THE IMPACT OF URBAN DEVELOPMENT ON AIR QUALITY AND ENERGY USE

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Summary
Melbourne has been used as a case study to investigate the effects of six alternative urban forms on air quality. The forms are Dispersed City, Compact City, Corridor City, Multi-Nodal City, Fringe-Development City and 'Business-As-Usual' City.

We took 1991 as the base year, using emissions, population and transport data supplied by EPA Victoria. We specified changes in activities for each alternative development to the year 2011. We used an integrated landuse-transport optimisation model (Topaz 2000) to predict the changed emissions for each scenario. A coupled 3-D meteorological model (LADM) and photochemical airshed model (extended CIT model) were used to predict the hour by hour air quality conditions on an adverse winter day and an adverse summer day. For the modelled cases we found:

Photochemical Smog. The exposure levels show a 55% improvement from base year for the Corridor City, compared with a 71% worsening for Business as Usual.

Particulate Pollution. With particulate build up, there would be an improvement of 14% for the Corridor City and a worsening by 61% for Business as Usual compared to the base case. Exposure in the Compact City is, for the given emission load, substantially worse than in any other.

Keywords: Urban form, modelling air quality, pollution exposure, particulate pollution, photochemical smog, landuse-transport modelling.

1. Introduction
What alternatives are there for the “shape” or structure of our cities? The most prominent archetypal alternatives are illustrated in Figure 1. These may be described as follows (after: Pressman, 1985; Minnery, 1992; Newton, 1997)

- **Business As Usual** – extrapolation of current patterns into the future;
- **Compact City** – increased population and density of an inner group of suburbs;
- **Edge City** – increased population, housing densities and employment at selected nodes within the city; increased investment in orbital freeways linking the edge cities;
- **Corridor City** – a focus of growth along linear corridors emanating from the CBD and supported by upgraded public transit infrastructure;
- **Fringe City** – additional growth predominantly on the fringe of the city; and
- **Ultra City** – additional growth primarily in provincial cities within 100 km of the principal (capital) city and linked by high speed rail transport.

All cities, irrespective of their geographic location, can be re-shaped to generate greater liveability. Which of the above archetypal urban forms is most desirable, from an environmental perspective?

Research undertaken for the recently completed Inquiry into Urban Air Quality in Australian Cities (Newton, 1997) attempted to explore, for the first time, the nexus between urban form and three key dimensions of the environment, namely: ambient air quality, greenhouse gas emissions, and transport energy use.

This new research employed integrated landuse-transport-environment (LUTE) modelling to assess the ‘performance’ of Melbourne in the year 2011 (from an environmental perspective) in the context of the above six contrasting archetypal urban development scenarios.

2. The Environmental Performance Appraisal Model
Since urban development and urban form can be characterised by changes in land use, this work used the TOPAZ 2000 landuse-transport model (considerably enhanced from Brotchie et al. 1980) (see Figure 2) integrated with prognostic airshed modelling (see Figure 3) as the tool for evaluating the impact on air quality of different urban growth scenarios.
The landuse component of the LUTE model divides a region into zones, with the list of land uses or activities specified. A scenario is then defined by specifying the population engaged in each activity within each zone, for a given time period. For each land use scenario, the area-based emissions are obtained by multiplying the activity population with the corresponding per capita emission factor. Point-based emissions are then added from sources that fall within the zone. Emissions of volatile organic compounds (VOCs), nitrous oxides (NOx), carbon monoxide (CO), sulfur dioxide (SO2) and fine particles with effective diameters of 10 microns or less (PM10) were modelled. Biogenic emissions could not be considered due to unavailability of data.

Link emissions (emissions from roads) are obtained by applying a transportation gravity model to the land use component. The gravity model generates and distributes trips between each pair of zones, depending on the trip generation and travel impedance properties of each pair of activities. The trips are then loaded into a road network to produce traffic flow. The level of congestion on each link determines the amount of emission produced for that link. The aggregation of zone and link emissions onto grids then follows.

