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ORIGINAL ARTICLE

Models of travel demand with endogenous preference change and heterogeneous agents

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Abstract In the literatures of regional science, urban economics, and urban development planning, a working assumption is that individuals respond to incentives and regulations, given their preferences. Models for planning and policy analyses are used to consider what might occur if the incentives or regulations were different. In these models, however, preferences are usually assumed to be given and stable, and agents are usually assumed to be homogeneous. This paper focuses on the implications of making preferences in models of policy implementation endogenously determined and time varying heterogeneous agents. We consider first the recent literature on intertemporal choice and preference change, which cuts across many disciplines, and more briefly the literature on norm-regarding behavior. We then elaborate a simple model of transportation demand—from a static to a dynamic orientation, from fixed and exogenously given preferences of strictly self-regarding agents to endogenously determined and policy-induced preferences of heterogeneous agents—and illustrate its characteristics with simple numerical examples.

Keywords Travel demand · Preference change · Heterogeneous agents

JEL Classification C63 · D03 · R22

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1 Assumptions about preferences and behavioral foundations in regional science models

Governments, firms, public organizations, and individuals make plans and set policies with the intention of changing the future behaviors of themselves or their constituents from behaviors that would otherwise occur. These plans or policies may have equity, efficiency, quality of life, or obligations to future generations as an underlying premise. Land-use decisions, industrial location, transportation and infrastructure locations, travel behavior, energy use, and waste generation are familiar subject areas for such plans and policies.

In the literatures of regional science, urban economics, and urban development planning, a working assumption is that individuals respond to incentives and regulations, given their preferences. Models for planning and policy analyses are used to consider what might occur if the incentives or regulations were different. Investigations with such models have produced explicitly dynamic frameworks in which information and adjustments are costly (e.g., Donaghy and Schintler 1994; Intriligator and Sheshinski 1986). In these models, however, preferences are usually assumed to be given and stable. In this paper, we will focus on the implications of making preferences in models of policy implementation both endogenously determined and time varying.

Policy makers, however, are aware that the agents whose preferences they seek to influence are heterogeneous and that, while some may be more self-regarding and influenced by incentives, others may be more other-regarding and influenced by regulations that stigmatize antisocial behavior. One of the by-products of recent research on the economy as an evolving complex system has been the explicit introduction of not only models with heterogeneous agents but also models in which interdependent heterogeneous agents' behaviors are influenced by norms, regulations, and social emotions, such as altruism, guilt, shame and spite. In his famous paper on 'rational fools', Sen (1977) remarked that one could not explain the workings of so much as a checking account without an appeal beyond enlightened egoism to emotions and norms, such as trust and commitment. But more recently we have also learned from the work of Ostrom (2000) and her colleagues on collective choice that many ostensibly complex social phenomena—such as the management of public resources—require the stable interaction of agents characterized by distinctly different types of behavior. Studies in experimental economics also suggest that, as Hirschman (1985) anticipated, publicly set norms and preferences evolve together (see Bowles and Gintis 2006). Thus in this paper, we will also explicitly consider *heterogeneous* agents, some of whom are influenced more by social norms than others.

Durlauf (2005, p. 226), who has written extensively on economic complexity (both theoretical and empirical), defines complex systems as "those [systems composed] of a set of heterogeneous agents whose behavior is interdependent and may be described as a stochastic process". This paper may be viewed as a contribution to the formal specification of models of policy implementation in which there may be emergent systems properties arising from the interaction of interdependent heterogeneous agents and the co-evolution of norms and preferences, although stochastic processes remain to be introduced at a later stage.

We first consider the recent literature on intertemporal choice and preference change, which cuts across many disciplines, and more briefly the literature on norm-regarding and emotionally influenced behavior. We then elaborate a simple model of transportation demand—from a static to a dynamic orientation, from fixed and exogenously given preferences of strictly self-regarding agents to endogenously determined and policy induced preferences of heterogeneous agents—and illustrate its characteristics with simple numerical examples. Finally, we conclude with a summing up of work completed and indications of what further might be done.

