Simulating the Dynamic Effect of Land Use and Transport Policies on the Health of Populations

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Objectives. We identified the features of a land use–transportation system that optimizes the health and well-being of the population.

Methods. We developed a quantitative system dynamics model to represent relationships among land use, transport, economic development, and population health. Simulation experiments were conducted over a 10-year simulation period to compare the effect of different baseline conditions and land use–transport policies on the number of motor vehicle crash deaths and disability-adjusted life years lost.

Results. Optimal reduction in the public health burden attributable to land transport was demonstrated when transport safety risk reduction policies were combined with land use and transport polices that minimized reliance on individual motorized transport and maximized use of active transport modes. The model's results were particularly sensitive to the level of development that characterized each city at the start of the simulation period.

Conclusions. Local, national, and international decision-makers are encouraged to address transport, land use, and health as an integrated whole to achieve the desired societal benefits of traffic safety, population health, and social equity. (*Am J Public Health.* 2015;105:S223–S229. doi:10.2105/AJPH.2014.302303)

Road traffic injuries are currently the eighth leading cause of death worldwide.[1,2] Ninety percent of these deaths occur in low- and middle-income countries.[1,2] Deaths from road traffic injuries are expected to increase over the next 10 years, and by 2030 will become the fifth leading cause of death.[1] The vast majority of this increased burden will be experienced by countries undergoing economic development.[1,2] Better understanding of the relationship between development and road traffic injury is urgently needed to support implementation of policies to prevent this global epidemic.

Economic development and increased ownership of personal motorized transport are closely associated.[3] Projections have suggested that the number of vehicles in the world will have increased from 800 million in 2002 to 2 billion vehicles by 2030, with the proportion of total vehicles in non–Organisation for Economic Co-operation and Development countries rising from 24% to 56%.[4] In parallel with the escalation in motor vehicle numbers, the length of road networks has increased. In China, for example, expressway distance increased from just 175 kilometers in 1988 to 25 130 kilometers in 2005.[5]

The importance of the association between transport and development is usually understood in terms of the role of mobility as a determinant of human health and well-being.[6] The term *mobility* as used here refers to the means by which people can achieve interaction with other people, goods, and services. Increased mobility is believed to increase individual and national productivity and thus increase individual and national wealth. In turn, increased wealth is believed to increase health and quality of life.[7] The main justification for increasing the number of new motor vehicles and new roads is the argument that ownership of personal motorized transport increases mobility and thus drives further development.[8]

However, increased ownership of personal motorized transport vehicles, and increased building of roads, leads to increased kilometers driven and thus increased exposure of individuals to the risk of road traffic injury. The drive to increase exposure to motor vehicles to improve wealth, thence health, is the very reason for the increased number of transport crash injuries, which by definition decrease health. The reason for the projected global increase in the number of transport crash deaths over the next 20 years is not that motor vehicles are becoming more dangerous but, that as countries develop, more people are exposed to risks of motor vehicle–related harm.

Relationships between development, road traffic injury, and health and the possible effects of policies that could be implemented to achieve population-level outcomes are complex. Economies and populations grow and decay. Communities evolve. The effect of change in organic systems is more frequently exponential than linear.[9] Any 1 outcome becomes an antecedent for consequences in other parts of the system at future points in time. Social policy takes advantage of the dynamic nature of communities to affect action[9] by restricting growth in 1 direction and encouraging growth in another. System dynamics is a quantitative method designed explicitly to analyze problems of growth and decay in systems with interdependent components.[9–12] System dynamics can model the effect of gradual change through social growth rather than simply consider differences between 1 existent reality and its counterfactual. By making the consequences of interactions explicit, comparisons between simulations aid decision-making in a situation too complex to be fully processed by conscious cognition.

