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SYSTEM DYNAMICS FOR ESTIMATING SUAS OPERATIONS

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ABSTRACT

The *sUAS Adoption and Operations* model incorporates the impacts of public perception of small Unmanned Aircraft System (sUAS) operations and policy implementation into a holistic model to complement sUAS forecasts. The model is intended to help policymakers, regulators, and analysts understand key drivers and test the impact of policy, perception, and safety on adoption and operations. This paper provides an overview of the model, its relevance to Federal Aviation Administration (FAA) forecasting of sUAS adoption and operations, and a case study to demonstrate the "what if" capability of the model.

1 INTRODUCTION

According to the Federal Aviation Administration (FAA), registrations of small Unmanned Aircraft Systems (sUAS) went from just over 100,000 registered owners in 2015 to over 772,000 registered owners in 2017 (FAA Forecasts 2018). With potential application in package delivery, infrastructure inspection, emergency services, agricultural applications, and many other applications, use of sUAS will only continue to grow. As regulations expand to enable operations over people (Federal Register 2019), there may be additional concerns of noise, privacy, safety, and security. To prepare for operational challenges, the FAA needs forecasts of the number of sUAS operations. Current FAA forecasts are based on site registrations, industry research, and economic analysis of industry (FAA Forecasts 2018) that tend to focus on number of airframes, not number of operations. While sUAS forecasts account for economic drivers, few account for feedback of public reaction and policy, which are seen as major drivers by industry stakeholders (FAA Workshop 2016).

We are pursuing a modeling framework that incorporates a holistic approach to complement existing FAA methods to forecast sUAS. This approach may provide additional help to policymakers, regulators, and analysts as they may be able to test the impact of policy, perception, and safety on adoption and operations. A key component of that framework is a dynamic simulation model of sUAS growth in adoption and daily operations. The *sUAS Adoption and Operations* model incorporates:

- concerns associated with public perceptions of noise, privacy, safety, and security
- enablers such as traffic management and Beyond Visual Line of Sight automated flight
- Federal and local policy and regulations.

Public perception with respect to various potential concerns can have negative feedback on potential growth in applications and sUAS operations. Public perception can affect the amount of public pressure on policymakers, which impacts the strength of polices and regulations surrounding sUAS and the timing of new regulations which may expand access. Understanding the potential impact of public perception will

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help the FAA think strategically about public engagement and response to UAS activity. Thus, including such feedback in the *sUAS Adoption and Operations* model was a primary objective of this effort.

In addition to public perception, the *sUAS Adoption and Operations* model incorporates potential future enablers such as traffic management and Beyond Visual Line of Sight (BVLOS) automated flight and the associated policies, regulations, and procedures that enable their operational use. Traffic management refers to the ability to have real-time information on sUAS operations that would facilitate higher density operations through both tactical and strategic coordination, especially in close proximity to legacy traffic. Traffic management is likely to include some sort of capability of the sUAS to identify itself and broadcast its position, similar to how commercial aircraft currently operate. BVLOS refers to the ability for sUAS to operate beyond the distance that a remote pilot can physically see them. The allowance of BVLOS refers to the general use of BVLOS and not the approval of individual waivers. Our subject matter experts (SMEs) believe that once traffic management is implemented and BVLOS automated flights are allowed, the floodgates could be open for significant increases in adoption and the number of sUAS operations. As operations rise, so too could the number of undesirable incidents which could negatively affect public perception. Finally, the *sUAS Adoption and Operations* model incorporates the level of restrictions imposed on operations and implementation timing of both Federal and local regulations, which can affect how many sUAS can operate and with what frequency. Policies and parameters are substantiated as inputs to the dynamic model, which after running for a pre-determined length of time will estimate the number of sUAS adopted and the number of hours of operation over that time period.

2 BACKGROUND: SYSTEM DYNAMICS AND RELEVANT APPLICATIONS

System dynamics is a high-level simulation technique to study and manage the behavior of complex systems as they evolve over time. It allows for a holistic view that can incorporate outside factors and interdependencies among those factors. It relies heavily upon the structure of interactions in a program using basic building blocks of stocks (amounts accumulated) and flows (rates filling and depleting stocks) (Sterman 2018).

System dynamics has been used to model technology diffusion in many applications including renewable energy (Bernardes 2016), cloud computing (Tsai and Hung 2014), and RFID technology (Chen 2011). Normally, new technology is adopted in an S-shaped curve as shown in Figure 1. The innovation catches on with a few early adopters, and then contact with these early adopters reaches a critical mass among imitators and leads to the fast spread of this new idea and an exponential growth of adoption. After a period of exponential growth, the adoption rate eventually slows down as it reaches an equilibrium level and may even drop slightly below this peak (Bass 1969; Rodgers 2003). A classic example is the spread of adoption of the internet in the 1990s (Rodgers 2003).

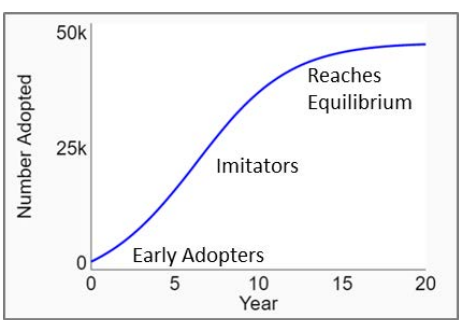

Figure 1: Technology is adopted in an S-shaped curve.

