



15.879 Advanced System Dynamics Modeling

Spring 2025

Exercise 1- Architectural Choices for Two Models

No submission is required but see below for preparations. To be discussed in class on Friday 2/7/2025

The purpose of this exercise is to think through key architectural choices in building system dynamics simulation models. The focus of this course is on the quantitative modeling process, so we assume a broad problem definition and a set of mechanisms and/or dynamic hypotheses have already been developed (e.g. in consultation with clients, stakeholders, theory, or qualitative data) and can inform our modeling process. Here that background information is provided for the two problems adopted from chapter 5 of Business Dynamics (by John Sterman).

In the class we will be discussing a few key architectural choices that we will need to take if we were building models for these cases. Those choices are summarized below, with additional discussion and explanation provided in the memo titled “Common Modeling Challenges: A brief guide for aspiring modelers”. **In preparation for the class please read that memo, then go through the case information and think through the questions below.**

1- What is a good problem definition?

A clear problem definition is critical for a successful modeling project. Each case provides various information relevant to the problem definition, but also leaves out much that is informative for an actual modeling project. In a real project you will fill in those gaps in consultation with your stakeholders. Here you have more freedom to make those choices as you see fit. Focus on clarifying the problem definition by considering who will be using the model, and for what purpose? How would you know that your modeling project has been a success? It may be helpful to consider which of these common purposes apply to the desired model, and spell out more concrete criteria for success in a given case:

- Bringing stakeholders together to share their perspectives and appreciate others’
- Offering plausible explanations of historical reference modes
- Assessing alternative dynamics that may emerge from a set of mechanisms
- Designing management flight simulators for teaching and learning
- Designing policies to manage a system using some policy levers (what are those levers?)
- Estimating the strength of different mechanisms empirically
- Providing decision support tools for policy makers to be embedded in routine decision making

Other purposes may also be considered. A typical project may focus on one (or two closely related) of such primary purposes, but attempting to do several of them with the same model is not a good idea. These choices have a huge impact on all of the later decisions and may change the scope and complexity of a project by orders of magnitude, so consider them carefully in any project. In this exercise you can specify any purpose -- as long as that is consistent with the case information-- and explore its implications for the other architectural choices.

2- What is a good time horizon for the problem?

Identify the time horizon for the model, so that it can serve the purpose you have identified.

3- What high level mechanisms should be included in the model, and what should be left out?

For our exercises here we are providing prepared causal loop diagrams (CLDs) that specify the high-level mechanisms to be included in the model. In practice much research goes into determining those

boundaries and developing the CLDs. Yet, even if the ultimate model boundary is defined, the path to getting there is not prioritized. So, in lieu of specifying the model boundary from scratch, focus on prioritizing the feedback loops and other mechanisms in the existing CLDs, with an eye on an iterative modeling process. Which part will you model first, what comes next, and what you may add only if you have plenty of time?

4- What is the right level of aggregation?

With the model boundary and key mechanisms at hand, consider the appropriate level of aggregation. Some of those choices may be interwoven with the next question about stock variables, so you may consider them together. Think through the pros and cons of alternatives as you consider different aggregation levels.

5- What are the key sources of inertia and what are good stock variables?

Focus on sources of inertia within your model boundary that are central to the mechanisms in CLDs. Then for each source identify at least one primary stock variable that can capture the source of inertia. If you think more than a single stock (e.g. a stock and flow chain) is more appropriate, highlight those and justify, with an eye on your selected level of aggregation. Finally, prioritize those stocks: if you had to build your model with minimum number of stocks possible, which ones would you choose? Which stocks will be at the next level of priority? Why?

Below you can find the information on the two cases.

Case 1- The Thoroughbred Market: Demand, Supply, and Speculative Bubbles

The racing horse market in the U.S. went through an overshoot and collapse during the 1990's. The basic mechanisms for this overshoot and collapse are documented in Sterman's Business Dynamics (challenge on page 174), and the discussions and causal loop diagrams he develops in the instructor manual. These discussions and causal loop diagrams are summarized below¹.

Demand for Thoroughbreds: Economics and Social Status

Exhibit 5-16 adapts a general market structure to the thoroughbred horse market, illustrating the factors that drive demand and supply. On the demand side, two primary motivations drive the purchase of thoroughbred horses: economic investment and social status.