2 Review of the literature

In consumer choice theory, notions of preferences, utility functions, and demand functions are used interchangeably. Given any two, the third can be derived straightforwardly, *provided* regularity properties, specified by economic theory, are satisfied. The idea of preferences (or preference orderings) is a primitive or elemental concept. In consumer choice theory, preferences, as parameterizations of demand functions, do the work of mapping information on income and prices into the space of quantities of goods and services purchased. In addition to being complete and consistent, they are also assumed to be fixed exogenously.

What is preference change? In economics, it is most simply a change in a demand curve, rather than a move along one. Learning about preferences is different from learning about how things work. Whereas the second concerns knowledge of action–outcome relationships, the first concerns changes in attitudes toward outcomes. A preference change results in a change in behavior that remains even after incentives that induced it are removed.

Although its formal characterization is recent, the idea that the history of a person's consumption shapes his or her preference is one that has appealed to applied research workers in demand analysis for quite some time (Deaton 1992; Frank 1988; Loewenstein and Elster 1992). The Stone–Geary utility function, although essentially static in nature, was an early attempt to capture this intuition (Stone 1966). Uzawa (1968) exploited a version of the Stone–Geary function to examine how increased consumption affects time preferences, and in his famous 1970 paper, Weiszacker (1971) explicitly endogenized preference change. Although in the latter paper only consumption in the previous period matters, the notion of a cumulative history of consumption experience has come to feature prominently in recent work. As consumer theory has focused increasingly on intertemporal optimization, e.g., in life cycle consumption models, the notion of 'learning by doing' (or 'learning by consuming') has been explicitly incorporated. The consumption of flows of services from stocks of physical or financial capital is made contingent upon 'stocks of habits' that grow with consumption but wear off over time (Becker and Murphy 1988; Heaton 1990).

Opinions differ over whether the inclusion of stocks of habits constitutes a true endogenization of preferences (compare Becker and Murphy 1988; Elster 1984). In identifying the 'deep structure' of preference formation and change, it is argued that ultimately a parameterization must be made that is not time varying. Whatever is 'hard-wired' in at this level, it can be argued, is what is stable about preferences. We think that there are at least two credible responses to this line of argument. First, as long as the level of expenditures and commodity prices at a point in time do not completely determine what goods and services are purchased, and then endogenous preference change is a useful concept in achieving further understanding. Second, if one is willing to acknowledge habit change and include it as a stylized fact of a dynamic model of consumption behavior, as are Becker and Murphy, it is difficult not to accord the same recognition to preference change.[1]

Previous study of preference change has been motivated in part by an interest in how a rational consumer might manage the evolution of his or her own preferences so as to maximize his or her utility subject to a budget constraint, especially in the case of addiction (see, e.g., Becker and Murphy 1988; Hernstein and Prelec 1992). Interest in how the evolution of consumer's preferences might be steered to the ends of public policy has, in general, generated fewer formal analyses (see March 1978 for a wide-ranging, albeit dated, discussion of the literature). Hopkins (1974) considered the problem of choosing simultaneously among targets and among costly incentive-based policies to achieve these targets. In his analysis, if resources are expended to implement incentives or enforce regulations, then, without preference change, the gains in behavior will cease when the incentives or enforcement cease. If a portion of the resources are expended intentionally to change preferences, perhaps indirectly through incentives to change behaviors that result in preference changes, then *the changes in behavior will not cease when the resources for the incentives are exhausted.*

Turning to assumptions about what motivates agents, we note that there has been much written lately in economics, political science, and the social sciences more broadly about the roles played by norms, social orientations, and such emotions as guilt, shame, envy, or spite in influencing behavior involving collective action. (see Frank 1988; Becker 1996; Elster 1998; Ostrom 2000; Gintis et al. 2005). Ostrom (2000) in particular notes that both 'conditional co-operators' and 'willing punishers'—which are decidedly *not* rational egoists—are needed for collective action to succeed and to successfully explain such action. Bowles and Gintis (2006), Bowles and Hwang (2008) have moreover illustrated how these types of agents and social emotions can be formally modeled. In the sequel, we can make only an allusionary gesture to this literature but hope to capture some of the spirit of this research thrust.

