *et al.*, (2012)

115 The role of technology in delivering a more sustainable city is gaining more widespread
116 attention, and indeed, is changing the perception of what a sustainable urban form might be.
117 For example, in a life-cycle assessment study of the Greater Helsinki region, Heinonen *et al.*
118 (2011) found that the city of Espoo, with a lower density than Helsinki city, was becoming
119 lower carbon emitter (per capita) than its neighbour, due to the greater potential to
120 implement renewable energy technologies (solar capture, heat pumps etc) including those

121 needed to power electric vehicles (a higher consumption of material goods in Helsinki city
122 also partly explained the observations). This contrasts to those prior studies, which do not
123 incorporate technology effects and conclude compactness is most able to deliver low carbon
124 urbanisation (e.g. Glaeser and Khan, 2010).

125 The role of technology in city sustainability has long been of interest to those concerned with
126 urban form (see Brotchie *et al.* 1985) yet form-technology combinations are challenging to
127 investigate so relatively under- studied. The internal combustion engine radically altered
128 cities in the past, and we can similarly anticipate that new 'disruptive technologies' will alter
129 forms in the future. In the transport sector technology mediated interests include:
130 electrification of road transport, 'intelligent' mobility (such as 'Mobility as a Service' - MaaS),
131 and automation of the driving task (Manyika *et al.*, 2013). Electrification in the medium to
132 long term may result in on-street air quality benefits, although this appears dependent on
133 how and where that electricity is generated (Yu and Stuart, 2017).

134 In addition to these technological 'game changers', air quality problems have resulted in a
135 European regime of both mandated continual improvements to new internal combustion
136 engine vehicles (the 'Euro standards', ACEA, 2018), as well as developments of retrofit
137 solutions (e.g. particulate filters and de-NO_x catalysts) for existing vehicles. Internationally,
138 these Euro standards have been adopted elsewhere, for example the Bharat stage
139 emissions standards in India (ICCT, 2016), and in the "Jing" standards in the Chinese capital
140 (Transport Policy, 2018). Consumer choice is also turning against light diesel vehicles
141 (SMMT, 2018) due to concerns over NO_x emissions, leading to changes in UK Vehicle
142 Excise Duty (colloquially 'Road Tax') (Gov.uk, 2018), even though such vehicles have
143 historically been more fuel efficient than comparable petrol vehicles. Whilst elements of fleet
144 turnover and on-vehicle technologies are routinely incorporated into air quality studies, their
145 application within urban form appraisal, remains a novel topic for study.

146 Our prior work on sustainable urban form (Echenique *et al.*, 2010; Mitchell *et al.* 2011;
147 Echenique *et al.*, 2012) examined the sustainability of current and proposed spatial planning
148 strategies in the UK. We used Land-Use/Transport Interaction (LUTI) modelling to drive a
149 multi-criteria sustainability appraisal of radical, but realistic, alternative urban forms, with an
150 analysis of three UK regions: London and the Wider South East, Tyne and Wear, and
151 Cambridge Sub-Region. This work indicated the challenge to sustainability posed by rapid
152 urban growth, but indicated the potential for sustainability gains, through appropriate
153 combinations of urban form and technology, that were greater than those possible with urban
154 form policies alone (Echenique *et al.*, 2012). Our analyses addressed global and local
155 emissions but stopped short of addressing implications of form-technology combinations for
156 air quality. Therefore, in this paper we report on work, for Cambridge and its sub-region, that
157 examines the impact of packages of measures comprising of complementary urban forms,
158 transport schemes and vehicle technologies. We assess impacts in terms of VKT, global and
159 local emissions, and local air quality (PM, NO_x, NO₂ and HC).

160 **2. Modelling Methodology**

161 The modelling methodology and framework we employ, builds on the tools and outputs of
162 the SOLUTIONS project (Echenique et al, 2010). Figure 1 outlines the modelling framework,
163 where grey boxes represent elements inherited from SOLUTIONS, whilst blue boxes
164 represent the novel elements discussed in this paper. In brief, the four tools used were: 1)
165 the MENTOR land use/transport interaction model (Echenique *et al.*, 2010); 2) The tactical
166 traffic model SATURN (Simulation and Assignment of Traffic in Urban Road Networks) (Hall
167 *et al.* 1980); 3) The data extraction and emissions calculation tool PITHEM (Platform for
168 Integrated Transport, Health and Environmental Modelling) (Namdeo and Goodman, 2012)
169 and 4) The air-quality dispersion model ADMS-Urban (McHugh *et al.*, 1997). The operation
170 of each of these components is briefly outlined below. ESRI's ArcGIS software (ESRI, 2011)
171 was used to visualise outputs from each.

172 ***Figure 1: Modelling framework adopted in the ReVISIONS project***

173 **2.1 Land Use/Transport Interaction and Transport Modelling**

174 MENTOR is a windows-based version of the MEPLAN model (Echenique *et al.*, 2010;
175 Echenique *et al.*, 2012), and is characterised as a 'spatial-economic LUTI' model (Wegener
176 2004; Simmonds and Feldman, 2011). It estimates the locations of households and
177 employment in zones across a study region, and the transactions between households and
178 employment that generate transport demand (Hargreaves and Echenique, 2008). It models
179 land and labour markets as being in equilibrium for a given time period. In a period, supply is
180 fixed (i.e. land markets are constrained), whilst prices are adjusted so that demand matches
181 supply (Abraham, 1998). An explanation of the structure of the model, and of the steps
182 undertaken in an iteration are presented in Hargreaves and Echenique (2008). The
183 Cambridge-specific MENTOR model (MENCAM) was specifically designed to test
184 combinations of land use and transport policies at the Cambridgeshire sub-regional scale.

185 The SATURN traffic-assignment model serves a two-fold purpose: Firstly, it provides an
186 indication of the inter-zonal costs of transportation during an iteration of the MENTOR model
187 (Hargreaves and Echenique, 2008). Secondly, SATURN-derived, link-based flow and speed
188 information drive the emissions calculations of PITHEM (see below). SATURN is a
189 'mesoscopic' transport model, in that it incorporates two phases: a 'traditional' assignment
190 phase where trips from O-D (Origin-Destination) pairs are assigned network routes, and a
191 simulation phase, in which delays at intersections are calculated (Hall *et al.*, 1980). Iterative
192 assignment using both phases provides a better indication of the effects of congestion on
193 link costs (for MENTOR) and on flow patterns (for PITHEM), than via assignment alone.

194 Given the modelling platform developed in the SOLUTIONS research, use of the coupled
195 MENTOR and SATURN models for the Cambridgeshire region was axiomatic. However,
196 historically, both models have enjoyed considerable use both within the UK and

197 internationally, e.g. see Echenique *et al.* (1990) regarding the use of MEPLAN in three
198 European cities, or Shepherd *et al.* (2006) regarding SATURN in the UK context.

199 **2.2 Emissions and Dispersion Modelling**

200 Emissions modelling was carried out using the PITHEM tool (Namdeo and Goodman, 2012)
201 which generates a link-based emissions inventory from an imported SATURN network.
202 Inventories may be built from a palette of country, road, vehicle and technology types.
203 Different inventories may be applied to pre-defined, spatial-temporal areas, or routes (e.g.
204 between O-D pairs) making the tool attractive for analysing technology based options. The
205 tool contains a database of over 600 vehicle types (defined by chassis-type, fuel, engine
206 size, weight, Euro class and exhaust treatment technology) for inventory definition.
207 Emissions calculations for a particular vehicle are based on application of polynomial speed-
208 emissions curves (see section 3.4). PITHEM has been used successfully on several UK and
209 EU-based projects (Goodman *et al.*, 2014; 2016).