From an economic perspective, purchasing a thoroughbred can be viewed similarly to investing in an asset with a risky return, analogous to holding common stock. The return on such an investment comprises two key components: (1) the present value of the horse's potential earnings from race winnings and breeding fees, and (2) potential capital appreciation in the horse's market value. These economic incentives create a demand structure akin to that depicted in Exhibit 5-15, albeit adapted for the thoroughbred market. Specifically, the higher the price of a thoroughbred relative to its expected earnings, the lower the net present value of the investment, leading to reduced demand (feedback loop B1).

Expected winnings are primarily determined by the horse's quality and the size of prize purses in races. These purses, in turn, depend on the total handle—the total amount wagered on horse racing each year. Similarly, breeding fees are influenced by the horse's market value. While the handle, purses, and breeding fees are interlinked in a feedback system, these additional loops have been omitted from Exhibit 5-16 for clarity.

However, as an investment, thoroughbreds generally offer poor financial returns. The initial purchase price is high, and the associated risks are even greater. While top-tier horses—such as Kentucky Derby winners—can generate millions in earnings, academic research suggests that, on average, horse owners incur financial losses. This may be partly because social status plays a crucial role in the decision to own a thoroughbred.

Thoroughbred ownership has long been associated with elite social circles, often referred to as the "sport of kings." Owning a high-priced thoroughbred signals substantial wealth, refined taste, and aristocratic status. The more expensive the horse, the greater the prestige it conveys, forming a reinforcing loop of conspicuous consumption (R2). Furthermore, participation in the thoroughbred market grants access to exclusive networks of wealthy, powerful, and famous individuals. This social capital can facilitate upward mobility for those seeking to integrate into elite circles, creating another reinforcing loop—referred to here as the Gatsby loop (R3). This dynamic aligns with the broader category of Veblen effects, named after the institutional economist Thorstein Veblen, which describe consumer behaviors where higher prices enhance perceived value and desirability. Such effects are especially prevalent in markets where the intrinsic value of an asset is ambiguous and difficult to quantify—such as fine art, rare wines, and even high-priced management consultants.

The Supply Structure of the Thoroughbred Market

The supply side of the thoroughbred market follows the same general structure outlined in Exhibit 5-15 but is adapted to include the breeding and birth processes of horses, which involve inherent delays. These delays play a critical role in shaping market dynamics, as breeding responses to rising demand take years to materialize in the form of new racehorses.

Speculative Dynamics and Market Bubbles

In the early 1970s, as inflation accelerated in the United States, thoroughbred prices began to rise.

¹ This material is adopted with minor edits from Instructor's Manual to accompany "Business Dynamics: Systems Thinking and Modeling for a Complex World" by John Sterman (McGraw-Hill, 2000)

Regardless of which specific event triggered the collapse, a downturn was inevitable. Had these particular shocks not occurred, prices would likely have continued rising until an even less consequential event precipitated the decline.

The Aftermath: Market Collapse and Panic Selling

Once price appreciation ceased, the speculative demand vanished, and debt-laden horse owners rushed to sell their holdings before prices declined further. This panic selling accelerated the downturn, consistent with economist J.S. Mill's observation that speculative asset prices often fall much more quickly than they rise.

As prices plummeted, banks called in loans that had been secured by now-depreciating thoroughbreds, triggering further forced selling. This phenomenon, known as a margin call loop, is a common feature of speculative bubbles but is not explicitly depicted in Exhibit 5-16.

An alternative hypothesis suggests that the market remained in equilibrium at all times and that price fluctuations merely reflected changes in expected earnings from racing and breeding. However, Exhibit 5-17 contradicts this notion by showing that total race purses at North American tracks remained relatively constant in real terms throughout the 1970s and 1980s, despite the dramatic rise and fall in horse prices.

Supply Responses and Delayed Adjustments

Exhibit 5-18 illustrates how supply-side adjustments lagged behind price movements. The birth rate of thoroughbreds in the U.S. grew modestly from 1965 through the mid-1970s. Once the price surge began, birth rates accelerated, nearly doubling between 1977 and 1987. However, due to biological and operational delays, the peak in births did not occur until 1987—three years after thoroughbred prices had peaked in 1984.

Similarly, the total stock of active racehorses continued to grow even after prices collapsed, as existing foals matured into racing age. The breeding stock itself declined only after the rate of new births dropped below the rate at which older horses were retired from breeding. These extended lags illustrate a fundamental challenge in markets with long production cycles: supply responses often overshoot demand trends, exacerbating the boom-and-bust dynamics.

