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Cost of Oil and Biomass Supply Shocks under Different Biofuel Supply Chain Configurations

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Abstract

This analysis estimates the cost of selected oil and biomass supply shocks for producers and consumers in the light-duty vehicle fuel market under various supply chain configurations using a mathematical programing model, BioTrans. The supply chain configurations differ by whether they include selected flexibility levers: multi-feedstock biorefineries; advanced biomass logistics; and the ability to adjust ethanol content of low-ethanol fuel blends, from E10 to E15 or E05. The simulated scenarios explore market responses to supply shocks including substitution between gasoline and ethanol, substitution between different sources of ethanol supply, biorefinery capacity additions or idling, and price adjustments. Welfare effects for the various market participants represented in BioTrans are summarized into a net shock cost measure. As oil accounts for a larger fraction of fuel by volume, its supply shocks are costlier than biomass supply shocks. Corn availability and the high cost of adding biorefinery capacity limit increases in ethanol use during gasoline price spikes. During shocks that imply sudden decreases in the price of gasoline, the renewable fuel standard (RFS) biofuel blending mandate limits the extent to which flexibility can be exercised to reduce ethanol use. The selected flexibility levers are most useful in response to cellulosic biomass supply shocks.

Blending biofuels with petroleum fuel increases the diversity of the fuel mix used to satisfy U.S. light-duty vehicle (LDV) travel demand. By displacing petroleum barrels, biofuels reduce the exposure of the U.S. economy to petroleum supply shocks. Biofuels can mitigate fuel price volatility if their prices are not too tightly correlated with those of gasoline and diesel (*1*). The biomass feedstocks used to produce biofuel experience their own supply shocks due to adverse weather conditions, pests, and competition from other non-biofuel demand uses. Climate change could affect long-term average corn yield and bioenergy crop yields (*2,3*). A more diverse fuel mix has the potential to be more resilient to supply shocks, depending on, for example, supply chain configuration. The petroleum and corn ethanol portions of the supply chain are already fully developed, but adjustments can still be made to enhance system resilience. Petroleum refinery operations that allow for quick adjustments of ethanol content in fuels, in response to changes in relative prices, can help mitigate price volatility at the pump after a petroleum or biomass supply shock. The supply chain for biomass feedstocks used in producing cellulosic biofuels is still at a nascent stage and its evolution will have implications for system resilience in case of biomass supply shocks. We propose that effectiveness in mitigating supply shocks should be one of the criteria, along with cost and environmental sustainability targets, for biofuel supply chain planning. This analysis explores the costs of selected supply shocks of varying origin (biomass or petroleum), sign (supply increases or decreases), and size under various biofuel supply chain configurations. It provides insight into the effectiveness of different supply chain flexibility levers in mitigating supply shocks.

Methods

The mathematical programming model used for this analysis, BioTrans (*4*), contains a detailed representation of the U.S. farm-to-pump supply chain for biofuels and its competition with the petroleum sector in fulfilling LDV fuel demand. This representation is summarized in Figure 1. BioTrans is a dynamic model that captures intertemporal linkages between periods and solves for the supply chain investment and operation levels that maximize social surplus. The modeling horizon is multi-decadal (2010–2040)