For this article, we developed a quantitative system dynamics model to help further refine our understanding of the complex relationship between transport and health. We began by placing the problem of road crash injury in its broader context of population health, then constructed a complex quantitative model of the relationships among land use, transport, health, and development to make explicit the key factors and relationships. The intention of the modeling was not to generate estimates of actual numbers of injuries or health outcomes we could expect some time in the future but rather to compare results produced by the model for a range of baseline conditions and land use and transport policies and thereby learn more about the dynamics of the modeled system.

The aim of the analysis was to demonstrate the implications of replacing the focused policy question "How do we stabilize and then reduce the forecast level of road traffic fatalities around the world by 2020?" with the more holistic question "What are the features of a land use–transportation system that optimizes the health and well-being of the population?"

METHODS

We developed a conceptual model of the relationship among land use, transport, population health, and development over a period of 12 months. This development commenced with a systematic review of the literature, then involved a series of workshops and discussions between teams of researchers, policymakers, and practitioners from across the world (described in Appendix A, available as a supplement to the online version of this article at http://www.ajph.org). The final qualitative model was articulated in terms of a causal loop diagram, with its mathematical representation constructed in Powersim 9 (Powersim Software AS, Bergen, Norway).

The mathematical expression of the causal loop diagram was a system dynamic model structured as 3 simple stocks and flows modules connected by auxiliary information to form an interdependent set of co-flows. The main population health outcomes of the model that were of interest in this study were transport crash deaths and all-cause disability-adjusted life years (DALYs) lost and prevented proportion of potential deaths and DALYs lost. We calculated the prevented proportion measure as a percentage, with the numerator being health loss as a result of each policy and the denominator being the difference between the maximal and minimal simulated health losses that we observed across the various simulations. The advantage of this measure is that it makes clear the relative values of each of the policy options in terms of the potential health loss prevented.

In the model, the concept of mobility is quantified in terms of trips, and exposure is measured in kilometers and risk of crash in terms of crashes per kilometer. These distinctions allow us to model maintenance or increase mobility (i.e., number of trips) while at the same time decreasing number of crashes by decreasing risk or decreasing exposure. These hypothesized changes encapsulate the land use scenario entailed by increased urban density. For a detailed specification of the remaining parameters of the model, see Appendix A.

The 3 hypothesized main loops can be summarized as follows:

Loop 1: gross domestic product per capita increases, population wealth increases, car ownership increases, transport use increases, mobility increases, and gross domestic product per capita increases (reinforcing or positive feedback loop).

Loop 2: population wealth increases, car ownership increases, transport use increases, transport health risks increase, morbidity and mortality increase, population health loss increases, population wealth loss increases, and population wealth decreases (balancing or negative feedback loop).

Loop 3: population wealth increases, health determinants and access to and quality of health care increases, population health loss decreases, and population wealth increases (reinforcing or positive feedback loop).

We developed the base model using exogenous inputs for the model parameters extracted from a series of Australian public access databases and published national reports (described in full in Appendix A). Verification performed included logical tests, extreme value tests, and mass balance tests. Validation of the model was undertaken for each of the 4 cities for which sufficient quality data were available by backdating the baseline conditions to match those prevailing in these cities in 2003, setting the policy switches to represent the policy prevailing in each city over that period, and then running the simulations for 10 cycles. We compared predicted crash injury deaths for each city with actual recorded transport deaths.

We created variants of the base model for 6 cities from around the world: New York, NY; London, England; Delhi, India; Beijing, China; Copenhagen, Denmark; and Melbourne, Australia. Workshop participants selected cities so as to include both a range of land use and transport designs and a set of cities for which quality data were known to be available. We customized the model to each city in the study by changing the model's baseline values to match city-specific data obtained from published reports. Once the base model and international variants were developed, we performed a status quo simulation for each city to establish outcomes for the simulation period. We then undertook an experiment to explore the results obtained by varying crash and injury risks and mode of transport distribution. For all simulations, the city boundary was considered the scope of each model.

Simulation Experiment and Modeled Policy Options

The simulation modeled 3 different policy options.