Conclusion

The thoroughbred horse market exhibits many characteristics of speculative asset markets, driven by a mix of economic and social factors. While race winnings and breeding fees provide a fundamental basis for valuation, social status and speculative expectations often dominate market dynamics. Historical price movements suggest that speculative bubbles in thoroughbreds—like in other asset markets—are fueled by reinforcing feedback loops and eventually collapse when speculative demand dries up. Additionally, supply-side responses are inherently delayed, contributing to prolonged boom-and-bust cycles. These insights have broader implications for understanding the role of speculation, status-driven consumption, and delayed supply adjustments in other asset markets.

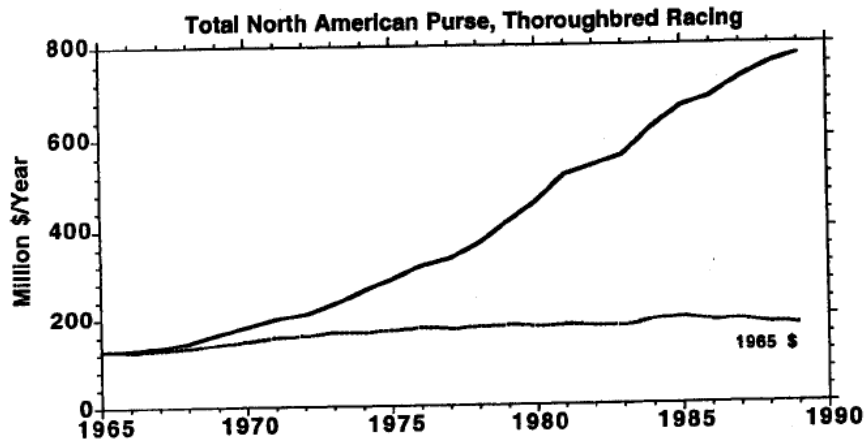


Exhibit 5-17 Thoroughbred purses remained roughly constant in real terms.

Source: Hermann and Link (1990)

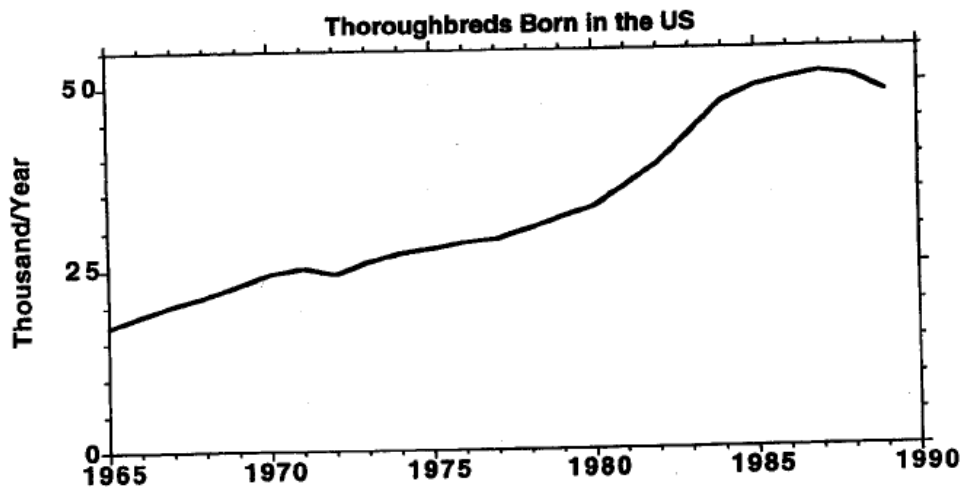


Exhibit 5-18 The expansion of thoroughbred supply

Source: Hermann and Link (1990)

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Case 2- Congestion, sprawl, and transportation mode

Sections 5.6.1-3 in Business Dynamics discuss some of the challenges in managing congestion in urban areas. In summary, the traditional view of traffic congestion sees it as a simple open-loop problem: when there's congestion, build more roads. However, the reality involves multiple interconnected feedback loops that make this solution ineffective.