System dynamics is not only used to model technology diffusion; it is often used to help the public policy process more generally. Applications of system dynamics to urban planning as well as social welfare policies can yield important lessons for policymakers and regulators (Ghaffarzadegan et al. 2010; Zagonel et al. 2004). Often, implementing a public policy or regulation can trigger unexpected feedback in the environment. Additionally, experimenting with different types of regulations can be expensive because once implemented, some policies are hard to reverse, or it will be difficult to regain the public's trust (Ghaffarzadegan et al. 2010). System dynamics allows the modeling of a complex system to include these potential feedbacks and also allows "what-if" analysis and experimentation.

Our research is intended to demonstrate the feasibility of applying system dynamics of perception to sUAS technology forecasts to help inform FAA regulators on the potential impacts of various policies and regulations. Applying system dynamics to this research area provides a framework for "what-if" analysis .to help understand the drivers impacting growth in sUAS operations. The fidelity of the systems dynamics modeling approach lends itself best to comparative analysis not specific absolute forecasts.

3 MODELING AND METHODOLOGY

The *sUAS Adoption and Operations* model was built using a System Dynamics simulation software package called Stella Architect developed by iSee systems. Following the system dynamics framework shown in Figure 2 we identified key factors and causal relationships which we used to substantiate the stocks, flows, and feedback formulas defining the model. For example, in the *sUAS Adoption and Operations* model, the number of sUAS adopted, level of perception, and level of rules accumulate in stocks and change through a rate of flow based on interdependencies in the model.

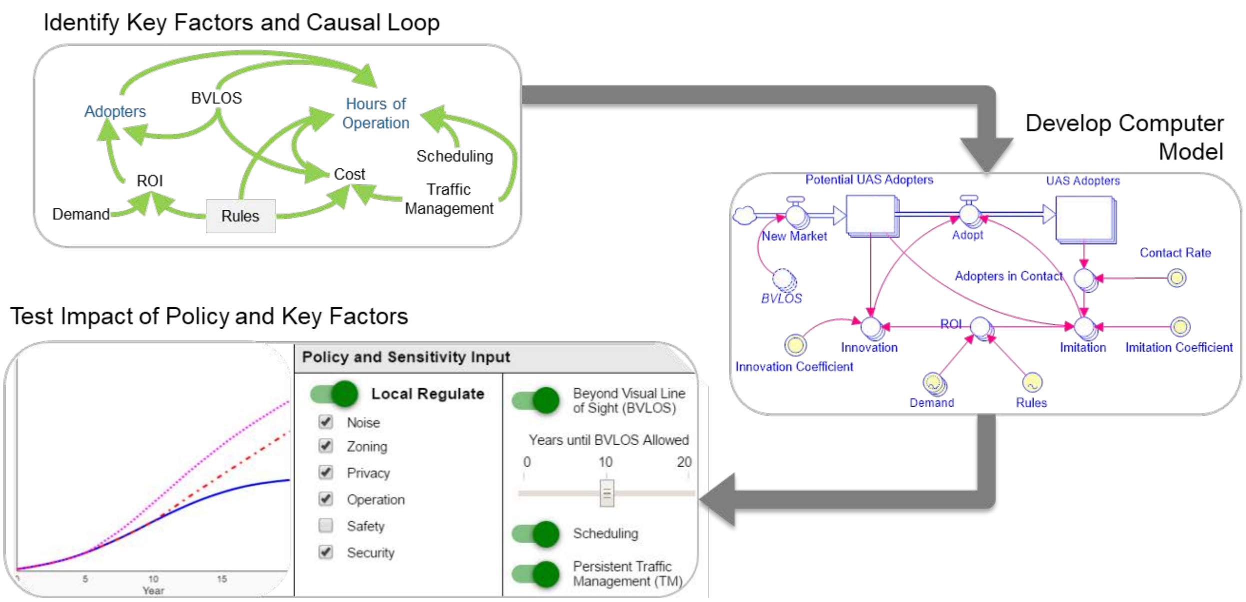

Figure 2: Applying system dynamics to identify key factors and to model and test system behavior.

The complexity of the system, subjective components, and early stage of sUAS use posed several challenges to the model development. While the system dynamics technique is powerful because of its capacity to model complex systems, one of the biggest challenges is to accurately and completely define such a complex model. Each component, key factor, and interdependency was discussed with SMEs during model development to ensure the validity of the model.

A second challenge with the system dynamics approach is modeling perception and the lack of available data for perception and response. To handle the subjectivity, perception is modeled as a relative level from 0 to 100 based on surveys on public reaction to drone use (Office of Inspector General 2016; Bajde et al. 2017). The fidelity of the model of such a complex system is intended to be at a level appropriate for comparative analysis to discern sensitivities to assumptions, initial conditions, and implications of potential policy changes.