3 A model of transportation demand with endogenous preference change

The setting of our analysis is a simple transportation system in which origin and destination patterns of travel are fixed between two locations, *k* and *l*, for, say,

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[1] Most generally, in his review of the literature on endogenous preferences, Bowles (1998) defines preferences as "reasons for behavior, that is, attributes of individuals that (along with their beliefs and capacities) account for the actions they take in a given situation (p. 78)". As such, Bowles sees preferences as being different from and going beyond mere tastes. See also Innocenti (1996) for a somewhat different take on the relationship between preferences and tastes.

employment-related commuting. The route or path of travel is also given. We model the demand for transportation services associated with travel between k and l as the solution to a problem of consumers (or households) maximizing utility subject to a budget constraint.

3.1 Underlying consumer choice theory

Assuming that the representative consumer's utility function is weakly separable in expenditures on commuting transportation, households seek to maximize the utility derived from transportation services, given the amount of income budgeted for such services. More concretely, they choose a vector of transportation services, q, to maximize the contribution to utility of these services, $f(q)$, subject to a budget constraint, $p'q = c$, in which p' is a transposed vector of user costs (each of which subsumes out-of-pocket costs, costs of waiting, and relevant opportunity costs), and c is the level of total expenditures on transportation services. If transportation services derive from different modes of travel, the elements of q can be construed loosely as quantities of mode choices.[2]

To impose some additional structure on the problem, we assume that the cost function characterizing expenditures on transportation services is in the MPIGLOG (or modified price-independent generalized logarithmic) family of cost functions specified by Cooper and McLaren (1992). We make this assumption because, for certain combinations of component aggregator functions, the demand functions implied by the general form of MPIGLOG cost functions are globally regular and hence integrable. Regularity is essential if inferences about the effects of policies intended to manage demand are to be supported by neoclassical consumer theory.

The MPIGLOG family of cost functions is a generalization of the PIGLOG family developed by Muellbauer (1975) and is an instance of the Gorman polar form (Gorman 1976), in which preferences are represented by a combination of price aggregator functions. For a utility level u and price vector p, the MPIGLOG family of cost functions can be written as

$$\ln C(u,p) = \ln P1 + uP2/[C(u,p)]^{\eta}, \tag{1}$$

in which ln denotes the natural logarithm of a variable, u is defined to lie between zero and one, and $P1$ and $P2$ are price aggregator functions. $P1$ is generally assumed to be homogeneous of degree one (HD1) in p, and $P2$ is HDη in p. Since Eq. 1 is an implicit function, it is easier to discuss the specification terms of the indirect utility function that is dual to it,

$$U(c,p) = \ln (c/P1)\,(c^{\eta}/P2). \tag{2}$$

In (2), c is the level of expenditures budgeted by the household for transportation services.

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[2] The problem statement is more general that it may seem because the elements of q can be broken out more finely according to alternative routes and departure times, etc.

Applying Roy's identity to (2) yields expenditure share equations of the form[3]

$$s_j = [\varepsilon_{1j} + \varepsilon_{2j}\ln(c/P1)]/[1 + \eta\ \ln(c/P1)], \tag{3}$$

where $s_j = p_j q_j / c$, $\varepsilon_{1j} = \partial \ln P_i / \partial \ln P_j$, $\sum_j \varepsilon_{1j} = 1.0$ and $\sum_j \varepsilon_{2j} = \eta$.

Defining a weighting expression, $Z = \eta \ln(c/P1)/[1 + \eta \ln(c/P1)]$, the share equations can be rewritten in terms of Z as

$$s_j = \varepsilon_{1j}(1 - Z) + (\varepsilon_{2j}/\eta)Z \tag{4}$$

The MPIGLOG demand system (4) will be globally regular when $P1$ is a linearly homogeneous function and $P2$ is Cobb–Douglas. The improved regularity properties of MPIGLOG demand systems mark an advantage for empirical work over PIGLOG SYSTEMS, such as Deaton and Muellbauer's (1980) almost ideal demand system (AIDS). But the former no longer aggregate exactly over individual consumers or households, as do the latter. While this may not constitute a grave concern (see Deaton 1992); Cooper and Mclaren 1992 suggest that in working with aggregate data, a vector of additional suitable exogenous variables, x, should be added to account for the distribution of consumer or household purchasing power. In the aggregate case, (4), then, becomes (or would be estimated as)

$$s_j = \varepsilon_{1j}(1 - Z) + (\varepsilon_{2j}/\eta)Z + \mu' x, \tag{5}$$

in which μ is a vector of parameters. In the sequel, we will, for expository purposes, ignore the last term on the right-hand side of (5).