Policy 1: reduce travel mode risk. The objective of policy 1 was to reduce the risk of crash per kilometer (primary prevention) and the risk of serious injury per crash (secondary prevention) to decrease the number of deaths and serious injuries from road crashes.

Policy 2: change the transport mode distribution. The objective of policy 2A (mode shift) was to change the transport mode distribution from individual motorized transport (i.e., motor cars and motorcycles) to mass transport and individual active transport modes. The objective of policy 2B (mode shift plus mode separation) was to ensure adequate purpose-specific infrastructure was available for each mode of transport so that users of 1 mode did not increase the crash risk of users of other modes.

Policy 3: combined implementation of policy 1 and policy 2. The objective of policy 3 was to reduce crash risk, and risk of death per crash, while at the same time achieving a shift to mass transport and active personalized transport modes.

Data Sources

Inputs into the model were public access data in 3 main categories. First were the basic parameters that distinguished the population contexts (Appendix A). These included the extent of motorization and the size, health, and wealth of the country's population. Second were the data inputs related to calculation of mode and country-specific transport crash outcomes (Appendix A). Third were the data inputs relating to the feedback loop values (Appendix A).

RESULTS

Results of the 10-year simulations for each of these outcomes are presented in Figure 1 and Figure 2, respectively.

London and Copenhagen

For London, simulating no change to current policy resulted in a 15% increase in land transport deaths from 187 at baseline to 216 deaths in the 10th year (Figure 1). Addition of primary and secondary prevention road safety measures (policy 1) to the simulation overcame the population growth factors and decreased projected transport crash deaths to a minimum of 165 deaths in the final simulation year.

Policies that limited motor car usage to its baseline level and distributed all new mobility growth to public and active transport options without necessary changes in infrastructure to protect pedestrians and cyclists (policy 2A) led to a small decrease in crash outcomes among those individuals opting for public transport but increased injury and death for those who become pedestrians (Figure 1). Mode shift plus protective infrastructure (policy 2B) was sufficient to overcome the adverse effect of policy 2A. Combining policy 1 and policy 2 provided a solution to the problem of transport crash deaths and resulted in an estimated 140 deaths per annum after 10 years, that is, a reduction of 25% on baseline deaths.

Over the 10-year simulation period under a no-change-to-current-policy option, the total DALYs lost in London increased from 34 754 to 36 762. A 2% reduction in these expected DALYs was achieved simply by implementing policy 1; implementing policy 2A resulted in a 3% reduction. When the mode shift was coupled with better active transport user protection (policy 2B), walking and cycling transport deaths decreased, leaving an overall reduction in transport deaths from baseline and further DALYs benefit (Figure 2). The clear benefit in terms of both land transport deaths saved and overall DALYs was achieved by combining primary and secondary road safety interventions together with mode shift and mode separation (policy 3). Such a combined package achieved a 6% reduction from a projected 36 762 to 34 590 DALYs per annum at the end of the 10-year simulation period.

For Copenhagen, a 10-year simulation under no change to current policy, assuming continuance of current population growth, wealth growth, and mobility growth, resulted in a 29% increase from 14 deaths at baseline to 18 and a 13% increase in DALYs from 2852 to 3216. With active transport already being a safe means of transport in this city, ensuring further growth in active transport at the expense of increased motor vehicle trips (even without extra expenditure on active transport infrastructure) resulted in a substantial population health benefit with a pattern that was identical to that of London's (Figure 2). Modeling the combined implementation of all strategies (policy 3) produced a 28% reduction to only 10 deaths at the 10-year mark (Figure 1) and a 6% reduction from a projected 3216 DALYs to only 3012 (Figure 2).

Beijing and Delhi

For Beijing, a 10-year simulation of no change to current policy resulted in the total crash deaths per year by the 10th year increasing from a baseline of 3640 deaths to 8246 deaths (a 126% increase) in the final year (Figure 1). The single most effective policy for reducing road transport deaths was to focus on reducing this risk (Figure 3). Despite the lack of a marked marginal benefit of the mode shift achieved through Policy 2, there was still a clear benefit in terms of total transport deaths prevented if mode shift was added to road safety strategies in accordance with policy 3. The effect of combined implementation of all policies together had the potential to reduce the death rate at 10 years by 92% from a projected 8246 under the no-change-to-current policy option to 626 (Figure 1).