3.1 Model Overview

sUAS adoption and operations is modeled as part of a complex system with feedback from incidents, public perception, and regulatory response. Figure 3 illustrates a high-level view of the model flow and major components. Each component represents a module within the model. In the model, hobbyists and commercial and public entities adopt sUAS through early adoption and imitation until the market becomes saturated. Growth in adoption increases daily operations. Daily operations can benefit individuals and the community through, for example, package delivery, safety inspections, or first responder support. However, increases in sUAS operations can also result in privacy, safety, and security incidents at varying levels and contribute to visual and auditory noise. Incidents and tolerance influence the level of perceived benefit and negative perception of sUAS operations. The level of perceived concerns and operator input influences the public response of rules, regulations, or conversely incentives. Rules, regulations, and incentives may impact the cost and frequency of operations (zoning laws, for example, may limit when or where sUAS can fly). It may also impact the return on investment perceived by adopters impacting rates of adoption.

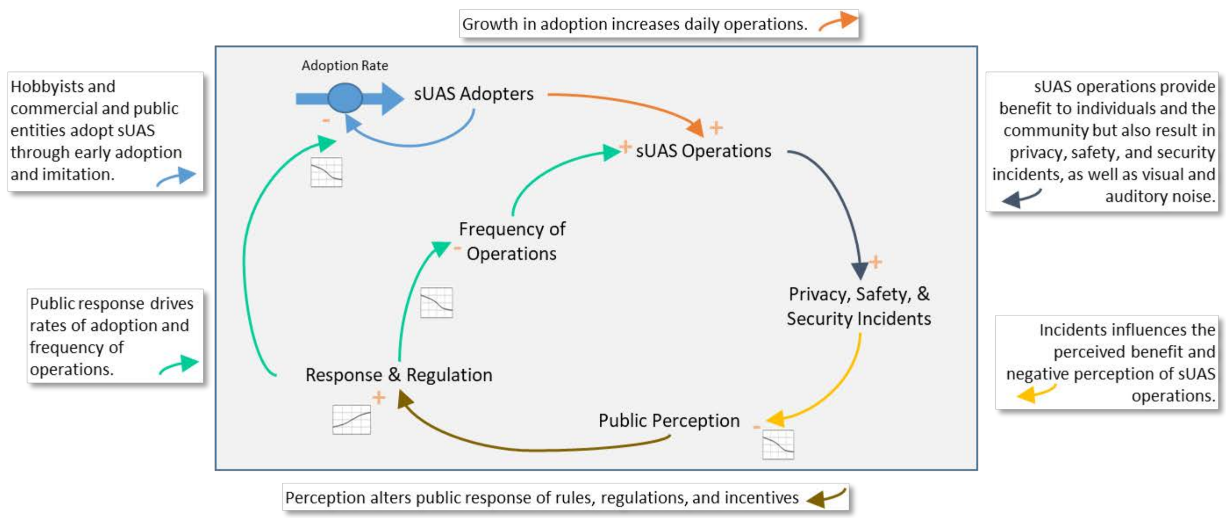

Figure 3: *sUAS Adoption and Operations* major components and model flow.

3.2 Policies and Input Parameters

Many of the input parameters and policies can be changed by the user before running the model, which allows the user to compare results from a variety of "what-if" scenarios. The user interface includes several policies and parameters that influence relationships in the model including local and Federal rules, community parameters, the level of safety and security incidents and other drivers such as traffic management and BVLOS automated flight. Appendix A provides a list of the major policies and input parameters included in the model interface, as well as the value range. These parameters include:

- BVLOS automated flight and traffic management regulations
- Probability of incidents (good and bad)
- Community type (urban/suburban/rural)
- Rules and regulations (Federal/local)
- sUAS fleet and operations (initial values)

The first type of major policy input parameters are parameters for BVLOS automated flight and traffic management. The model includes two types of traffic management: 1) scheduling air space to allow deconfliction and 2) persistent traffic management with real time availability of information with sUAS broadcasting position to other aircraft. BVLOS automated flight refers to sUAS operations where the pilot is unable to see the aircraft and collision and avoidance functionality is automated. The ability to have BVLOS automated flight increases the potential public and commercial market for sUAS while traffic management supports more frequent and safe operations.

Next, the model includes input parameters for the probability of incidents, both good and bad, and the community type. These incident probabilities affect social perception which can in turn affect the amount of regulations and dampen or increase the number of operations. The model additionally has parameters for community type, since population density may influence the frequency of incidents and the perception of those incidents. Different types of communities are assumed to respond differently to incidents and have different levels of engagement with respect to regulation. Population density also impacts the likelihood of incidents. Parameters for community type are modeled as urban (>=1,000 people per square mile), suburban (100<= X <1,000 people per square mile), and rural (<100 people per square mile).

The model additionally includes options for local and Federal regulations related to noise, zoning, privacy, operations, safety, and security as well as parameters for the level of response (strict or lenient). Regulations can affect the cost and frequency of operations as well as the perceived return on investment for adopting sUAS. Finally, the last set of parameters include the current fleet and potential market for sUAS as well as the baseline hours of daily and nightly operations. Feedback on perception, regulations, and policy impact the number of sUAS adopted and the frequency of operations during the simulation.