210 Dispersion modelling used the commercial ADMS-Urban model (McHugh *et al.*, 1997;
211 CERC, 2018), a quasi-Gaussian dispersion model, that takes into account meteorology,
212 atmospheric boundary layer structure, height-dependence of wind speed, turbulence and
213 stability, and NO_x photochemistry, and able to calculate concentrations over spatial scales
214 from street to region (CERC, 2018). ADMS is routinely used in the UK for assessment
215 purposes, though it has also seen use in Europe, the United States and Asia (e.g. to study
216 traffic restriction measures associated with the Beijing Olympic Games (CERC, 2018; Cai
217 and Xie, 2010). Numerous validation studies exist (e.g. Owen *et al.*, 2000; Stocker *et*
218 *al.*, 2012; Hood *et al.*, 2018). ADMS was selected for this study based on its demonstrable
219 utility and accuracy for dispersion modelling, and its appropriateness for modelling at the city
220 scale. Conversion of modelled NO_x to NO₂ concentrations was done via post-processing
221 ADMS outputs using the DEFRA conversion spreadsheet (DEFRA, 2012a), in the absence
222 of detailed background ozone information for the sub-region.

223 **3. Study Area and Scenario Design**

224 **3.1 Study Area**

225 Figure 2 shows the area addressed in this analysis, which comprises four district councils
226 including the main population centres of Cambridge (2011 pop. ~123k, area: 116km²),
227 Huntingdonshire (~170k pop., 352km²), as well as South and East Cambridgeshire (~150k,
228 348km² and ~84k, 252km² respectively). In terms of form, the area may be described as
229 monocentric, based around Cambridge itself. Figure 3 shows the main transport links in the
230 area, and the extent of local air-quality modelling (blue inset box). The A1/A1(M) represents
231 a primary North-South corridor in the UK, whilst the A14 is a key East-West corridor, carrying
232 goods to the port of Felixstowe in Suffolk. The southbound M11 feeds into London's North
233 Circular road.

234 Both Cambridge and Huntingdon have declared, central Air-Quality Management Areas
235 (AQMA), and further areas along the A14 between the two settlements. These AQMAs are
236 based on exceedence of annual NO₂ standard (DEFRA, 2018).

237 **Figure 2: Major population centres and baseline extent of urban development in**
238 **Cambridgeshire**

239 **Figure 3: Major transportation routes and corridors in Cambridgeshire**

240 **3.2 Scenarios Tested**

241 The scenarios examined in this paper derive from those previously examined in Echenique
242 *et al.* (2012), and may be summarised as:

- 243 • A 'Trend' scenario, based on policies from the 2003 Cambridge Structure Plan, and;
- 244 • Alternate scenarios based on allocation of households and employment under the
245 principles of 'Compaction', 'Planned expansion' and 'Market led dispersal'.

246 The scenarios considered in SOLUTIONS are summarised in Table 1 with a brief generic
247 description and specifics for the Cambridge study area. Further information may be found in
248 Echenique *et al.*, 2010 and 2012. Each alternate scenario is considered 'a response to
249 differing views on what should be the priorities for urban development' (Echenique *et al.*,
250 2010) and 'designed to be as distinct as possible from the trend to show their benefits and
251 disadvantages (Echenique *et al.*, 2012). As with the 'Trend' scenario, the base year is 2001
252 with a modelled target year for the alternate scenarios of 2021.

253 **Table 1: Urban form scenarios considered (Echenique *et al.*, 2010)**

254 Data driving the LUTI scenarios was sourced from the Cambridgeshire County Council
255 (CCC) MENCAM model (Echenique *et al.*, 2012). This was calibrated using 1990's socio-
256 economic data, with some updating using 2001 household and employment data. The
257 SATURN networks were also provided by CCC and used in the second 'Cambridge Futures'
258 study (Echenique and Hargreaves, 2008), as well as in SOLUTIONS.

259 **3.3 Technology Packages**

260 The technology packages selected were tailored to each scenario based on what were
261 considered feasible adoption rates for those technologies (Wright, 2012), but also to highlight
262 distinctions between option. Two compaction options were tested, Compaction and
263 Compaction+, with the latter favouring the uptake of electric vehicles within the centre of
264 Cambridge. Each technology package was applied by building an appropriate emissions
265 inventory in the PITHEM tool, then processing the LUTI/SATURN outputs via PITHEM, into
266 an ADMS-Urban input deck. Required data was drawn from a number of sources. Fleet
267 proportions, based on scrappage of old vehicles and uptake of new vehicles, used for the
268 Trend scenario, and as a basis for the alternate scenarios, were taken from Venfield and
269 Pang (2012). Speed-emissions curves for the inventories were taken from the UK Emissions

270 Factors Toolkit V5.2c (DEFRA, 2013). Modifying (scaling) factors for alternate fuel and
271 hybrid vehicles were derived from Murrells and Pang (2013), and further fuel economy
272 savings for freight and public transport vehicles were adapted from Li *et al.* (2009). Diurnal
273 and seasonal emission scaling factors were from the Department for Transport (DfT, 2013).

274 **Table 2: Vehicle technology options applied to the 2021 urban form scenarios**
275 **(Echenique *et al.*, 2010; Wright, 2012).**

276 **3.4 Dispersion modelling**

277 The ADMS model was run over a 10km x 10km grid, with cell dimensions of approximately
278 125m x 125m, over the blue box area in Figure 2. Additional background (ambient) pollution
279 information, and concentrations arising from non-traffic sources were taken from DEFRA
280 background maps (DEFRA, 2012b). Meteorological information was sourced from the UK
281 Met Office from the Monkswood station, to the north of Cambridge, as the closest available
282 site.

283 **4. Results**

284 **4.1 Vehicle Kilometres Travelled and Emissions**

285 Results from the Trend 2021 scenario were first compared to a baseline 2001 scenario. Total
286 vehicle kilometres travelled (VKT) would increase by +11.5%, but technology changes in the
287 fleet resulted in projected CO₂ emissions falling by -16%, PM₁₀ by -37% and NO_x and HC
288 emissions by over -80%. However, primary NO₂ emissions only fell by -9%. Over the same
289 period and region, the SOLUTIONS project (Echenique *et al.*, 2012) showed increases in
290 CO₂ emissions of 16% for the transport and building energy sectors for the Cambridge sub-
291 region. The fall in CO₂ emissions reported here are due to more aggressive assumptions on
292 fuel consumption improvements to light-duty IC vehicles than were present in the EFT
293 emissions figures (DEFRA, 2013) in the light of European Union CO₂ targets, than in the
294 SOLUTIONS modelling.

295 **Table 3: Network performance (absolute values) of alternate planning scenarios**
296 **relative to the Trend scenario**

297 Table 3 provides the results for the 2021 urban form-technology scenarios, with reductions
298 compared to the 2021 Trend scenario shown as negative values. These results are further
299 illustrated in Figure 4 with results for each scenario (dashed lines) plotted relative to the
300 Trend case (solid blue line). Note that the change in pollutant emissions associated with the
301 scenarios falls into a relatively small range (-12.7% to +7.1%), although these variations in
302 emissions are greater than the changes in vehicle kilometres travelled (-4.2% to +4.7%).
303 This indicates that the vehicle technologies have a larger impact on emissions than the
304 changes in urban form alone, consistent with the findings of Echenique *et al.* (2010, 2012),
305 and Mitchell *et al.* (2011). Furthermore, note that the SOLUTIONS modelling for Cambridge

306 found that, for the 2021 urban form scenarios (with conventional fleet technology), carbon
307 dioxide emissions varied from Trend by only $\pm 4\%$ for the sub-region as a whole, much less
308 than the -13% to $+7\%$ observed here where newer clean technology is represented in the
309 fleet.