Health burden changed from 218 336 DALYs at baseline to 218 943 DALYs in the 10th simulation year (Figure 2). Road safety–specific interventions resulted in a higher proportion of overall DALY outcomes than did the mode shift policies. The combined policy approach reduced a projected 218 943 DALYs by 23% to 167 327 DALYs by the 10th simulation year (Figure 2).

Under no-change-to-current-policy conditions, transport deaths in Delhi increased 53% in the 10th simulation year, from a baseline 2587 deaths to 3962 deaths. The population burden simulated for the no-change-to-current-policy scenario was a decrease by 17% from 384 887 DALYs at baseline to 318 888 DALYs at 10 years. The greatest single strategy for reducing transport deaths was improving primary and secondary road crash risk. Nevertheless, the best result in terms of transport crash lives saved and population health burden reduced was achieved by modeling the implementation of the combined full range of policies. Modeling the implementation of policy 3 resulted in an 82% reduction (from status quo projections) in the number of deaths at 10 years to 489 (Figure 1) and an 18% reduction in DALYs to 262 806 (Figure 2). The rank order of these policies in terms of deaths and DALYs benefit was almost identical to the pattern for Beijing (Figure 3).

New York and Melbourne

For New York, under the no-change-to-current-policy conditions, simulation resulted in 354 transport crash deaths in the 10th year, an increase of 14% from 310 deaths at baseline. Modeling the addition of primary and secondary prevention measures (policy 1) resulted in an overall reduction of 31% of the no-change-to-current-policy projection to 244 deaths in the final simulation year. The simulated relative benefits of the policy 2A and 2B options in New York followed the same crash-deaths-by-policy-type pattern as demonstrated for London. Policy 3 resulted in the most substantial benefit, reducing total crash deaths from the baseline 310 transport crash deaths to 195 deaths (45% of the no-change-to-current-policy projection) at the end of the 10-year period.

Over the 10-year simulation period under the no-change-to-current-policy option, the total DALYs lost in New York increased only