3.3 Outputs and Model Validation

The model tracks output for the cumulative number of sUAS adopted by type—public, commercial, and hobby—as well as the total daily hours of operations per type. The level of negative perception and benefits are given on a scale from 0 to 100 also for every day of the simulation run, with 100 representing the maximum possible negative perception or positive benefit and 0 representing the minimum. Regulation is divided into levels of rigidity, incentives, and ambiguity tracked daily on a scale from 0 to 1. Rigidity is the level of regulations that impose restrictions and costs on sUAS operations; incentives is the level of regulation that encourages the use of sUAS operations; and ambiguity is the remaining unregulated space. The levels of rigidity, incentives, and ambiguity of regulations add to 1.

The structural and behavioral validity of the model was tested according to standard validation techniques in the system dynamics field (Barlas 1996; Zagonel et al 2004). The standard way to validate a systems dynamics model is to first validate the internal structure of the model and then to test the behavior of the model (Barlas 1996).

The structure of the model was validated in several ways. First, we involved SMEs in the model building process to ensure the relationships and feedbacks in the model were what they would expect in the real world. Next, we used historical data whenever it was available for model parameters. For parameters without any available data, we consulted with these same experts to help us come up with estimates for parameters and functions.

After validating the internal structure of the model, the behavior of the model was tested. Extreme values for various parameters were tested to ensure extreme conditions would yield expected results. For example, if the potential sUAS market is 0, then there should be 0 adopters in the system at the end of the run. Additionally, we conducted a sensitivity analysis and worked with SMEs to confirm that the key variable impacts on model output were as expected and that the model responds to changes in an intuitive way. For example, increases in operational cost or in the strictness of regulatory response would be expected to dampen operations and adoption. Increases in operations would be expected to increase negative perception of safety due to the absolute increase in the number of safety incidents. The sensitivity analysis showed that adoption was most sensitive to the allowance of BVLOS, timing of BVLOS, the potential market for sUAS, costs impacts of traffic management, and the strictness of regulation. Impacts of BVLOS are further explored in Section 4.

Comparing model output data to historical data would be the ideal next step in the data validation process. However, while there is some recent historical data on sUAS registrations and limited data on UAS sightings and incidents, sUAS adoption and use is still in its infancy. Additionally, the full extent of the sUAS market and supporting technologies cannot be known this early on nor is there any data source for the number of operations.

4 ANALYSIS OF BEYOND VISUAL LINE OF SIGHT (BVLOS) REGULATIONS

An important case study for regulators is how the routine use of BVLOS automated flight will affect the market and public perception. Allowing sUAS to fly beyond the visual line of sight could facilitate increased adoption and more hours of operation, as BVLOS further enables commercial and public entities to use drones for package delivery, inspection, and other applications. To understand the impact of BVLOS and the timing of when such operations will be allowed, the *sUAS Adoption and Operations* model was run under three scenarios:

1. Baseline model without BVLOS
2. BVLOS allowed in 15 years
3. BVLOS allowed in 5 years

The model is run for a 20-year period for a medium-sized urban area. The baseline scenario includes both Federal and local regulations (with zoning and privacy laws left to localities and safety at a Federal level) and traffic management (initially scheduling air space and then replaced with real-time traffic management). For the BVLOS scenarios, it was assumed that only public and commercial entities would use the BVLOS technology; hobbyists would be limited to within line of sight operation.

A sensitivity analysis was conducted to identify which key input variables impacted adoption and operations. To identify the required runs, the model was run until the average value of the output converged. The average value for all output variables converged in less than 250 runs. The model was then run 500 times for each scenario with distributions assigned for each key input based on their level of uncertainty. All non-binary input followed a triangular distribution. The main output values were compared between the three scenarios across public, commercial and hobby entities (each entity is compared along its own scale). The dark blue in Figures 4 to 7 represents the 25^{th} to 75^{th} percentile while the light blue represents the 10^{th} to 90^{th} percentile. The absolute numbers in the output are not as valuable as the comparison between the three scenarios.

4.1 Adoption Results

Figure 4 below shows the number of sUAS adopters in the three different scenarios. For the purpose of the model, we count one adopter for each aircraft. As one would expect, allowing BVLOS increases the potential market, which in turn increases the number of public and commercial adopters. However, there is a substantial difference in the number of adopters depending on if BVLOS is allowed in 5 or 15 years. Allowing BVLOS earlier makes a bigger impact by year 20, as potential adopters have had more time to enter the market. The number of both public and commercial adopters at year 20 is almost twice as high between allowing BVLOS at 5 years versus not at all. Allowing BVLOS at year 15 does not allow for the full adoption of the technology by year 20, so while there is still an increase in number of adopters, it is not as stark. Note that there is no major effect on hobbyists since the model assumes they will not be able to use BVLOS technology.