310 Figure 5 presents the spatial distribution of the uCO_2 emissions intensity (emission/area)
311 across the sub-region for the Trend scenario. Cambridge City Centre is clearly visible
312 towards the lower right of the sub-region, as is the town of Huntingdon to the north-west. The
313 junction of the M11 and A14 at Girton (part of the A14 Corridor AQMA) also represents an
314 emission 'hot-spot'.

315 ***Figure 5: Intensity of CO₂ emissions across the modelled sub-region***

316 Figure 6 presents the change in total NO_x emission for each scenario relative to Trend. The
317 'Compaction' and 'Compaction+' options reduce NO_x emission (by up to 40%) in the areas
318 north, east and south of Cambridge and around Huntingdon. Unfortunately, these areas are
319 not Air Quality Management Areas (AQMAs), but increases in Cambridge City may be in
320 AQMAs (emissions in West Chesterton and Market wards increases up to $+50\%$). The
321 'Compaction+' option limits the maximum increase to $+45\%$.

322 The Dispersal option increases emissions, primarily in wards north of the city (especially
323 those bordering the A14 between Cambridge and Huntingdon) and to the south (in Queen
324 Edith's, Shelfords and Stapleford, Harston and Hauxton wards). The Planned Expansion
325 option gives more marginal changes (-9% to $+17\%$) across the study region, with the
326 greatest increases again along the A14 corridor to the west of Cambridge. Maps for the other
327 pollutants show the same general spatial patterns were observed, though actual percentage
328 changes in each zone differed. Changes in PM and NO_x/NO_2 were more sensitive in those
329 zones carrying a greater relative proportion of heavy duty traffic, whilst larger changes in
330 HCs and overall uCO_2 were observed in areas carrying a greater relative number of light
331 duty vehicles.

332 Note that the mass-based changes in emissions (Table 3 and Figure 4), plus the spatial
333 analyses in Figures 5 and 6, present only a partial picture of the atmospheric impact of the
334 planning scenarios – concentrations of NO_2 within Cambridge itself are described in the next
335 section.

336 ***Figure 6: Spatial changes in NO_x emissions across Cambridgeshire, relative to the***
337 ***'Trend' scenario (Anti-clockwise from top left: Compaction, Compaction+, Planned***
338 ***Expansion, Market-led Dispersal)***

339 **4.2 Spatial changes in air pollutant concentrations**

340 Given that local air-quality problems associated with NO_x/NO_2 that are present in the area,
341 and which are generally limited to within 200m of major roads, it is appropriate to consider
342 how the urban form-vehicle technology combinations also impact upon air quality. This

343 analysis, not conducted under SOLUTIONS, used ADMS to model changes to near-road
344 pollutant concentrations. Concentrations for 2001 were first modelled, and annual mean NO₂
345 levels were observed in excess of the prevailing 40µg/m³ annual mean standard, for areas
346 around the city centre, within the inner ring road. Figure 7 illustrates changes to annual mean
347 NO₂ concentrations for Cambridge (see Box area in Figure 2).

348 **Figure 7: Changes in predicted annual mean NO₂ concentrations across the City of**
349 **Cambridge, relative to the 'Trend' scenario (Anti-clockwise from top-left: Compaction,**
350 **Compaction Plus, Planned Expansion and Market-led Dispersal)**

351 These results illustrate that compaction delivers significant improvements in air quality at the
352 periphery of the city, but that the central area experiences a significant decline, which we
353 interpret as a congestion effect. Conversely, Dispersal results in an overall increase in
354 emissions and a decline in air quality along a link road around the south of the city that was
355 part of the Dispersal option but not included in the other options, but air quality is much
356 improved throughout the city, relative to Compaction. The Compaction+ option improves city
357 air quality relative to compaction, yet in air quality terms does not compete with dispersal,
358 whilst air quality under Planned Expansion sees no clear pattern, although all changes
359 observed are minor.

360 The results, as presented are somewhat in conflict with Borrego *et al.* (2006) who reported
361 little variation in NO₂ concentrations between compact and dispersed city forms, and Bechle,
362 Millet and Marshall (2011), who suggested that 'compactness' (defined as urban circularity)
363 was not a significant predictor of NO₂ concentrations, though cities and regions with more
364 contiguous (rather than 'leap-frogged' or dispersed) development could be associated with
365 lower NO₂ concentrations.

366 **5. Discussion and Conclusions**

367 **5.1 Limitations**

368 Before considering the results of the analysis more fully, it is appropriate to note a number of
369 methodological limitations. It is recognised that there have been a number of developments
370 in the field of air pollution post-completion of the modelling work, and secondly that the use
371 of available components and data from the decade-old SOLUTIONS project limits the current
372 applicability of results in the strictest sense – rather they need to be viewed as internally
373 consistent, and representative of their respective scenarios.

374 Considerable attention has been given in the past few years as to why predicted emission
375 and concentration decreases, expected from the implementation of the Euro 5/V and 6/VI
376 classes, and reflected in the type of modelling presented here, have not materialised in the
377 real-world (Carslaw *et al.*, 2011; Hagman, Gjerstaf and Amundsen, 2011; Keuken *et al.*,
378 2012, Weiss *et al.*, 2012, Hagman and Amundsen, 2013 and 2015). Issues surrounding the

379 real-world versus drive cycle performance of vehicles have received considerable research
380 and media attention of late, whether this be the under-performance of de-NO_x equipment
381 (Oxely, ApSimon and Valiantis, 2011; Velders, Geilenkirchen and de Lange, 2011; Carslaw
382 and Rhys-Tyler, 2013), increasing primary NO₂ fractions in late-model diesel exhausts post
383 2000 (Grice *et al.*, 2009; Rhys-Tyler *et al.*, 2011), outright 'cycle-beating' by manufacturers
384 (Ekberg *et al.*, 2015), or lack of understanding on deterioration of emissions with vehicle age
385 and mileage (Carslaw, 2018).

386 Examination of the light vehicle diesel emissions rates between PITHEM/EFT version 5
387 (DEFRA, 2013b) and EFT version 8 (DEFRA, 2017), for 2021, show that, for uCO₂ factors
388 agree within 1%, for particulate matter generally within 5% (though EFT v8 rates can be up
389 to 12% higher at low (<15kmh) speeds). For NO_x speed-dependent discrepancies are large,
390 reaching +63% at free-flow urban speeds (50-60 km/h), and are still significant, but smaller
391 (+36-54%) at lower and higher speeds. Hence we would expect an update to this work using
392 the latest emissions factors to be detrimental to the NO_x/NO₂ results for the Compaction and
393 Market-Led Dispersal options to a greater extent than the other options examined.

394 Court action against central government for ongoing exceedences of European annual NO₂
395 objectives have also lead to Clean Air Zones (CAZs), wherein certain vehicles are restricted,
396 and 'pollution charges' being examined in several cities – including Cambridge (GCP, 2017).
397 These developments threaten to overturn the historic dieselification of the vehicle fleet in the
398 UK, as assumed by the Market-led dispersal scenario. A further pledge for a ban on all new
399 petrol and diesel car sales by 2040 also seeks to drive penetration of alternate-fuelled
400 vehicles beyond previously assumed rates, such as those proposed by Wright (2012), and
401 used in the Compaction+ scenario. The current EFT places hybrid and electric VKT at
402 approximately 5.5% of the total in 2021 (DEFRA, 2017), above the 3.3% assumed in the
403 Compaction+ scenario, for example.