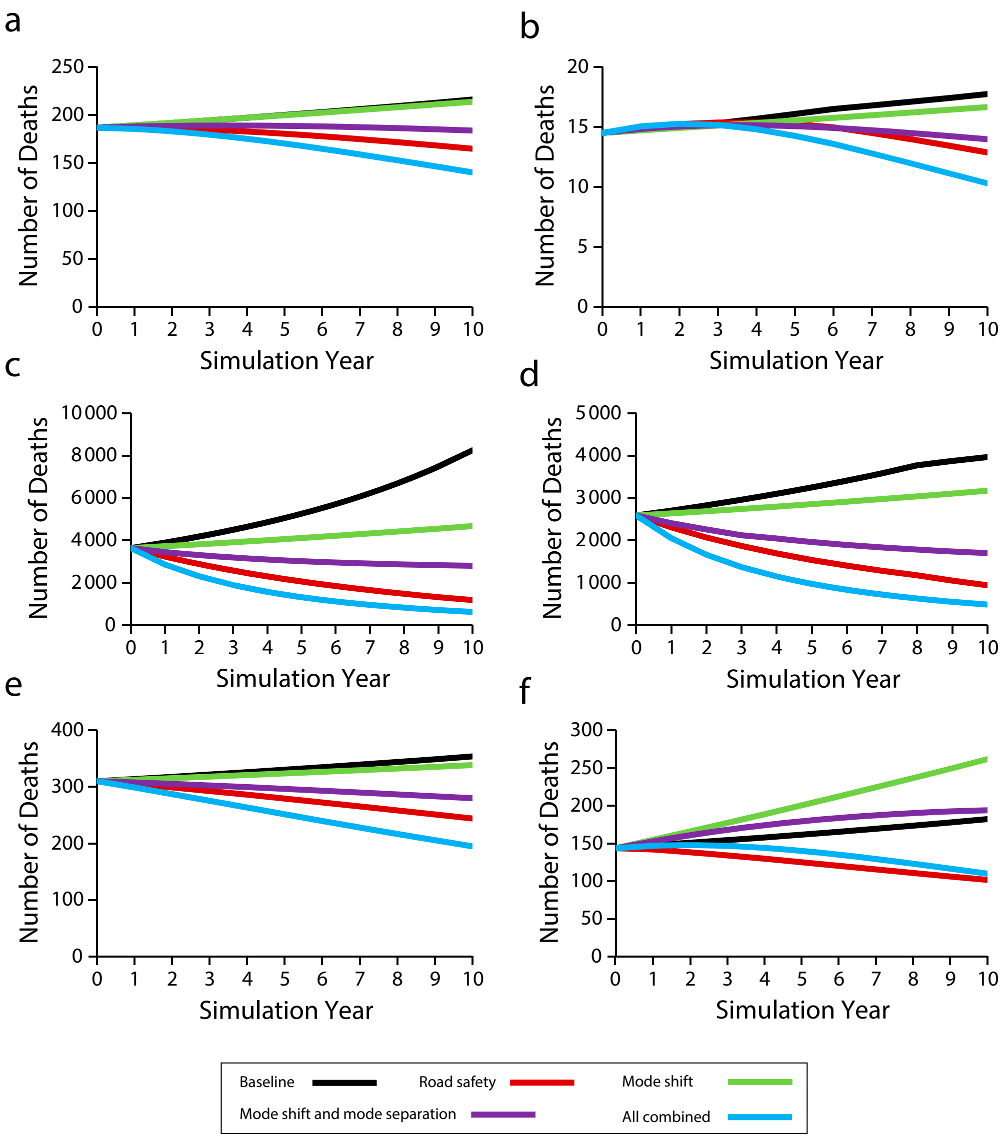

FIGURE 1—Traffic injury deaths by population and policy option for (a) London, England; (b) Copenhagen, Denmark; (c) Beijing, China; (d) Delhi, India; (e) New York, NY; and (f) Melbourne, Australia.

marginally from 52 106 in year 1 to 52 590 in year 10. A substantial reduction in these projected DALYs was achieved simply by reducing road death through primary and secondary road crash prevention. The mode shift policy option provided little additional DALYs benefit (Figure 3). However, the clear benefit in both transport deaths saved and overall DALYs was achieved by a combination of mode shift plus mode separation plus primary and secondary road safety interventions (policy 3). Such a combined package would achieve a reduction from a projected 52 590 to 50 731 over a 10-year period.

Modeling transport crash deaths for Melbourne under the no-change-to-current-policy scenario, the number of transport crash deaths rose 25% above baseline over the 10-year study period, from 143 deaths at baseline to 182 per year at the end of 10 years. Addition of primary and secondary prevention measures overcame the effect of increased kilometers traveled and effected a decline in transport crash deaths below baseline to 102 deaths in the final year (Figure 1). Adopting policy 2A effectively moves a large part of the growth in population mobility from motor car (which has the least number of crashes per kilometer) to those modes of transport with the highest risk per kilometer. Adopting policy 2B only partially compensates for the adverse effect of mode shift on total transport crash deaths. Policy 3 provided a benefit over baseline for