From information on expenditure shares, the aggregate level of transportation expenditures, and user costs, distributions of transportation service use and vehicle counts can be directly produced for the aggregate case. For example, the aggregate numbers of users of transportation services j traveling between k and l, R_{jkl}, will be given by

$$R_{jkl} = s_j c / p_j, \quad \text{for } j = 1, \ldots, J, \tag{6}$$

where c now denotes an aggregate transportation expenditure level and letting r_j denotes the number of riders per vehicle of transportation services j, the numbers of vehicles per user of services j traveling between k and l, q_{jkl}, will be given by

$$q_{jkl} = s_j c / (p_j r_j), \quad \text{for} j = 1, \ldots, J. \tag{7}$$

Equation 2 is an instantaneous indirect utility function and share Eq. 3 represents a static equilibrium relationship. The solution to the consumer choice problem can be given a dynamic cast, however, by writing the time rate of change in an expenditure share as a disequilibrium process, in which 'habit persistence' or existing commitments prevent instantaneous adjustments in expenditures made in response to change in income or user costs. For example,

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[3] Roy's identity states that the Marshallian (or ordinary market) demand for good i is given by the negative of the ratio of the partial derivative of the indirect utility function taken w.r.t. the price of the good to the partial derivative of this function taken w.r.t. the aggregate expenditure level. See e.g., Varian (1978), p. 93.

$$\mathrm{d}s_j/\mathrm{d}t = \alpha_j(s_j^e - s_j), \tag{8}$$

where s_j^e denotes the partial equilibrium level of expenditure share j at time t (with time subscripting suppressed) and is given by the right-hand side of Eq. 4.

$$s_j^e = \varepsilon_{1j}(1 - Z) + (\varepsilon_{2j}/\eta)Z. \tag{9}$$

3.2 Preference change through consumption

We now wish to incorporate explicitly in the model changes in preference that accompany changes in 'consumption capital', which, following Becker and Murphy (1988), we define as knowledge of (or familiarity with), in this case, transportation services gained through their use. To operationalize this notion, let s_{j0} denotes the share of expenditures on transportation alternative j at an initial point in time t_0, and define the partial-equilibrium level of consumer knowledge about alternative j at any point in time t, to be $k_j^e = s_j/s_{j0}$. Then, assuming the existence of a disequilibrium adjustment process through which learning occurs [formally similar to (8)], the time rate of change in k_j, i.e., the rate of 'learning by consuming', can be written as

$$\mathrm{d}k_j/\mathrm{d}t = \theta_j(k_j^e - k_j), \tag{10}$$

when no 'decay' in consumption capital is assumed or as

$$\mathrm{d}k_j/\mathrm{d}t = \theta_j(k_j^e - k_j) - \delta_j(k_j - k_{j0}), \tag{11}$$

when allowing for a 'backsliding' effect. It is possible that rates of decay might be higher for decrements in initial allocations of knowledge capital, as consumers demonstrate a propensity to gravitate back to prior habits of consumption (Loewenstein and Elster 1992).

In the analysis to follow, we define $P1$ to have constant elasticity of substitution (C.E.S.):

$$P1 = \left[\sum_j \phi_j p_j^{-\rho}\right]^{-1/\rho}, \tag{12}$$

and $P2$ to be Cobb–Douglas:

$$P2 = \beta_0 \prod_j p_j^{\beta_j}, \qquad \text{where } \sum_j \beta_j = \eta < 1.0. \tag{13}$$

We now replace the 'distribution' parameters of $P1$ and $P2$ in (12) and (13), ϕ_j and β_j, with coefficients that vary directly over time with levels of consumption capital, $\phi_j^* = k_j\phi_j$ and $\beta_j^* = \eta k_j\beta_j/\sum_i k_i\beta_i$. For the forms chosen for the price aggregator functions and the time-varying coefficients, Eq. 9 takes the explicit form:

$$s_j^e = \phi_j^*(P1^*/p_j)^\rho(1 - Z^*) + (\beta_j^*/\eta)Z^*, \tag{14}$$

in which $P1^* = \left[\sum_j \phi_j^* p_j^{-\rho}\right]$ and $Z^* = \eta\,\ln(c/P1^*)/[1 + \eta\,\ln(c/P1^*)]$. Note that defining the partial equilibrium levels of consumption capital associated with transportation services j in terms of *normalizations of shares* ensures that, while the distribution parameters of $P1$ and $P2$ will vary over time, the respective degrees of homogeneity of these functions will remain constant.