404 There is also on-going discussion within the air-quality community as to whether it is
405 appropriate to use strategic macro- or meso- transport models such as SATURN for local air-
406 quality assessments, or if traffic micro-simulation coupled with a suitable instantaneous
407 emissions model is preferable (Boulter *et al.*, 2007), as these models may be better able to
408 represent congestion effects, such as those that may be expected in the Compaction
409 options. Broadly, we would expect emissions and concentrations under such a modelling
410 scheme to increase substantially in areas of congestion.

411 Conversely, there is an argument that speed-emission curves, such as those used in the
412 EFT, used in conjunction with assignment models such as SATURN, give a 'false sense of
413 accuracy' regarding marginal speed changes in a network. This has led to the adoption of a
414 'speed and congestion band' approach for the appraisal of new road schemes by Highways
415 England, the UK-body responsible for the strategic road network (HE, 2015).

416 Following this idea, the SATURN model used for this study had been calibrated to the traffic
417 conditions and networks of the Base Year (2001) and the Trend scenario. Its main purpose
418 was to provide car travel times and costs for the spatial allocation modelling of the land use
419 activities within the sub-region, rather than air pollution concentration modelling. The
420 Compaction option would greatly increase the population densities within Cambridge
421 compared to the Trend and so forecasts of the traffic speeds, flows and queuing may be less
422 reliable than for the Trend within and around Cambridge.

423 This is unlikely to have had much effect on the findings for the sub-region as a whole, but
424 means that the forecasts of absolute air pollution concentrations within Cambridge may be
425 unreliable, especially for Compaction, because there would be higher volumes of traffic on
426 roads that are already congested. Traffic queues and peak-spreading could have a
427 disproportionate impact on traffic emissions. This is an example of how further, more
428 detailed traffic simulation modelling would be useful in conjunction with other measures to
429 reduce air pollution in a higher density city such as traffic demand management, cleaner
430 fuels and attractive and sustainable alternatives to car use. The models used for this study
431 were calibrated using data that is now somewhat outdated and so may not take into account
432 current choice behaviour and travel options. Note also that the options tested were a
433 combination of land use policies and supportive transport schemes. Therefore, the findings
434 on air quality concentrations are affected by location specific combinations of transport
435 schemes and land use policy. Also, Cambridge is atypical of most small cities in the UK
436 because of its university, historic setting within a rural hinterland and its strong growth of
437 employment within and around the city. Similar research would be useful on the relationship
438 between land use transport planning and vehicle technologies on emission for other cities as
439 a comparison.

440 Likewise, for CO₂ emissions there are discrepancies between values (in terms of g/km rates)
441 calculated via the EFT (versions 5 or 8), and those in the National Transport Model (NTM) (Li
442 *et al.*, 2009) or the Greenhouse gas conversion factor repository (Hill *et al.*, 2013; DEFRA,
443 2013b) used for official reporting of CO₂ emissions. Whilst light vehicle emission (cars, vans,
444 motorcycles) tend to correspond well between data sources, greater discrepancies exist for
445 heavy vehicles (HGVs and buses). These discrepancies increase with time, as the NTM and
446 DEFRA CO₂ values assume improvements in fuel efficiencies (CO₂ emissions are analogous
447 to fuel consumption) of heavy vehicles (by approximately 5% every 5 years), that are not
448 present in the EFT figures. Indeed, the presence of de-NO_x technologies (e.g. Selective
449 Catalytic Reduction) and regenerating particulate traps on modern heavy vehicles (Euro V
450 and VI) is assumed to marginally increase fuel consumption (by approximately 1%) in the
451 EFT dataset. The CO₂ emissions values generated (Table 3) are tank-to-wheels (TTW)
452 values, and further assumptions on the efficiency of fuel production and distribution are
453 required to convert these to well-to-wheels (WTW) values for carbon foot printing (Hill *et al.*,
454 2013), or to accurately calculate displaced emissions from BEVs (i.e. from transport to
455 electricity generation).

456 Regarding urban topography, taller building forms associated with the compaction options
457 may alter street canyon dimensions, leading to entrapment of pollutants. Such changes may
458 be expressed in general surface roughness properties in Gaussian models such as ADMS-
459 Urban, or application of canyon modelling. More rigorous analysis would require robust
460 simulation e.g. via Computational Fluid Dynamics modelling. Other researchers have taken
461 this approach when studying urban form (e.g. Yuan et al., 2014).

462 Finally, we note some limitations associated with the specific geography of the case study.
463 The modelled strategic networks do not provide full coverage of the city or region, but are
464 focussed on key routes. The congested assignment part of the SATURN model had a
465 detailed road network for Cambridge and its periphery which approximately corresponded to
466 the area of the blue box in Figure 2. There is uncertainty arising from the background
467 pollution maps and the DEFRA sector removal tools (DEFRA, 2012b), and pollution
468 contributions from minor roads may be misrepresented. Climate information does not reflect
469 changing meteorology relevant to the air quality analysis, though relevant elements of the
470 UKCP09 weather generator data, for example temperature and precipitation predictions,
471 could, in principle, be included (EA, 2018).

472 **5.2 Interpretation and Conclusions**

473 Despite the caveats above, we conclude that the results of the analysis provide a credible
474 *comparative* analysis of the combined role of urban form and vehicle technology on emission
475 and air quality for a small city surrounded by a largely rural sub-region of market-towns and
476 villages. Previous work by the authors (Mitchell *et al.*, 2011; Echenique *et al.*, 2012)
477 evidenced the differential impact of a range of urban spatial planning options on emissions of
478 CO₂, but concluded that such impacts would be modest in the context of underlying growth in
479 emissions over the long-term driven by population growth and socio-economic change.
480 Mitchell *et al.* (2011) reported a maximum 5% CO₂ emissions reduction due to the
481 compaction of urban form over a 30 year period compared to the trend, and hence that
482 technological advancements could thus be a greater driver for emissions abatement. This
483 conclusion was drawn for an analysis of both the transport and building sectors, with the
484 authors noting that prior studies based on analysis of the transport sector alone showed
485 larger elasticities. Echenique *et al.* (2012) summated that “Urban form policies can have
486 important impacts on local environmental quality, economy, crowding, and social equity, but
487 their influence on energy consumption and land use is very modest”.

488 The results in this study build on the author’s previous work, and are consistent with the
489 previous findings. Whilst this new analysis is based solely on the transport sector, it includes
490 more aggressive assumptions regarding the energy efficiency of motor vehicles over the
491 examined period, and includes electrification of the sector in the compaction scenarios.
492 Under the 2001-2021 Trend scenario, transport CO₂ emissions are projected to decrease by
493 16%, whilst for the Compaction policy the reduction achieved is 22%. Hence, we argue that,

494 in this paper, we have demonstrated that greater uptake of clean technology vehicles has
495 the potential to further mitigate emissions, but that the rate of reduction remains rather
496 modest. This reflects the limited rate of clean technology uptake represented in our
497 scenarios, which seek to reflect plausible technologies, and which operate over a modest
498 temporal range.