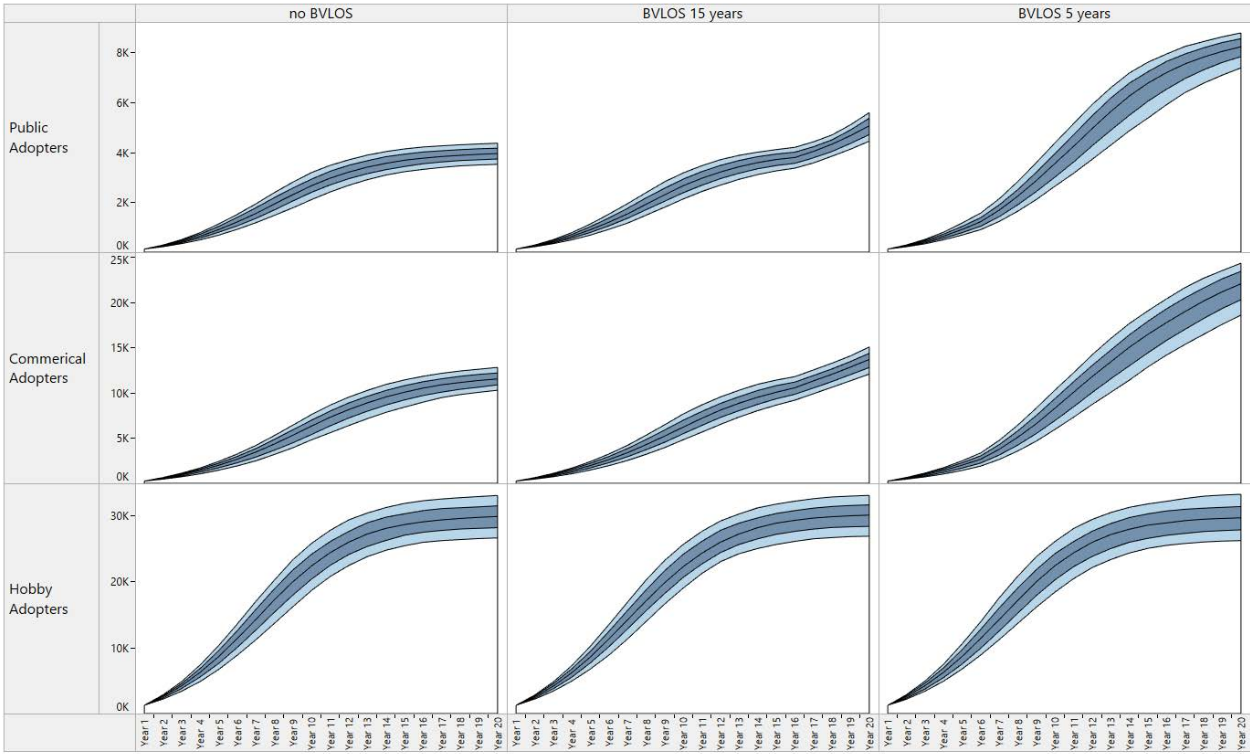

Figure 4: Impact of BVLOS at 15 and 5 years on sUAS adoption.

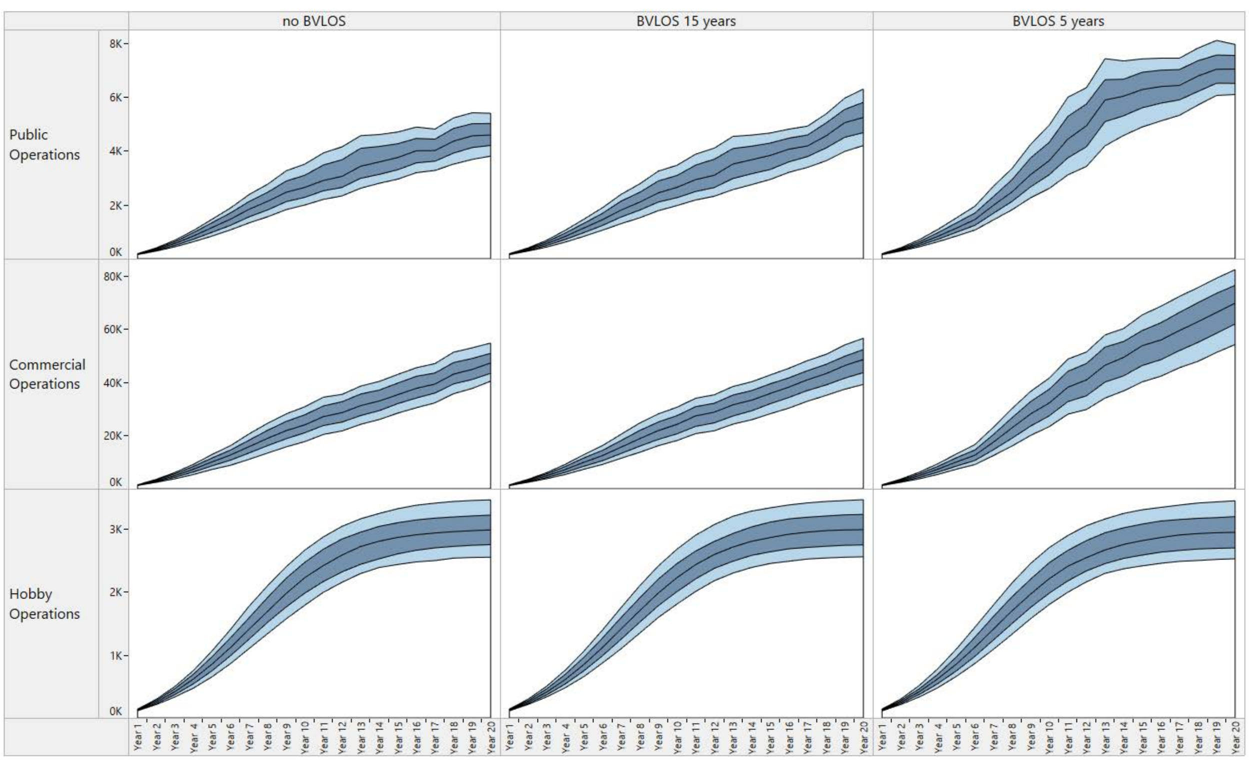

Figure 5: Impact of BVLOS at 15 and 5 years on sUAS daily hours of operation.