3.3 Numerical simulations

To examine what difference the introduction of endogenous preference change and other-regarding norms might make to a model of travel demand, we conduct four deterministic numerical simulations based on the stylized behavior of two representative agents—a 'rational egoist' and an 'other-regarding' individual. The first is a 'baseline' run, in which there are no policies implemented and there is no learning or influence of social norms. The second simulation is conducted to gauge the effects of price changes on demand with fixed preferences and the third to determine the effect of price changes on demand with learning and decay in accumulated changes in social capital. The purpose of the fourth simulation is to gain a sense of the combined effects of learning and decay in accumulations (and losses) of consumption capital and the presence of heterogeneous agents. In these simulations, we assume that there are only two transportation choices—e.g., driving by automobile or using mass transit—and that a subsidy is given to users of the second alternative to induce them to use it more intensively. There is also a congestion tax imposed when a critical level of congestion along the route is exceeded. The tax is proportional to the level of congestion. If learning occurs through increased consumption of transportation services of a particular mode, users may come to prefer these services more than they did initially—they may *learn to like them better*. (This is, in any event, the case we consider). If there is no learning effect, then after disequilibrium adjustments are made, the original pattern of expenditures should be re-established. The presence of congestion also causes a decrease in the consumption capital associated with auto use of the other-regarding representative agent and an increase in the consumption capital associated with mass-transit use. These changes in the consumption capital of the other-regarding agent are proportional to the extent actual traffic congestion exceeds some critical threshold, when it exceeds this threshold. Defining traffic between locations k and l by modes 1 and 2, respectively, to be $q1kl$ and $q2kl$, the period flow capacity of the connecting link to be $capkl$ and the critical congestion level at which consumption capital of the other regarding agent is affected as $congn$, then the changes in consumption capital are, for k_1^e, $+\sigma((q1kl + q2kl)/capkl - congn)$, and for k_2^e, $-\sigma((q1kl + q2kl)/capkl - congn)$. The parameter σ is 1.0 when $(q1kl + q2kl)/capkl - congn \geq 0$ and zero otherwise.

Defining tax to be the congestion tax imposed on auto users when the critical level of congestion is exceeded, p_1^x the user cost of autos, π the subsidy given to users of mass transit, and p_2^x the user cost of mass transit (i.e., absent the subsidy), the most general statement of the model to be solved is as follows:

$$\mathrm{d}k_1/\mathrm{d}t = \theta_1(k_1^e - k_1) - \delta_1(k_1 - k_{10}), \tag{15a}$$

where $k_1^e = (1 - s_2)/s_{10} - \sigma((q1kl + q2kl)/capkl - congn)$,

$$\mathrm{d}k_2/\mathrm{d}t = \theta_2(k_2^e - k_2) - \delta_2(k_2 - k_{20}), \tag{15b}$$

where $k_2^e = s_2/s_{20} + \sigma((q1kl + q2kl)/capkl - congn)$,

$$\mathrm{d}s_2/\mathrm{d}t = \alpha_2(s_2^e - s_2), \tag{15c}$$

where $s_2^e = \phi_2(P1^*/P_2)^\rho(1 - Z^*) + (\beta_2^*/\eta)Z^*$,

$$\mathrm{d}k_{1a}/\mathrm{d}t = \theta_{1a}(k_{1a}^e - k_{1a}) - \delta_{1a}(k_{1a} - k_{1a0}), \tag{15d}$$

where $k_{1a}^e = (1 - s_{2a})/s_{1a0}$,

$$\mathrm{d}k_{2a}/\mathrm{d}t = \theta_{2a}(k_{2a}^e - k_{2a}) - \delta_{2a}(k_{2a} - k_{2a0}), \tag{15e}$$