499 With respect to air quality, we observe a deleterious effect of compaction. Intensification
500 increases population density, and whilst per capita car use may be reduced with benefits in
501 terms of CO₂ emission reduction, intensification also increases concentrations of traffic,
502 which results in the observed decline in local air quality. This is the 'paradox of
503 intensification' phenomenon discussed above, and where Melia *et al.*, (2011) concluded that
504 any compromise involving limited intensification would merely act to redistribute problems
505 between local and global objectives. They therefore advocate intensification with more
506 radical vehicle constraint and provision for slow modes and public transport. We observe that
507 air quality benefits may be delivered under a compaction policy accompanied with more
508 aggressive uptake of clean technology ('Compaction+'), although other local traffic
509 externalities such as noise are not addressed.

510 The findings of our earlier SOLUTIONS project suggested that a policy of planned expansion
511 (such as polycentrism) offered a potential compromise between the relative pros and cons of
512 compaction and dispersal, in particular by providing better space (housing) standards than
513 compaction, but without the energy consumption of market led dispersal. The work
514 presented here furthers that conclusion, and indicates that, with respect to environmental
515 objectives a planned expansion policy coupled with clean technology has potential to deliver
516 reductions in CO₂ emission relative to the dispersal option, but without the risk to
517 exceedance of air quality objectives that compaction implies (Figure 7).

518 Further work is required to test this conclusion more thoroughly although this is challenging
519 due to the resource intensive nature of working with such linked-models. Because air quality
520 impacts are so context dependent (e.g. non-compliant air quality may occur in populated
521 town centres, or along sparsely populated main roads) it would also be beneficial to extend
522 the analysis to incorporate population exposure and health impact assessment. For
523 example, Martins (2012) reported that urban sprawl options lead to higher modelled
524 particulate matter and ozone concentrations in the Porto area of Portugal, compared to trend
525 and compaction options, but compaction lead to higher population exposure to particulate
526 matter (though ozone results were less clear).

527 The future work could also consider the environmental justice or equity implications of the
528 scenarios, developing an air quality environmental justice analysis as developed by Mitchell
529 (2005), and applied to Leeds by Namdeo and Stringer (2008), which would further enhance
530 the sustainability appraisal of the urban form-technology scenarios. Likewise, disease
531 burden estimations based on the spatial distribution of populations, exposure-response
532 curves and ADMS pollution concentration maps are being included in the PITHEM software,

533 based on the methodology outlined in Mitchell *et al.* (2000). The spatial forms may then also
534 be quantified in terms of 'disease-burden reduction' and 'health gains' in local areas.

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Table 1: Urban form scenarios considered (Echenique et al., 2010)

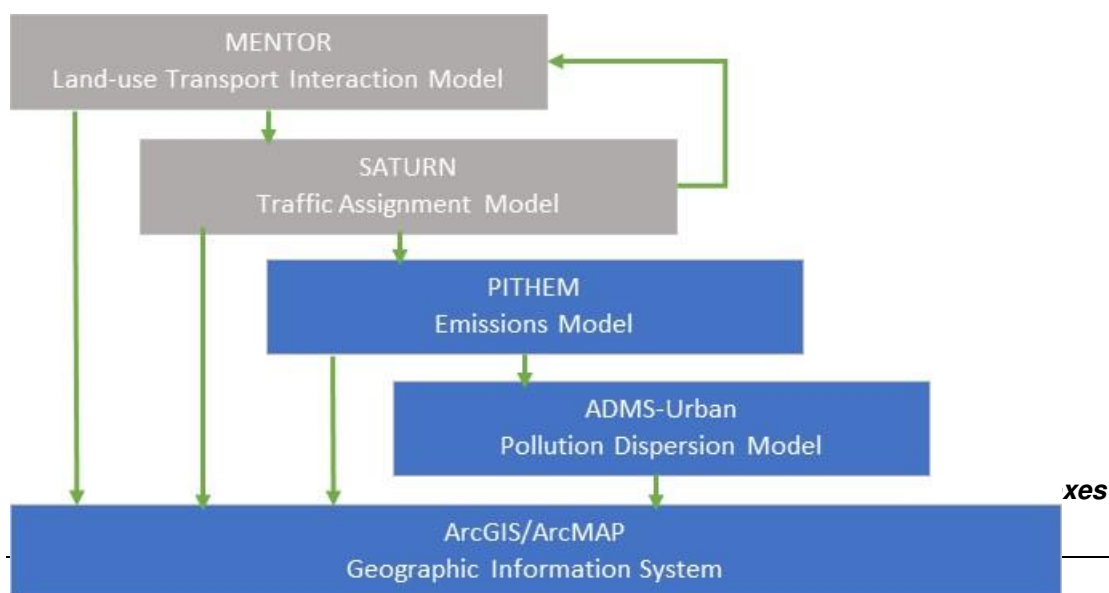
Name	Description
<p>Trend (21_Trend)</p>	<p>The Trend scenario was based on the 2003 Structure Plan for Cambridgeshire, with most new dwellings to be built within and around Cambridge and in the A14 corridor, plus a high rate of growth in East Cambridgeshire, particularly around Ely and a new settlement called Northstowe to the NW of Cambridge in South Cambridgeshire. Much of the new housing was allocated to sites within and around the edge of Cambridge where there are the greatest employment opportunities. This included some relaxation of the green belt constraints and thereby reduced the need to travel compared to the preceding planning policy that had allocated almost all development beyond the green belt. The increase in business and retail floorspace follows a similar pattern to the dwellings but with lower growth in East Cambridgeshire. The transport schemes included in the Structure Plan to 2016 were part of the Trend scenario (and were also included in the other urban form scenarios). The Trend scenario includes some additional schemes to represent investment from 2016 to 2021 including a guided bus extension to the east of Cambridge and a highway link from the east of the city to the A14,. This scenario reflects that the UK planning policy constrained suburban expansion and prioritised development to brownfield land and areas with good public transport. .</p>
<p>Compaction (21_Comp)</p>	<p>The Compaction option involves high density development within the existing urban footprint, and is public transport oriented. It attempts 'to reduce travel and resources use, and increase social cohesion and vitality'. In this scenario for compaction the Cambridgeshire region develops an extra 19,000 dwellings within Cambridge itself (30% more than under the 'Trend') and correspondingly fewer in the periphery. There would be a tunnel for guided buses under the city centre via the bus station and railway station but no new link road to the east of Cambridge.</p>
<p>Market-led Dispersal (21_Disp)</p>	<p>The Market-led Dispersal option involves lower density private transport oriented development. This option diminishes the intensity of urban land use, reflecting people's choice for space at affordable prices, and involves some land take from previously open land in areas where there would be strongest demand for development. This would be subject to local planning constraints to achieve densities of at least 20 dwellings per hectare to avoid sprawl. In the scenario, growth is primarily around the fringes of Cambridge, in settlements to the north of the city, and along transport corridors (A10, A14 and M11). The transport schemes would be similar to the Trend option.</p>
<p>Planned Expansion (21_Plex)</p>	<p>The Planned Expansion option comprises new settlements with mixed density in good transport corridors and a mix of private and public transport. It represents an attempt to mitigate against the perceived disadvantages of the above options, to give 'balanced communities' and protect open landscape via development as edge expansion, along defined corridors or as new satellite communities. In this scenario new dwellings are concentrated in areas where there is economic growth and good road and public transport connections. This includes the eastern edge of Cambridge, the A14/guided bus transport corridor, and the M11 corridor south of Cambridge. The areas would be polycentric new settlements clustered around the public transport stations. The transport schemes would be similar to the Trend option.</p>

781 **Table 2: Vehicle technology options applied to the 2021 urban form scenarios for**
 782 **emissions and dispersion modelling**