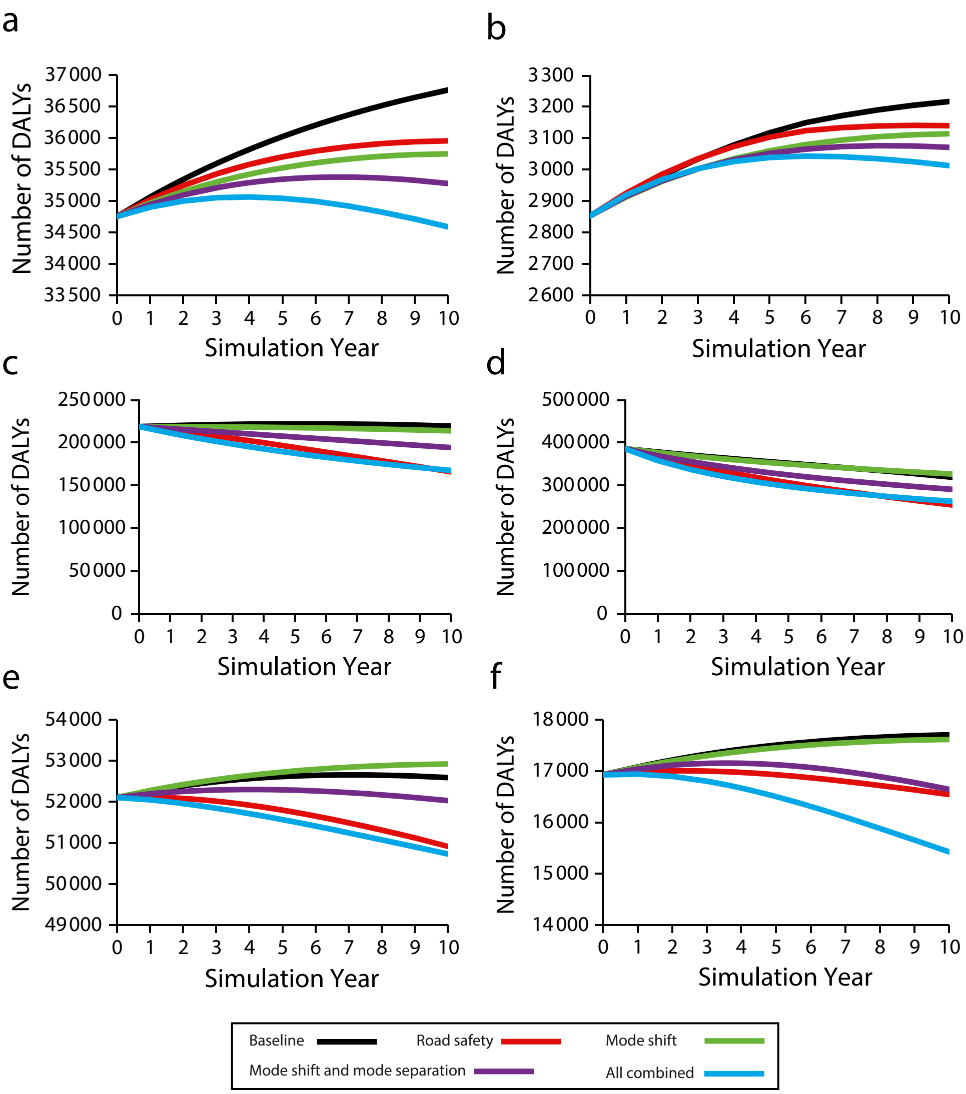

FIGURE 2—Disability-adjusted life years lost from all cause by population and policy option for (a) London, England; (b) Copenhagen, Denmark; (c) Beijing, China; (d) Delhi, India; (e) New York, NY; and (f) Melbourne, Australia.

transport crash deaths but not as large a benefit as was achieved simply by focusing on transport safety (Figure 1).

Primary and secondary road safety (policy 1) produced an overall DALY benefit. Modal shift without mode separation (policy 2A) resulted in no improvement in DALYs compared with the no-change-to-current-policy option. Mode shift plus percentage of increased expenditure on infrastructure to support this mode shift (policy 2B) had DALY benefits comparable to those of policy 1. By combining policies 1 and 2, the overall DALYs benefit was maximized. The clear benefit in overall DALYs achieved by policy 3 was a reduction from 16 889 at baseline to 15 760 over a 10-year period (Figure 3).