where $k_{2a}^e = s_{2a}/s_{2a0}$,

$$\mathrm{d}s_{2a}/\mathrm{d}t = \alpha_{2a}(s_{2a}^e - s_{2a}), \tag{15f}$$

where $s_{2a}^e = \phi_{2a}(P1_a^*/p_2)^{\rho_a}(1 - Z_a^*) + (\beta_{2a}^*/\eta)Z_a^*$,

$$p_1 = p_1^x + tax(q1kl/capkl + q2kl/capkl - congn), \tag{15g}$$

$$p_2 = p_2^x - \pi, \tag{15h}$$

$$q1kl = (2 - s_2 - s_{2a})c/(p_1 r_1), \tag{15g}$$

$$q2kl = (s_2 + s_{2a})c/(p_2 r_2), \tag{15i}$$

where all variables and parameters (and analogous variables and parameters) are as defined above. Note that since $\mathrm{d}s_1/\mathrm{d}t = -\mathrm{d}s_2/\mathrm{d}t$, the time rate of change of the share of expenditures on the first type of transportation services need not be explicitly modeled.

In each simulation, the model is solved for 30 time periods. The values of the exogenous price and income variables are determined by the following forcing functions:

$$p_1^x = 1.75e^{0.025t}, \quad p_2^x = 2.25e^{0.02t}, \quad \text{and} \quad c = 3.00e^{0.015t},$$

and the parameters (and analogous parameters) are set to the following values:[4]

$$\alpha_2 = 0.85, \quad \theta_1, \theta_2 = 0.85, \quad \phi_1 = 0.7, \quad \phi_2 = 0.3, \quad \rho = 0.50, \quad \beta_2 = 0.33,$$
$$\eta = 0.9, \quad r_1 = 1.5, \quad r_2 = 15.0, \quad tax = 0.2, \quad congn = 0.7.$$

In simulations 2–4, subsidy $\pi = 1.5$ at $t = 16$–21, and is zero at all other times. In the first two simulations, the first two equations effectively drop out, as $k_1 = k_2 = 1$ and $\delta_1 = \delta_2 = 0$ throughout. In the third and fourth simulations, $\delta_1 = 0.05$ and $\delta_2 = 0.10$.[5]

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[4] These values were chosen on the basis of past experience in working with demand systems of this type, intuition, and experimentation. They do not correspond to any empirical case that we are aware of. Note that if the exponential growth rates of p_1^x, p_2^x, and c are identical, Z is constant.

[5] When the rates of decay in consumer capital are the same, the decay factor has no effect.