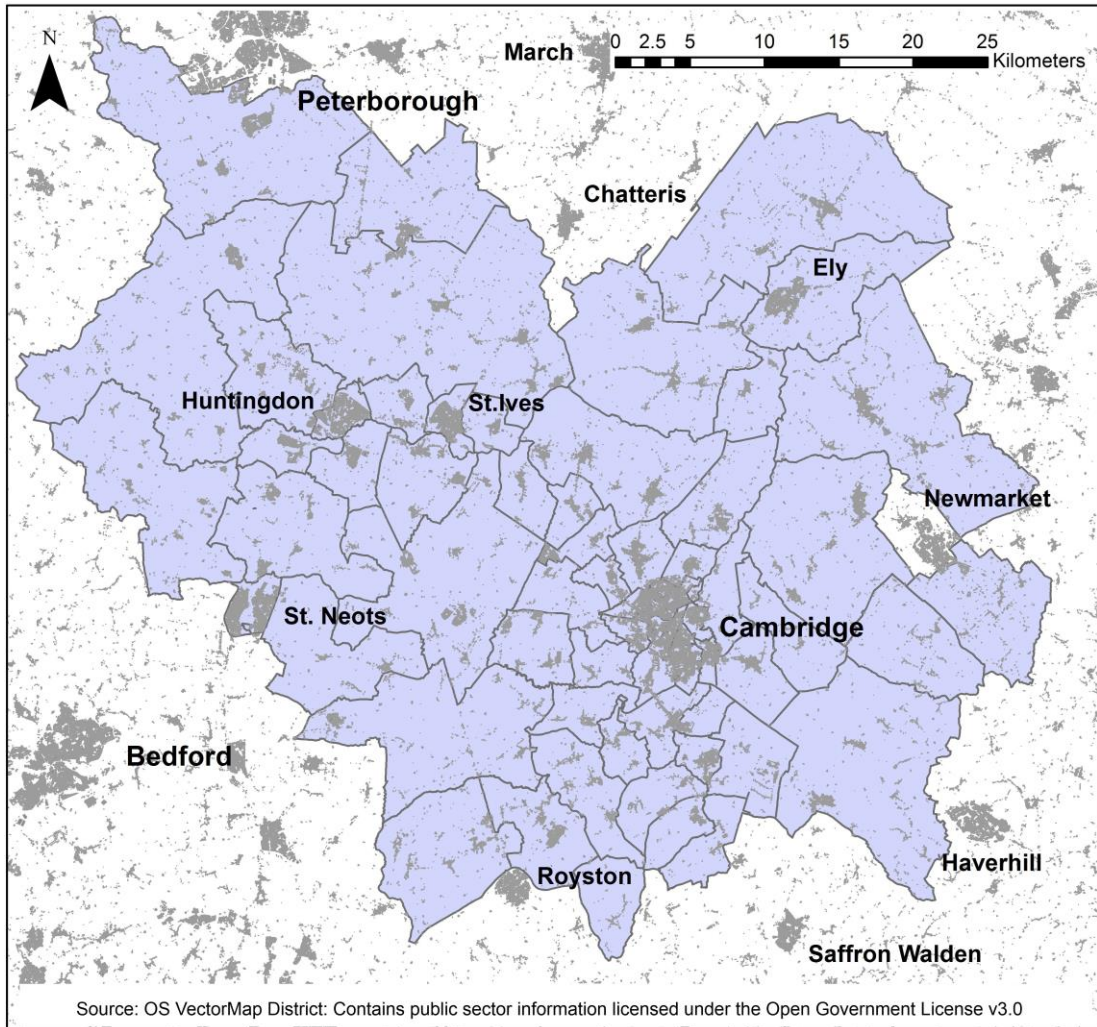
Name	Description
Trend (21_Trend)	Fleet projections from the National Atmospheric Emissions Inventory (NAEI) Venfield and Pang (2012) are used.
Compaction (21_Comp)	The historic pattern of uptake of diesel vehicles is reversed within the Cambridge City boundaries, with small, petrol engine 'city cars' becoming more prevalent, making ≈60% of trips within the city by 2021. There would be additional provision of public transport within the city at park-and-ride sites
Compaction Plus+ (21_Comp+)	As above, but there is additional uptake of Battery Electric Vehicles (BEVs) for private transport within 30km of Cambridge centre. Uptake of private BEVs is assumed to be <0.01% in 2012, rising at 0.1% per year to 2015, then at 0.5% per year beyond 2015. This equates to ≈3.3% of trips being made by BEVs in 2021. Hybrid electric buses are used for public transport within city boundaries.
Market-led Dispersal (21_Disp)	The historic pattern towards dieselification of the private fleet is continued, and compounded by a further trend towards larger-engine (2+ litre) vehicles, both within the city, and in the hinterlands, resulting in ~23% of trips being made by these vehicles, compared to ~13% in the Trend. Little investment in public transport
Planned Expansion (21_Plex)	Increased demand for bus/park-and-ride facilities and expansion of existing guided bus routes. All buses are assumed to be either 'Euro V+' hybrid buses, or 'clean', low NO _x buses, based on 'Euro VI/de-NO _x ' technologies. The increase in public transport patronage leads to a commensurate reduction in passenger car usage from the fringes and hinterlands of the city.

783 **Table 3: Network performance (absolute values) of alternate planning scenarios**
 784 **relative to the Trend scenario.**

Parameter	21_Trend	21_Comp	21_Comp+	21_Disp	21_Plex	Units
VKT	6320.7	-262.5 (-4.2%)	-262.5 (-4.2%)	+297.6 (+4.7%)	-129.4 (-2%)	m.km.
uCO₂	1018.9	-101.3 (-9.9%)	-129.2 (-12.7%)	+71.2 (+7%)	+37.4 (+3.7%)	kT
HC	236.8	-11.9 (-5%)	-21.3 (-9%)	+16.7 (+7.1%)	-1.9 (-0.8%)	T
NO_x	1361.7	-63 (-4.6%)	-102.5 (-7.5%)	+74 (+5.4%)	+39.4 (+2.9%)	T
pNO₂	445.2	-17.1 (-3.8%)	-30.9 (-6.9%)	+22.4 (+5%)	-5.2 (-1.2%)	T
PM₁₀	224.2	-8.3 (-3.7%)	-15.5 (-6.9%)	+10.8 (+4.8%)	+2.4 (+1.1%)	T
PM_{2.5}	127.6	-4.4 (-3.4%)	-8.6 (-6.7%)	+6.2 (+4.9%)	+1.7 (+1.3%)	T