Point emissions are obtained from data on stack sources that fall within a grid. A zone’s area-based emissions are divided equally among grids that fall within the zone.

The gridded emissions are passed on to prognostic pollution models for hour by hour dispersion analysis (see Figure 3). These are a coupled 3-D meteorological model (LADM; see Physick and Manins, 1994, Manins, 1995) and photochemical airshed model (extended CIT model; see McRae et al., 1992, Cope, 1997). The airshed model was developed specifically for the Melbourne region over several years by EPA Victoria.

The example region used for this study was the Melbourne metropolitan area. The region was divided into 26 zones, as used in a 1991 national study of Journey to Work (Gipps et al., 1997). These zones are consistent with the recently amalgamated municipalities in the inner, middle and outer rings of Melbourne. The zones in the outer ring or suburban fringe are large. However, the location of existing development within them is considered for calculation of trip lengths and zone centroids.

Alternative future scenarios can then be distinguished largely on the basis of the type of future development that is assigned to each of the rings and their associated zones.

To save time in this case study, we made a major simplification by predicting the air quality impacts on a single adverse winter day and a single adverse summer day. A thorough investigation would need to consider the impacts on days that represent all weather conditions.
3. Urban Development Scenarios

3.1. Modelling Future Scenarios related to Alternative Urban Systems

A range of scenarios that relate to alternative urban forms, defined in terms of land use changes and service improvement, were applied in modelling Melbourne’s development to the year 2011. The key challenge relates to the accommodation of an additional 500,000 people in Melbourne by 2011. In 1991 the base population was 3,168,300. Table 1 shows how the additional population has been distributed, as well as indicating how public transport (predominantly rail) has been varied.

Table 1: Scenarios and assumptions for an additional 500,000 people in Melbourne by 2011

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Transport Changes (some of)</th>
<th>% change public</th>
<th>Population Distribution</th>
<th>Employment Distribution</th>
<th>Change in % by Category†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 1991</td>
<td>Inner (7)</td>
<td>22/53/32</td>
<td>Inner (20)</td>
<td>Middle (58)</td>
<td>23/11/20</td>
</tr>
<tr>
<td>Business Increased as Usual 2011</td>
<td>Inner (7)</td>
<td>22/53/32</td>
<td>Middle (58)</td>
<td>55/36/47</td>
<td>23/11/20</td>
</tr>
<tr>
<td>Corridor Radial 2011</td>
<td>Inner (7)</td>
<td>0/0/0</td>
<td>Middle (0)</td>
<td>0/0/0</td>
<td>0/0/0</td>
</tr>
<tr>
<td>Compact Improved 2011</td>
<td>Inner (100)</td>
<td>0/0/0</td>
<td>Middle (33/0)</td>
<td>33/83/83</td>
<td>67/0/0</td>
</tr>
<tr>
<td>Edge Freeway 2011</td>
<td>Inner (0)</td>
<td>0/0/0</td>
<td>Middle (86)</td>
<td>33/83/83</td>
<td>67/17/17</td>
</tr>
<tr>
<td>Fringe Upgrade to 2011</td>
<td>Inner (0)</td>
<td>0/0/0</td>
<td>Middle (10)</td>
<td>10/10/10</td>
<td>7/7/16/10</td>
</tr>
<tr>
<td>Ultra Freeways, 2011</td>
<td>Inner (2)</td>
<td>7/16/10</td>
<td>Middle (17)</td>
<td>17/11/14</td>
<td>7/3/6</td>
</tr>
<tr>
<td>City fast rail 2011</td>
<td>Middle (11)</td>
<td>7/3/6</td>
<td>Outer (11)</td>
<td>7/3/6</td>
<td>7/7/10/7</td>
</tr>
<tr>
<td>Regional 2011</td>
<td>Outer (70)</td>
<td>7/10/70</td>
<td>Outer (70)</td>
<td>7/10/70</td>
<td>7/10/70</td>
</tr>
</tbody>
</table>

† Manufacture/Producer Services/Social Services

3.2. Business as Usual

In the business as usual scenario, the new half million population is distributed across the 26 zones in the Melbourne metropolitan area in proportion to the 1991 base, as shown in Table 2.