4.2 Operations Results

Figure 5 shows the number of hours of operations in the three different scenarios. As one would expect, the increase in the number of public and commercial adopters with BVLOS increases the daily operations. However, like with adopters, there is a substantial difference in the number of hours of operations depending on if BVLOS is allowed in 5 or 15 years. Allowing BVLOS earlier makes a bigger impact by year 20. While operations grow with the increase of BVLOS, they do not grow as fast as adoption. The increase in traffic impacts perception and rule rigidity which dampens the operations.

4.3 Perception Results

Figure 6 shows how the public's negative perception with respect to noise, privacy, safety, and security changes in the three different scenarios. The earlier BVLOS is introduced, the larger the increase in negative perception with regards to privacy and safety due to an expected increase in the number of incidents. The number of incidents is expected to increase because of the increase in the number of operations with the allowance of BVLOS.

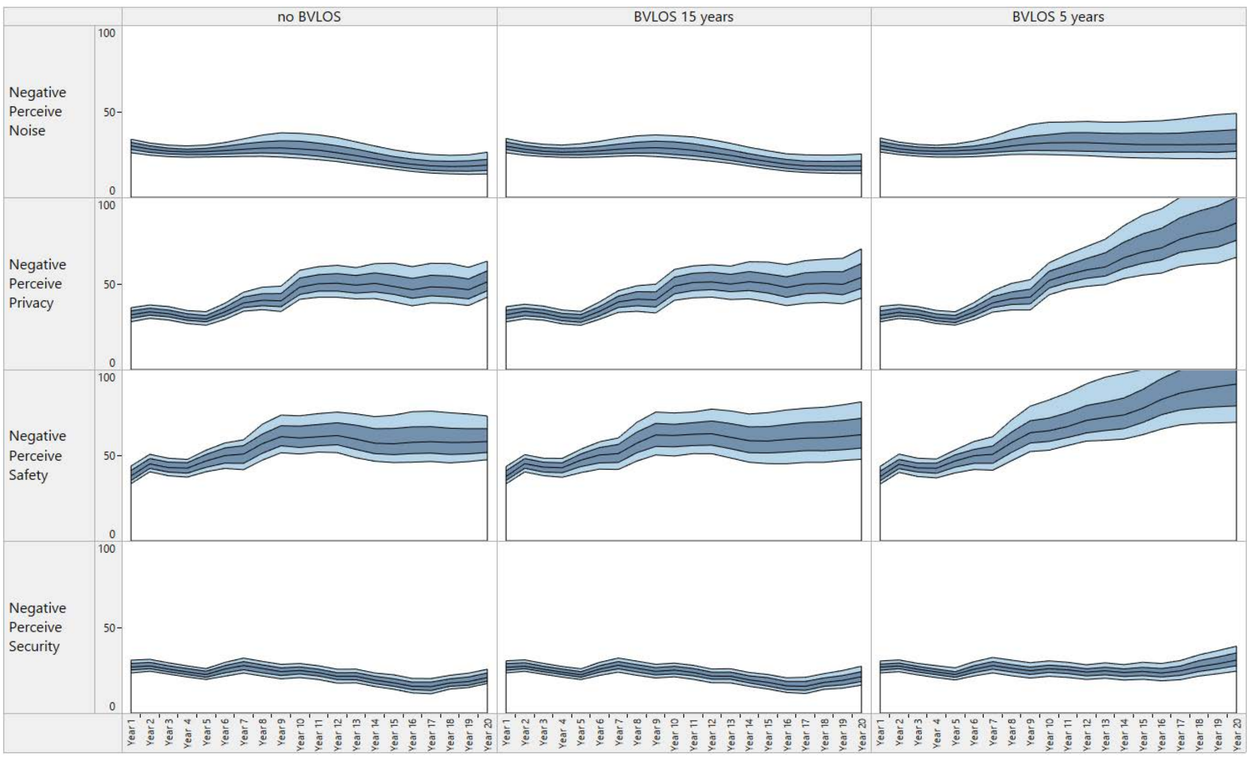

Figure 6: Impact of BVLOS at 15 and 5 years on negative perception.

4.4 Rules and Regulations Results

Figure 7 shows how the rigidity of rules/regulations and the ambiguity of those regulations change over time in the three different scenarios. In the base case, rule rigidity, the level of regulations that impose restrictions and costs on sUAS operations, increases until year 13 and then goes down over time with the increase in incentives as public tolerance of sUAS increases. With the allowance of BVLOS flights, the level of rigidity increases, and incentives decrease due to the expected public reaction and public pressure with the increased amount of traffic and incidents. The level of unregulated space, or ambiguity, decreases with the increase of rule rigidity and incentives.