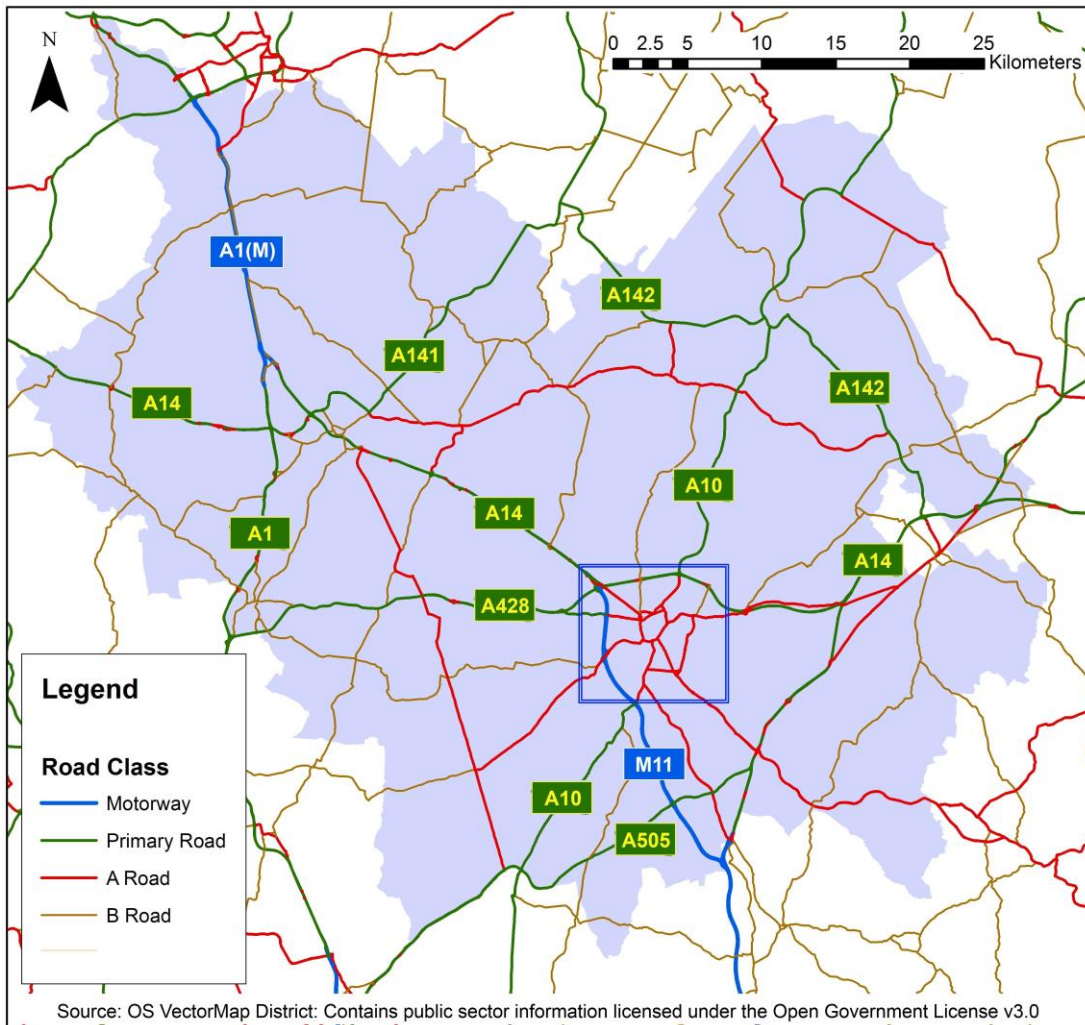


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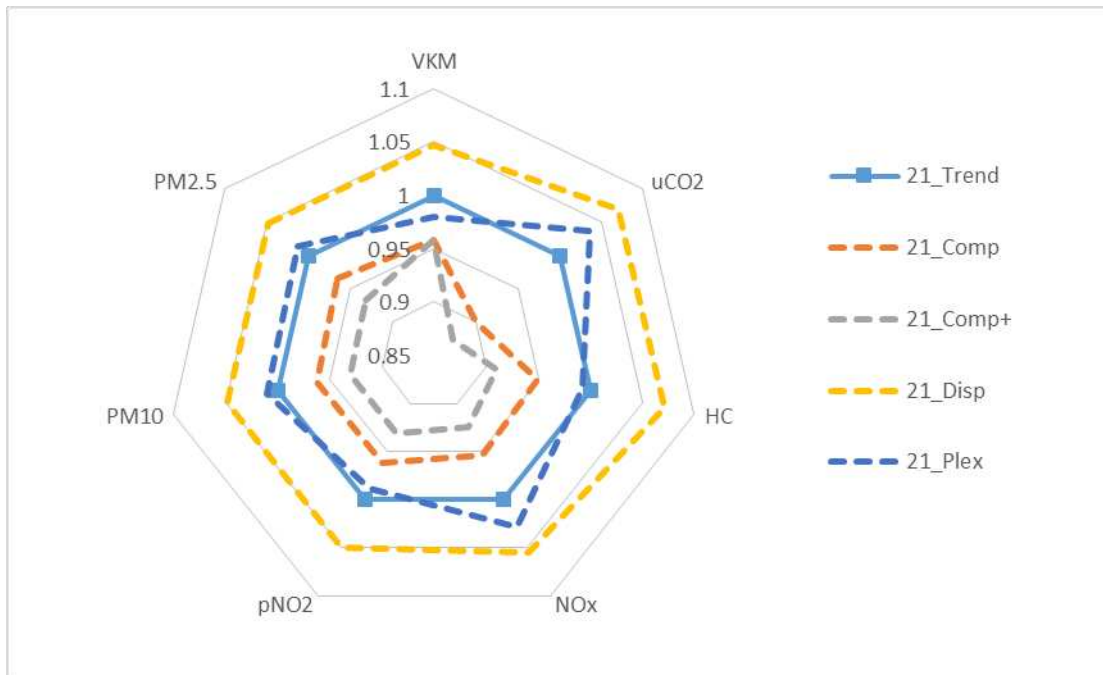


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789 **Figure 2: Major population centres and baseline extent of urban development in**
790 **Cambridgeshire.**