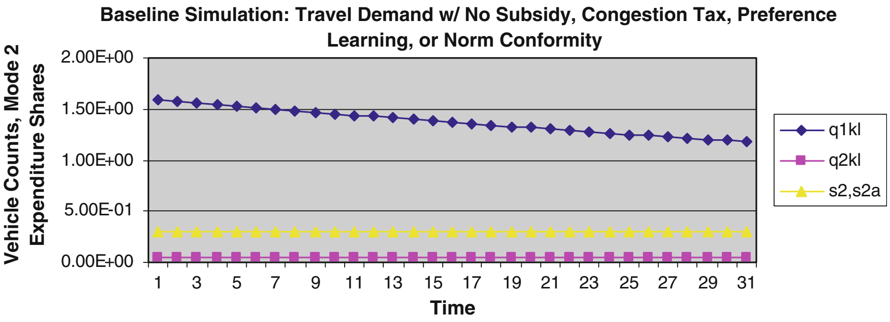

Fig. 1 Baseline simulation

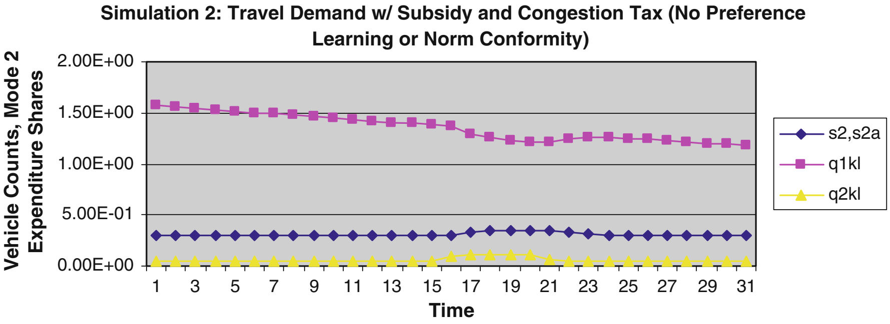

Fig. 2 Simulation 2

Figure 1 portrays the solution paths of the vehicle counts, and mode 2 expenditure shares of the two agents for the baseline run.[6] The gradual reduction in vehicle counts of mode 1 results from an income effect, as the budgeted amount available for transportation services grows at a slower rate than the service costs of the two modes. The mode expenditure shares of the two agents are identical and stable. Figure 2 portrays the solution paths of the same variables for the second run, in which the congestion tax is in force over the entire 30 periods and the subsidy is in effect between the 16th and 21st periods. The induced temporary shift in demand for the second type of service dissipates quickly after the subsidy is withdrawn and the expenditure shares return to the trajectories they were following prior to the subsidy's introduction. In Fig. 3, which portrays the solution paths of the featured variables for the third run, in which there is preference learning (with gradual decay), the introduction of the subsidy induces a more dramatic reduction in demand for auto travel and increase in demand for mass-transit services. Because of preference learning, the mode 2 expenditure share finds a stable growth path at a

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[6] The solution paths obtained for all simulations reflect stable 'growth' paths to which consumption patterns will return after exogenous shocks or learning effects occur. This property is due to the form of disequilibrium adjustment adapted for the model and the values of the adjustment parameters chosen. See Anderson and Blundell (1983).

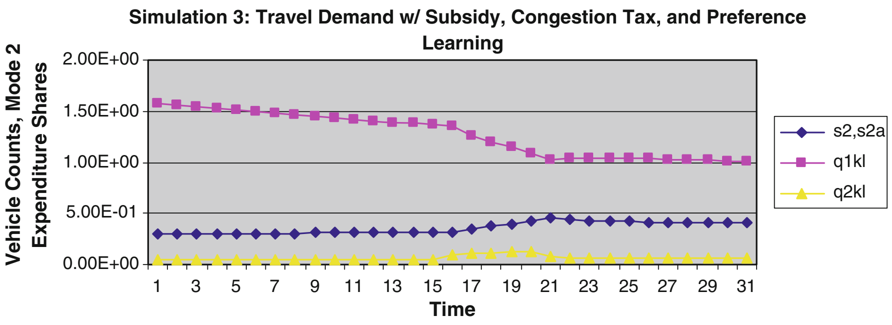

Fig. 3 Simulation 3

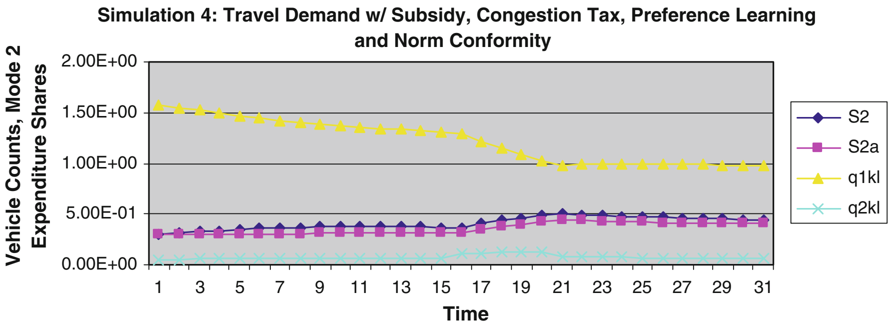

Fig. 4 Simulation 4

higher level than the baseline solution after the subsidy is withdrawn. In the final run, the combined effects of the subsidy and norm conformity on the other-regarding agent induce a higher mode 2 expenditure share on his or her part throughout the simulation (Fig. 4).

4 Conclusions

In the foregoing, we have suggested why and how the endogenous determination of preferences and heterogeneous motivations for economic behavior might be incorporated into models of transportation demand. We have explored the difference that the assumption of learning with decay of consumer capital and norm conformity might make in these models. Elsewhere, in Donaghy (1996), the author has investigated how optimal dynamic travel demand policies vary when learning by consuming is ongoing and has found in preliminary investigations that transportation demand policies that fail to account for such learning will be inappropriate (will generally over expend on subsidies). Clearly, much more remains to be done in investigating emergent systems properties in models with articulated networks, many interdependent heterogeneous agents, and intertemporally optimizing policy makers.