This essentially continues a dispersed pattern of constrained development with population increased proportionately in each ring shown in Figure 1. There is a significant amount of land which remains available for residential or commercial development on outer the fringes of Melbourne. Consolidation trends associated with dual occupancy and infill development would have some limited influence. As such, this scenario models many of the current trends operating in Melbourne, including a slight increase in density.

3.3. Compact City

In this scenario, the new population is distributed to the eight statistical local areas that comprise inner Melbourne. The density of new residential development or redevelopers in these zones is 300 persons/ha — well above business as usual levels for the inner city. The effects of an expected increase in the use of ‘slow’ modes of transport (walking, cycling) was not considered.

3.4. Multi-Nodal or Edge City

New population is allocated to six major district centres within Melbourne connected via a major ring road. The district centres are located in zones situated within or close to the middle ring of Melbourne, as shown in Figure 1.

A proposed ring road is the same as for the base case except that, in this scenario, improvements have been made in order to bring it to freeway status. The six nodes are also on radial rail networks centred on the CBD. These edge city zones are assigned medium density housing up to 80 persons/ha.

3.5. Corridor City

In this scenario, the new population is added to three corridor zones in the outer ring of the city. The three corridors receive transport infrastructure upgrades (of a radial nature) to both road and rail.

3.6. Fringe City

Here, 30% of new population is added to three development corridors in new green-field sites on the urban fringe. Of the remaining 70%, 10% is added to the middle ring of zones, 60% is added to the outer ring.

New manufacturing and service industries are also distributed to these same zones and in the same proportions, providing a balance between new homes and new jobs. The times of development of new homes and jobs will also be similar, increasing the opportunities for selection of a home and job in the same local area, thereby increasing self-containment of commuting, as well as of shopping, and other trips.
The new corridor development and distribution to existing middle and outer zones is another variation of present and recent trends, except that there is no addition to the inner city zones.

The new corridor fringe development is connected to the rest of the city with radial freeway/arterial links and with upgraded heavy rail links, thereby reducing travel times to these zones.

3.7. Ultra City

In this scenario, 70% of the new population is added to four provincial centres within a 100 km radius of Melbourne (Ballarat, Bendigo, Seymour, Warragul); the remaining 30% is dispersed throughout the 26 zones in proportion to the base-year distributions. Summarised in Table 1, it is almost business as usual, but represents a 21st century solution to the late-20th century problem of the future viability of many of Australia’s provincial cities. These centres are struggling to find a new economic base, yet they represent environments of high residential amenity and liveability much sought after by sections of the capital city’s population. The proposed solution (scenario) involves linking (selected) provincial centres with their capital city via high-speed rail, thereby making them part of the functional urban region of that city (functional urban being defined by patterns of daily commuting to work). In the scenario modelled, the four provincial centres are linked by fast train (150 km/h) and freeway to the centre of Melbourne.

4. The Impact of Urban Form

Within the stated limitations and assumptions associated with the landuse-transport-air quality modelling, we can advance the following conclusions related to air quality and urban form:

4.1. Urban Form and Photochemical Smog

When supported by the simultaneous installation or upgrading of appropriate transport infrastructure, any one of several strategies designed to deliberately channel and concentrate additional population and industry into specific ‘zones’ within a large city such as Melbourne will deliver environmental and efficiency benefits that consistently outperform those associated with a ‘business as usual’ approach. In the case of photochemical smog, for example, a corridor model for Melbourne’s metropolitan development in 2011 on a summer day of adverse meteorological conditions delivers a 55% improvement over the base situation on the same day for that city in 1991. Where new development is primarily concentrated at nodes on the fringe, within the inner suburbs or at key nodes within the city, the air quality enhancements are also significant (respectively, 39, 24 and 21% reduction in population exposure to smog compared to the base case for the same adverse summer meteorological conditions). For business as usual development, the result is an increase by 71% in the population exposure to smog at levels above those considered appropriate by present air quality standards (see Figure 4). No analysis was made for the ultra city model but it is expected to be similar to or better than the fringe city.