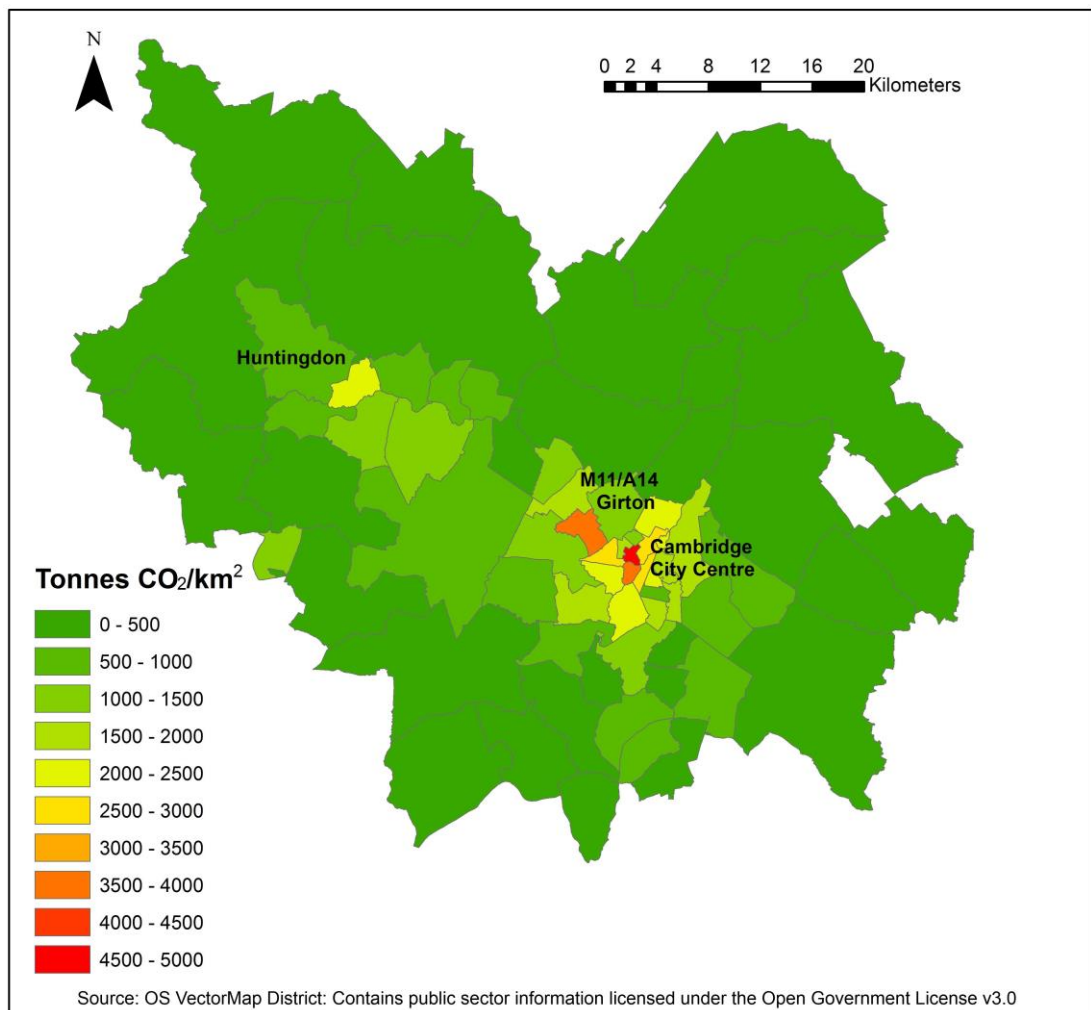


792 **Figure 3: Major transportation routes and corridors in Cambridgeshire and area of**
793 **detailed air quality study.**



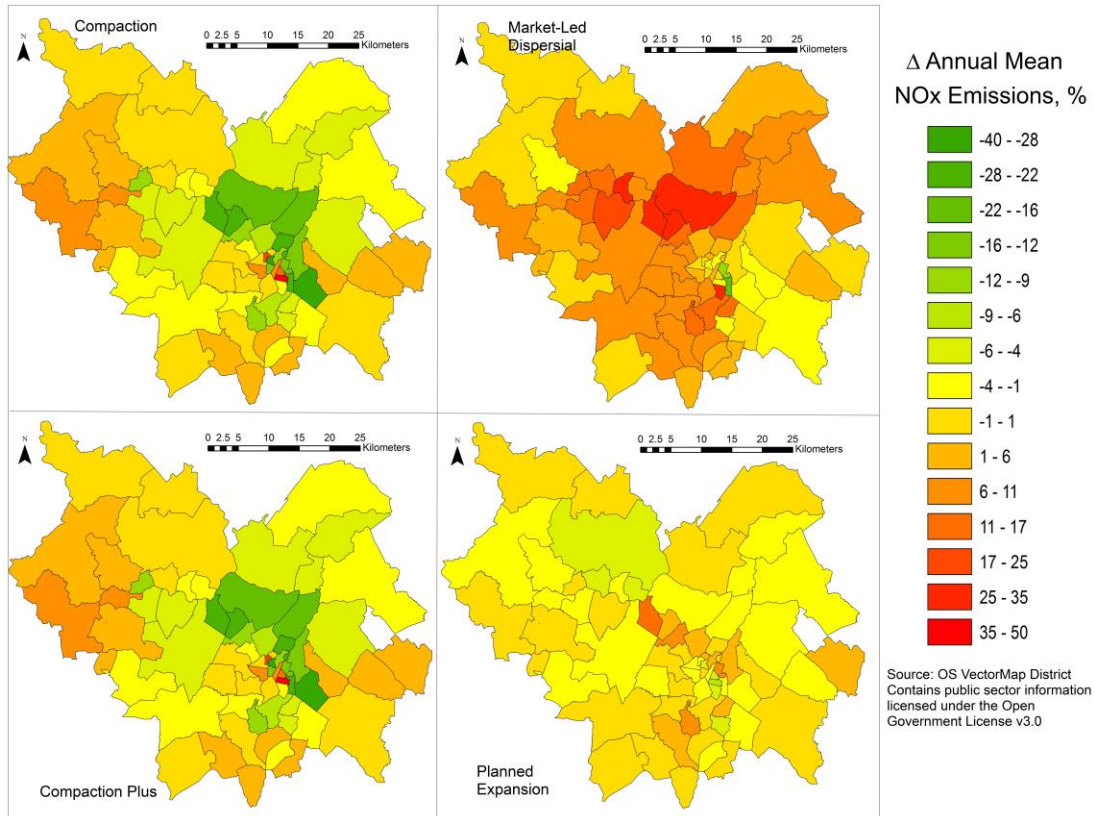
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Figure 4: Radar plot of network performance relative to the Trend scenario (Baseline performance = '1')



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Figure 5: Intensity of CO₂ emissions across the modelled sub-region

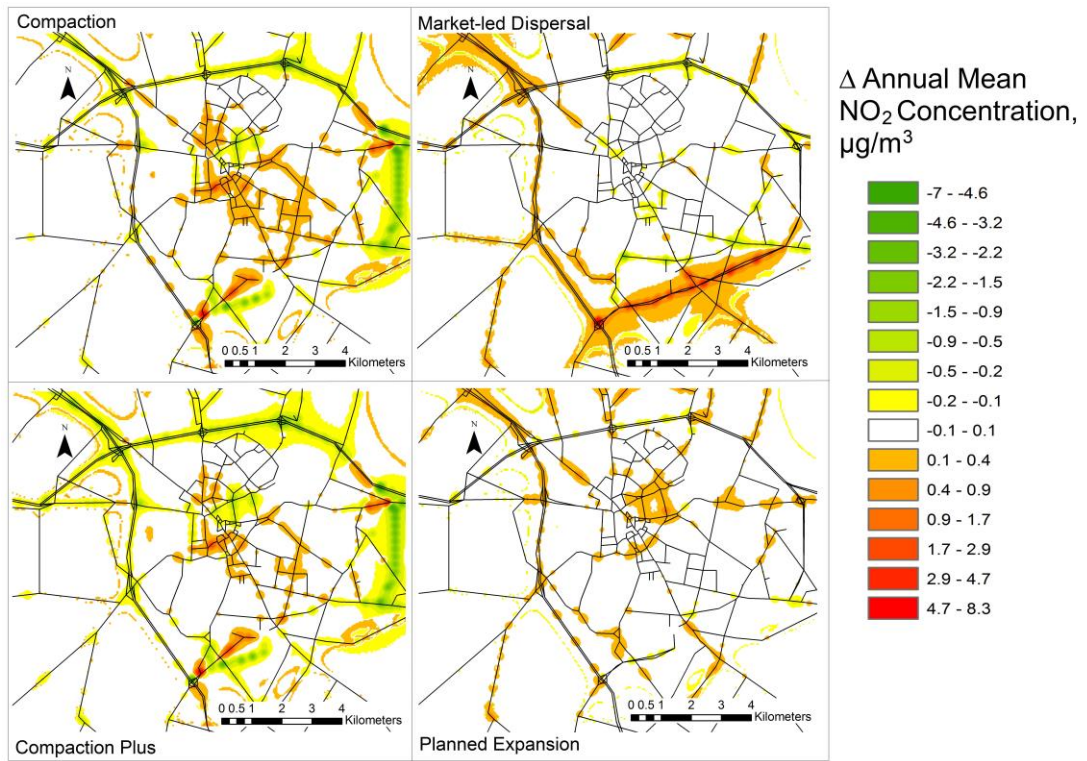


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800 **Figure 6: Spatial changes in NO_x emissions across Cambridgeshire, relative to the**
 801 **'Trend' scenario (Anti-clockwise from top left: Compaction, Compaction+, Planned**
 802 **Expansion, Market-led Dispersal)**

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Figure 7: Changes in predicted annual mean NO₂ concentrations across the City of Cambridge, relative to the 'Trend' scenario (Anti-clockwise from top-left: Compaction, Compaction Plus, Planned Expansion and Market-led Dispersal)