DISCUSSION

We developed and applied a quantitative system dynamics model to the problem of land use and transport for health and development. We demonstrated potential population health improvements through the implementation of transport safety risk reduction activities in conjunction with land use and transport polices that shift the distribution of people using cars and motorcycles to other modes of transport. Focusing only on road safety risk leaves unaddressed the substantial and growing burden of chronic diseases attributable to car-based mobility. Focusing only on modal shift without addressing the structural changes that would improve transport safety for motorized and nonmotorized forms of transport overlooks the

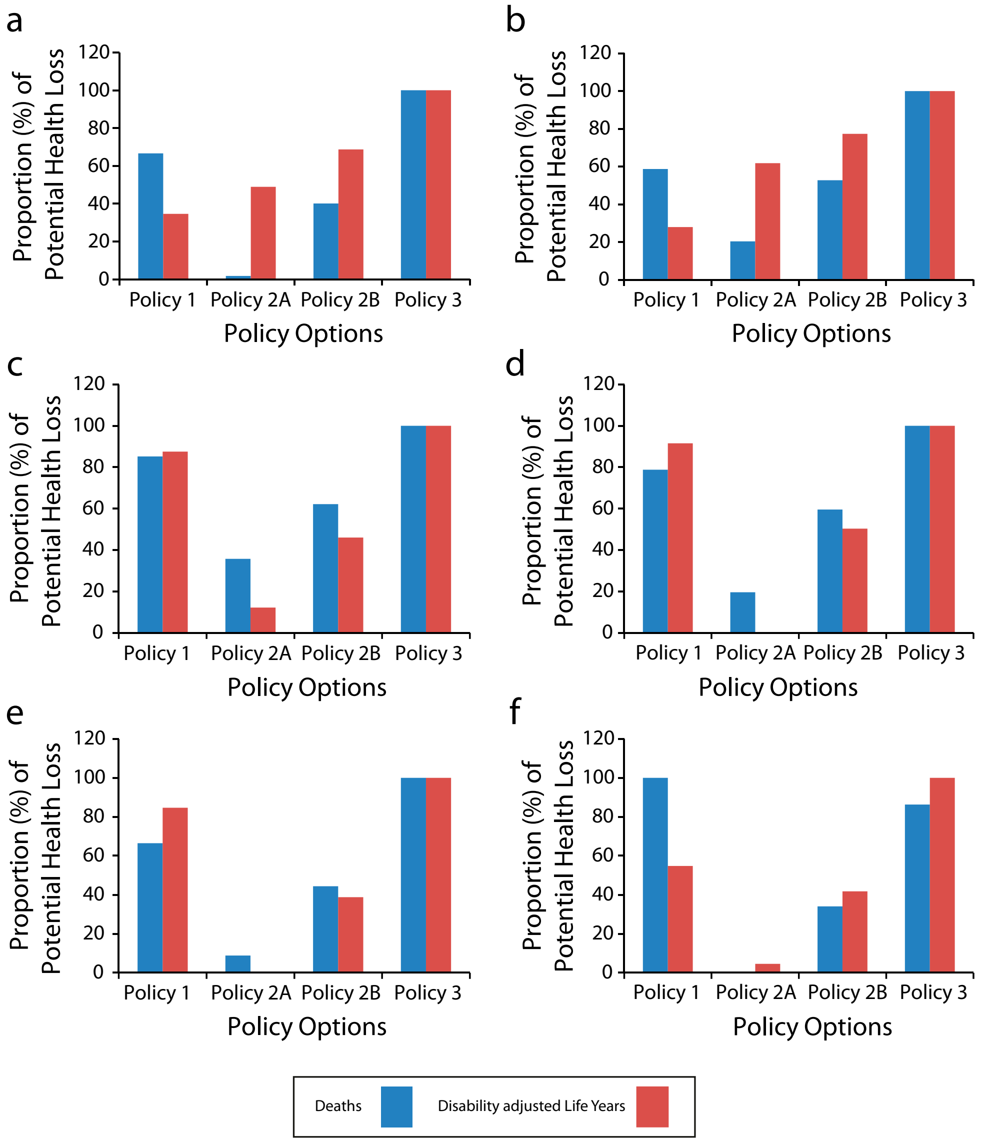

FIGURE 3—Policy prevented proportion of potential deaths and disability-adjusted life years lost by policy option for (a) London, England; (b) Copenhagen, Denmark; (c) Beijing, China; (d) Delhi, India; (e) New York, NY; and (f) Melbourne, Australia.

opportunity for additional, substantial injury-specific health and development gains.

To be useful, a model needs to include only a necessary and sufficient number of components.[9] We tested the validity of the model for only the high-income contexts for which availability of quality data is adequate to support a validation exercise. The evidence has suggested that the model is a sufficiently accurate account of reality to provide robust support for policy development purposes.

We developed the model using a parsimonious set of variables and a simple set of relationships. Of necessity, factors related to land use, transport, and health have been omitted, and these omissions will have affected the modeled outcomes. However, this did not materially affect the usefulness of the model because its purpose was not to predict the actual number of injuries or health outcomes we could expect some time in the future but rather to compare results produced by the model for a range of baseline conditions and land use and transport policies and, from this comparison, to learn more about the dynamics of the modeled system.

The initial analyses provide strong support for a coordinated data collection program being included in the global monitoring process so that the gaps in data can be addressed and the generalizability of the model improved. Future quality assurance efforts are also required to ensure increasing accuracy of the published data used as inputs into the model. The relationships between the co-flows (currently represented by simple assumptions of linear 1:1 multipliers) could be usefully refined using empirical information to more accurately account for the causal behavior. More subtle nonlinear effects of 1 variable with another may improve the fidelity of the model to the real world. Despite the assumptions underlying the simple linear 1:1 multipliers, the lack of sensitivity of the model to changes in these assumptions indicates the robust nature of the model's structure.