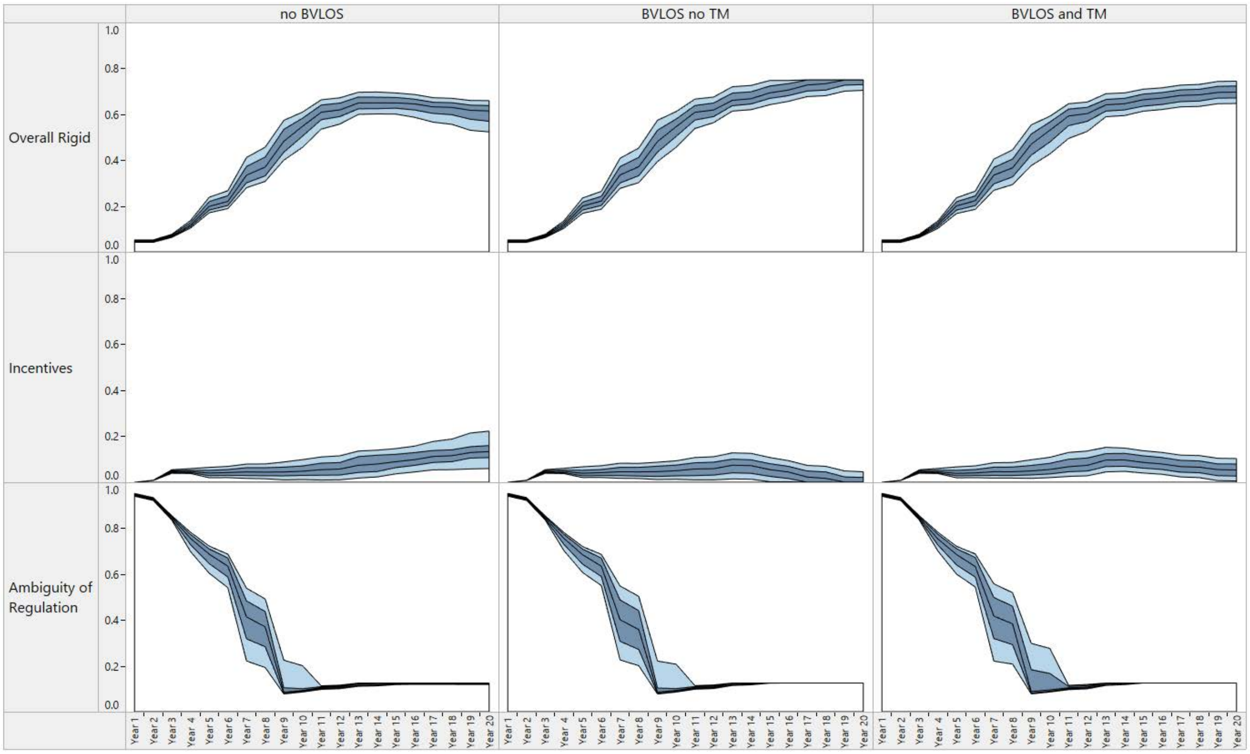

Figure 7: Impact of BVLOS at 15 and 5 years on rigidity, incentives and ambiguity of regulation.

This analysis shows that the timing of when routine use of BVLOS flights are allowed makes a substantial difference on the market. The FAA needs to balance the facilitation of the commercial market and the potentially large economic gains that would come from allowing BVLOS operations with potential public concerns. Our recommendation would be to allow routine use of BVLOS as soon as full-scale traffic management is implemented, to avoid negative incidents. Given the level of model fidelity and lack of historical data, the model results are intended to be used for comparative analysis only and are not intended to be used for concrete estimation.

5 CONCLUSIONS AND FUTURE RESEARCH

This research is intended to demonstrate the feasibility of applying system dynamics to incorporate perception and public policy into sUAS technology forecasts. Applying the *sUAS Adoption and Operations* model could complement sUAS forecasts and provide sensitivity to drivers not currently considered by the FAA when making sUAS forecasts. Understanding potential impacts of public perception and feedback will let policymakers, regulators, and analysts think strategically about public engagement concerning sUAS activity. The current model is designed to estimate sUAS adoption and operations for a limited geographic area. Future research will extend the model to national-level forecasts to evaluate the impact of new regulations and technologies (such as routine use of BVLOS and traffic management) on the national airspace to provide more operational value to the FAA. Aggregating to a national level could encounter some challenges, such as determining the best way to account for urban/suburban/rural differences in the number of sUAS adopted, which in turn will affect the number of incidents, public perception, and finally strength of regulations. A potential solution would be to aggregate all communities to one set of urban, suburban and rural areas with respect to these major variables when scaling up the model. This approach would allow the user to see the differences between these major community types.

Additionally, early registration data can be used in conjunction with SME input and economic forecasts to help validate the model results. Finally, this model can be extended to evaluate the societal implications of growth in sUAS (or other autonomous vehicles), such as on employment.

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A MODEL PARAMETERS

Table **1** and Table **2** lists the policy and input parameters that can be adjusted on the model interface. All non-binary input follows a triangular distribution in the scenario analysis.