The core mechanism starts with the physical relationship between travel time, highway capacity, and traffic volume. When new roads are built to reduce congestion, several compensating feedback processes kick in:

1. When travel times decrease due to new roads, people respond by:
 - Taking more discretionary trips
 - Making longer trips
 - Switching from public transit to cars
2. The public transit system faces its own challenges when road capacity increases.
 - Ridership declines as driving becomes more attractive
 - This leads to reduced revenue while fixed costs remain high
 - Transit authorities respond by either cutting service or raising fares
 - Both responses make transit even less attractive, creating a "death spiral"
 - Eventually only those who cannot afford cars remain as transit users
3. The suburban expansion effect:
 - New roads make outlying areas more accessible
 - People and businesses move to these areas
 - This creates new traffic and longer average trip lengths
 - The expanded region requires even more driving since destinations are spread out
 - The lower population density makes public transit less viable

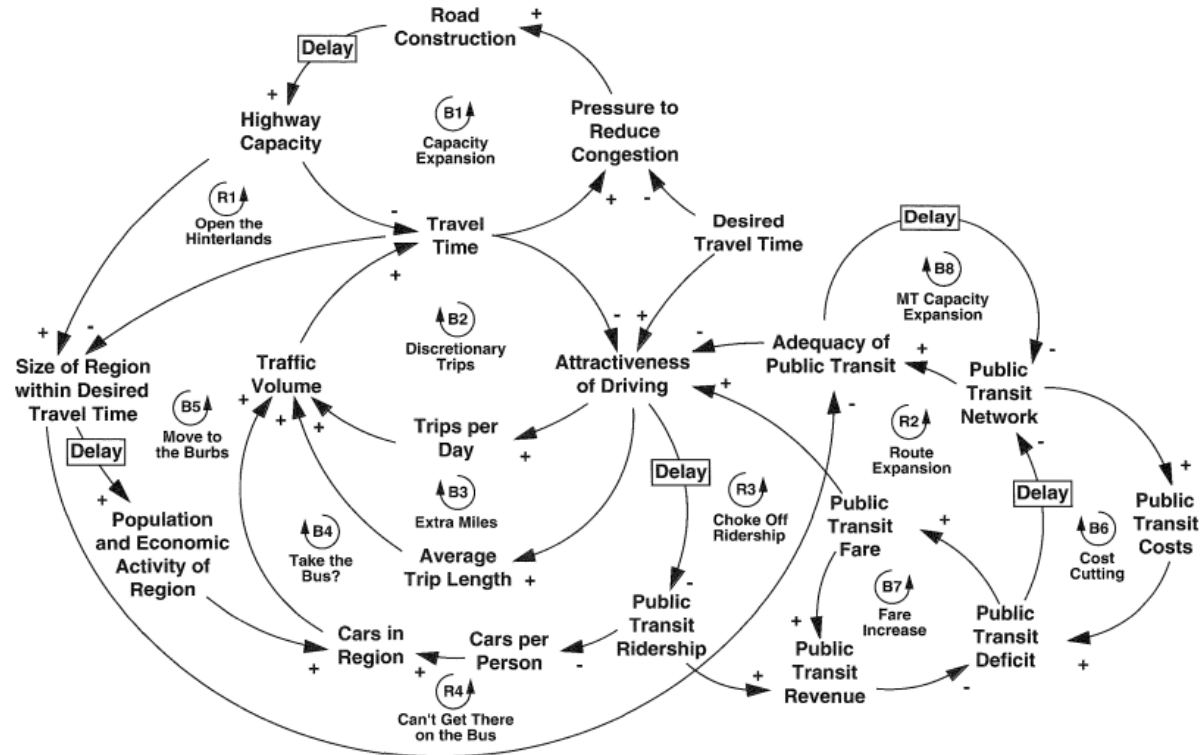
These feedback loops mean that any reduction in congestion from new road construction is temporary. Traffic expands to fill the available capacity, much like Parkinson's Law where "work expands to fill the time available." Studies show that within just 5 years, 90% of new road capacity is filled with induced traffic.

Sterman cites examples like Boston's Route 128 and London's M25 orbital motorway, which were repeatedly widened but continued to face severe congestion as each expansion attracted more local traffic and development. Rather than solving congestion, road building often creates a self-reinforcing cycle of car dependency, suburban sprawl, and eventual gridlock.

This analysis reveals why technological solutions focused solely on increasing road capacity are unlikely to solve congestion in the long term - the fundamental feedback mechanisms that generate traffic will still be in place.

Below you can find a copy of figure 5-37 from Business Dynamics. This figure is built through a detailed discussion of congestion feedback loops in a metropolitan area, summarized above. You may read the sections 5.6.1-3 of Business dynamics for more information.

FIGURE 5-37



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15.879 Building Serious System Dynamics Models from Scratch
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