Because we focused on the health outcomes of land use and transport policies, only the population health module within the model was developed in any detail, and we reported only health outcomes in this article. Each of the population and population wealth modules could be further refined to improve their accuracy and functionality as later developments of the model.

In conclusion, we offer 7 recommendations for future approaches to transport, land use, and health policy in the hopes of achieving the desired societal benefits of traffic safety, population health, and social equity:

- Investment to improve mobility should aim at influencing the entire land use transport system so as to maximize intended benefits across the full range of health and well-being outcomes.
- The greatest potential benefits of an integrated approach to land use and transport policy for population health are to be found in growth cities that are not yet dependent on motorized personal transport modes and whose infrastructure is still under development.
- Maximal benefits will be achieved by understanding mobility in terms of trips, not distance, and changing land use to reduce the average distance required per trip.
- Desirable land use changes are ones that increase the density of urban dwelling space so residential, work, and leisure environments are colocated within geographically defined nodes and where nodes are connected by safe, clean, rapid mass transport options.
- The focus of future investment in transport infrastructure should not be on increasing road length but on building purpose-specific infrastructure to support active transport and mass public transport options.
- Investment in current roads should be explicitly for the purpose of protecting pedestrians, cyclists, and motorcyclists from injury by motor cars and car drivers and occupants from injuring themselves.
- The full range of non–infrastructure-based supporting polices (e.g., regulation, financing, incentives) should be implemented to provide collateral policy support to minimize reliance on individual motorized transport and maximize use of active transport modes. ■

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All authors were equally involved in the development and application of the research concepts described in the article and in drafting and reviewing the article content. R. J. McClure undertook the quantitative modeling with additional data ascertainment and data management support provided by C. Mulvihill.

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Human Participant Protection

The project (CF14/1827–2014000942**)** was conducted with the approval of the Monash University human research ethics committee in accordance with the principles of ethical practice as articulated by the American Public Health Association.

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