Table 1: Policy and Input Parameters.

Parameter	**Baseline**	**Range**	**Explanation**
BVLOS and Traffic Management			
BVLOS	0	by scenario	Allow (1) or not allow (0) BVLOS automated flight.
Years Until BVLOS	0	by scenario	Year BVLOS is allowed.
Scheduling	1	by scenario	Use (1) or not use (0) scheduling.
Traffic Management	1	by scenario	Use (1) or not use (0) traffic management.
Delay Traffic Management	1	by scenario	Ramp traffic management to full capacity over time (1) or start fully functional (0).
Costs Impact of Traffic Management	1	0.75-1.25	A multiplier that indicates how much the traffic management affects operating costs.
Probability of Incidents			
Good Incidents	3 e-5	0.5 to 1.5 X default value	Likelihood of a good incident (e.g. life saved) for one sUAS as a function of the population per square mile. Good incidents apply only to public and some commercial sUAS.
Bad Incidents	Privacy: 4.4 e-7 Safety: 1.3 e-6 Security: 1.0 e-7	0.5 to 1.5 X default value	Likelihood of a bad incident for one sUAS. Likelihood of a privacy or safety incident is a function of the population per square mile. Likelihood of a security incident is a function of the critical infrastructure per square mile.
Environment	1	0.5 to 1.5 X default value	Commonality of incidents outside the community. Impacts public sensitivity to privacy, safety and security. Greater than 1 is more common.

Table 2: Policy and Input Parameters (continue).

<table>
<tr><th>Parameter</th><th>Baseline</th><th>Range</th><th>Explanation</th></tr>
<tr><td colspan="4">Community Type (default values for one Urban community)</td></tr>
<tr><td>Community Size</td><td>325 Sq M</td><td>by scenario</td><td>Square miles for a community.</td></tr>
<tr><td>Population</td><td>1,419,516</td><td>by scenario</td><td>Census 2017 population estimates.</td></tr>
<tr><td>Household Income</td><td>$68,117</td><td>by scenario</td><td>Census 2016 median household income.</td></tr>
<tr><td>Cost of Living Index</td><td>1.47</td><td>by scenario</td><td>Composite index measuring the relative standard of living from the Council for Community and Economic Research. Values are relative to 1.</td></tr>
<tr><td colspan="4">Rules and Regulations</td></tr>
<tr><td>Ability to Local Regulate</td><td>1</td><td>by scenario</td><td>Allow (1) or not allow (0) the local community to add regulations.</td></tr>
<tr><td>Rule Indicators</td><td>All rules = 1 except
Federal zoning / privacy = 0
Local safety = 0</td><td>by scenario</td><td>Allow (1) or not allow (0) Federal or local regulations for noise, zoning, privacy, operations, safety, and security.</td></tr>
<tr><td>Time to Codify Rules</td><td>Local: 410 days
Fed: 3 yrs</td><td>Local: 90 days to 2 yrs Fed: 1-5 yrs</td><td>Time for the Federal or local government to create new regulations.</td></tr>
<tr><td>Strict or Lenient</td><td>1</td><td>0.5 to 1.5 X default value</td><td>Relative level of regulator strictness or leniency. Greater than 1 is stricter; less than 1 is more lenient.</td></tr>
<tr><td>Rule Indicators</td><td>All rules = 1 except
Federal zoning / privacy = 0
Local safety = 0</td><td>by scenario</td><td>Allow (1) or not allow (0) Federal or local regulations for noise, zoning, privacy, operations, safety, and security.</td></tr>
<tr><td colspan="4">sUAS Fleet and Operations (default values for one Urban community)</td></tr>
<tr><td>Starting Fleet</td><td><table><tr><th></th><th>NonBVLOS</th><th>BVLOS</th></tr><tr><td>Public</td><td>125</td><td>0</td></tr><tr><td>Commercial</td><td>250</td><td>0</td></tr><tr><td>Hobby</td><td>1,250</td><td>0</td></tr></table></td><td>by scenario</td><td>Number of initial public, commercial, and hobby sUAS (by non-BVLOS/BVLOS) for selected community.</td></tr>
<tr><td>Potential Market</td><td><table><tr><th></th><th>NonBVLOS</th><th>BVLOS</th></tr><tr><td>Public</td><td>4,000</td><td>5,000</td></tr><tr><td>Commercial</td><td>12,000</td><td>15,000</td></tr><tr><td>Hobby</td><td>30,000</td><td>0</td></tr></table></td><td>0.8 to 1.2 X default value</td><td>Size of the potential market for public, commercial, and hobby sUAS (by non-BVLOS/BVLOS) for selected community.</td></tr>
<tr><td>Hours of Operations</td><td><table><tr><th></th><th>Day</th><th>Night</th></tr><tr><td>Public</td><td>0.5</td><td>0.5</td></tr><tr><td>Commercial</td><td>3</td><td>1</td></tr><tr><td>Hobby</td><td>0.1</td><td>0</td></tr></table></td><td>0.8 to 1.2 X default value</td><td>Number of expected hours of day/night operations per sUAS (by public, commercial, and hobby).</td></tr>
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