![Figure 4: Population exposure to photochemical smog](image)

4.2. Urban Form and Particle Concentrations

In this study we set PM$_{10}$ population-based emissions in winter to be equivalent to a summer week day in 1991, to reflect the expectation that domestic heating using solid fuels (the biggest cause of adverse winter particle pollution; EPAV, 1997) is likely to be severely controlled in the future. For the compact city scenario in winter the result is that PM$_{10}$ emissions are little changed from the 1991 summer base model. However, since all the population increase proposed for Melbourne in this scenario is to be accommodated in the inner suburbs, more people will be exposed to the ‘umbrella’ of particle emissions. Hence the considerably higher levels of population exposure represented in Figure 5 on a winter day of adverse meteorological conditions for the compact city.

![Figure 5: Exposure to fine particles on a day of adverse conditions](image)

Indeed, on the modelled day of adverse meteorological conditions in 2011, the compact city delivers a 160% increase in population exposure to particle emissions.
compared to the Melbourne base case (1991). For business as usual development, the level of increased population exposure is 61%. Edge, corridor and fringe developments all deliver improvements as far as population exposure to PM$_{10}$ particles is concerned. (The ultra city was not modelled but it is expected to give similar benefits to the fringe city.)

4.3. Urban Form and Carbon Dioxide Emissions

Here we focus on vehicle emissions for reducing CO$_2$ from urban areas. Figure 6 illustrates that a compact city form delivers the lowest output of CO$_2$ emissions, due to greater use of public transport and fewer vehicle hours (and kilometres) travelled compared to other forms of urban development. A shift by 2011 from business as usual urban development to a compact city form may give savings in CO$_2$ emissions of the order of 11,500 tonnes each day — a 43% saving. Development of an ultra city would lead to a similar result to that shown for the corridor city — a 16% saving.

![Figure 6: Daily CO$_2$ emissions from transport sources in Melbourne](image)

4.4. Urban Form and Energy Consumption

As one might expect from the results on CO$_2$ emissions, the compact city emerges as the most fuel efficient of all urban forms (see Figure 7) with 43% less fuel consumption than a business as usual form of development. The fact that in the corridor city scenario infrastructure investment was primarily radial in nature is the reason why higher levels of daily travel were generated than in other scenarios (i.e., limited prospects for cross-town trips). The addition of a higher-grade ring or orbital transport network to the current corridor city infrastructure, however, could be expected to generate positive benefits in travel time and energy consumption outcomes.

![Figure 7: Daily fuel consumption for base 1991 and five future scenarios for Melbourne.](image)

It is just this type of strategic planning and evaluation that is needed to chart the future infrastructure investments required for major metropolitan areas into the 21st century. In the United States, for example, the federal Clean Air Act is requiring a closer linking of funding in areas such as urban transport with a set of goals. These goals include air quality. Integrated landuse-transport-environment models provide the means by which impacts of proposed urban development can be evaluated across the spectrum of dimensions relevant to the key goals of economic efficiency, environmental sustainability and social equity.

5. Conclusion

Urban form does matter — and not just for urban air quality. In relation to indicators such as greenhouse gases and energy consumption, there appears to be universal concurrence from the landuse-transport-environment modelling that to maintain a business as usual model of urban development (viz, relatively laissez faire, low density, dispersed) is to condemn the population and industry of that city to a sub-optimal living and working environment into the future.

On most of the measures considered here, a trend to a compact city will lead to the greatest improvement compared with business as usual. However there is a sign that the situation is more complex: higher population density leads to higher concentrations of health-impairing fine particles, a factor of concern in winter in particular (Figure 5). Perhaps in the scenarios studied here this is just a consequence of the urban density not being high enough! But it is here that the social acceptability of different living arrangements enters into the debate. And it is one which is not readily resolved.

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References