But we hope to have contributed to the formalizations that such investigations might adopt.

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Technical appendix: properties of the MPIGLOG demand system

To discuss the regularity properties of Eq. 2, which we reprise here as

$$U(c,p) = \ln(c/P1)\,(c^{\eta}/P2), \tag{16}$$

it is helpful to recall the set of conditions associated with regular indirect utility functions that are dual to cost functions. From standard duality theory (Diewert 1982; McFadden 1978), the indirect utility functions should satisfy the following conditions:

U1: U is HD0 in (c, p),
U2: U is non-decreasing in c,
U3: U is non-increasing in p,
U4: U is quasi-convex in p.

If $P1$ and $P2$ are positive functions, HD1 and HDη, respectively, and $\eta \geq 0$, (2) will satisfy U1 and U2. If $P1$ and $P2$ are also non-decreasing in prices, then U3 will be satisfied over the region where $c \geq 0$. Finally, concavity of $P1$ and $P2$, when $c \geq P1$, ensures quasi-convexity of U in p (Greenberg and Perskalla 1971), although concavity of $P2$ also requires that $0 \leq \eta \leq 1$.

As noted above, applying Roy's identity to (16) yields expenditure share equations of the form

$$s_j = [\varepsilon_{1j} + \varepsilon_{2j}\ \ln(c/P1)]/[1 + \eta\ \ln(c/P1)], \tag{17}$$

where $s_j = p_j q_j/c$, $\varepsilon_{ij} = \partial \ln P_i/\partial \ln p_j$, $\sum_j \varepsilon_{1j} = 1.0$ and $\sum_j \varepsilon_{2j} = \eta$.

In the region $c \geq P1$, ln(c/$P1$) will be non-negative. Thus restricting the price elasticities of $P1$ and $P2$, ε_{1j} and ε_{2j}, to be non-negative will ensure that $0 \leq s_j \leq 1$. Following Deaton and Muellbauer (1980), Cooper and Mclaren 1992 take the MPIGLOG share equations to indicate that, for given prices and rising income, the share s_j moves monotonically from ε_{1j}, the level of the subsistence expenditure share for the 'poor', toward (ε_{2j}/η), the asymptote share level for the 'rich.'

Some insight into (17) can be gained by defining the following expression:

$$Z = \eta \ln(c/P1)/[1 + \eta\ \ln(c/P1)]. \tag{18}$$

Then, the share equations can be rewritten in terms of Z as

$$s_j = \varepsilon_{1j}(1 - Z) + (\varepsilon_{2j}/\eta)Z, \tag{19}$$

that is, as weighted averages of the shares of the 'rich', (ε_{2j}/η) and 'poor,' ε_{1j}.

It is apparent from the form of the share equations that the potentially unbounded variable, 'real expenditures', ($c/P1$), enters the right-hand side only through the bounded variable, Z, and the potentially unbounded price term enters through the HD0 elasticity terms ε_{1j} and ε_{2j}. From the perspective of co-integration accounting, then, the budget shares have an appropriate set of explanatory variables.

Other properties of the MPIGLOG system can also now be easily derived in terms of Z. The expenditure elasticities of demand for each type of service j, E_j, satisfy

$$E_j = 1 + (\varepsilon_{2j}/s_j - \eta)\,(1 - Z), \tag{20}$$

while the price elasticities of demand, M_{ij}, satisfy

$$M_{ij} = [\varepsilon_{1j}(1 - Z) + (\varepsilon_{2j}/\eta)Z - \varepsilon_{2i}\varepsilon_{1j}(1 - Z)]/[s_i - \delta_{ij} + \eta\varepsilon_{1j}(1 - Z)], \tag{21}$$

in which δ_{ij} is the Kronecker delta—i.e., assumes the value of 1.0 when $i = j$, and is zero everywhere else. A typical term of the Slutsky matrix is

$$S_{ij} = (c/p_i p_j)\,[s_i M_{ij} + s_i s_j E_i]. \tag{22}$$

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