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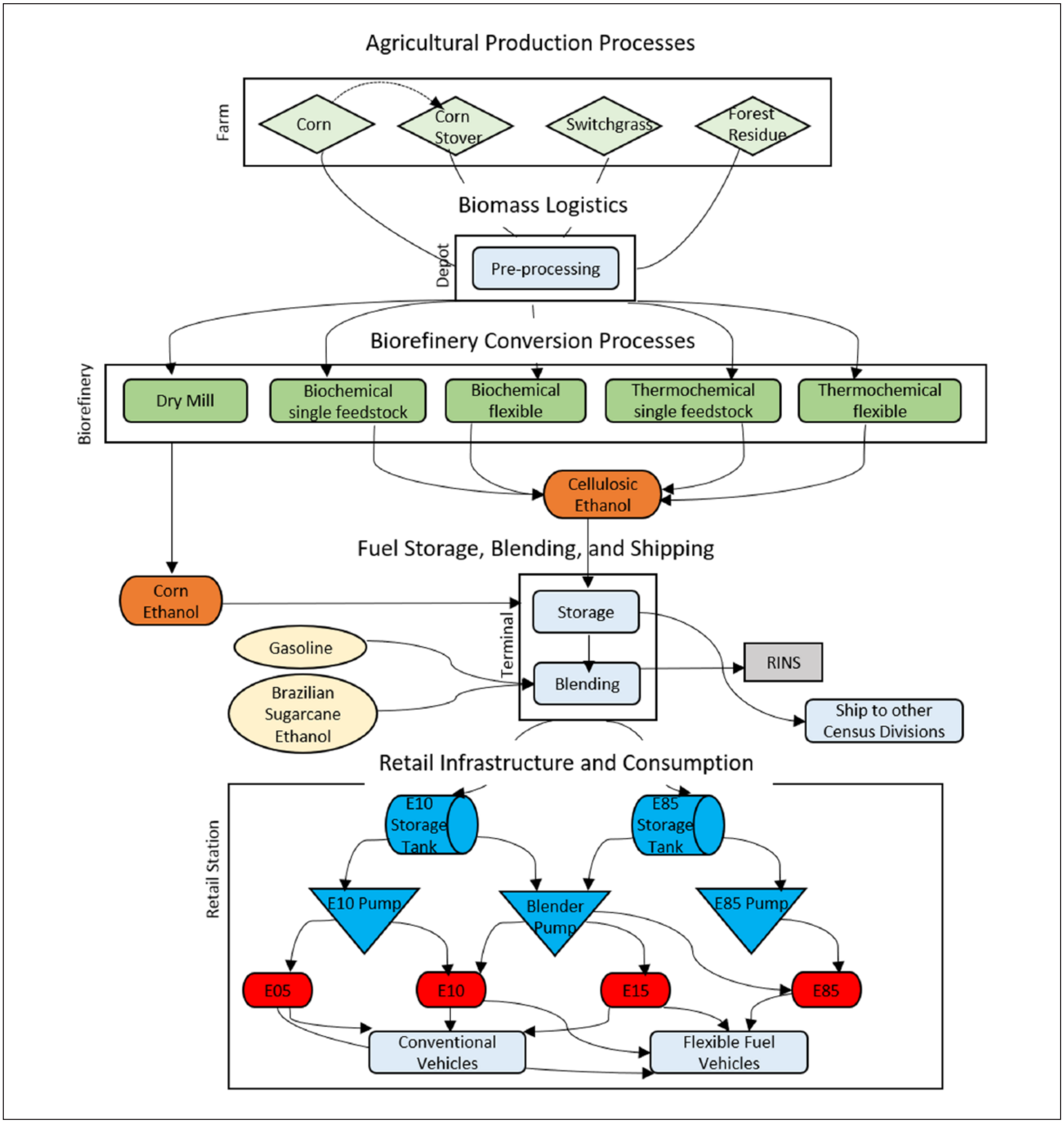

Figure 1. LDV fuel supply chain structure in the BioTrans model.

with annual periods as the unit of temporal disaggregation. BioTrans has national scope and includes regional detail at the census division level. Land allocation decisions and vehicle purchase decisions are the upstream and downstream model boundaries. Neither of them are explicitly modeled. Instead, biomass feedstock supply curves and vehicle stock projections are inputs to BioTrans.

For this study, BioTrans focuses on ethanol, produced from corn or one of three cellulosic feedstocks: corn stover, switchgrass, and forest residues. A biofuel blending constraint representing the renewable fuel standard (RFS) is included in the model. As the 2022 biofuel blending levels originally mandated by EISA 2007 appear too ambitious, a modified RFS target level that equals 60% of the maximum

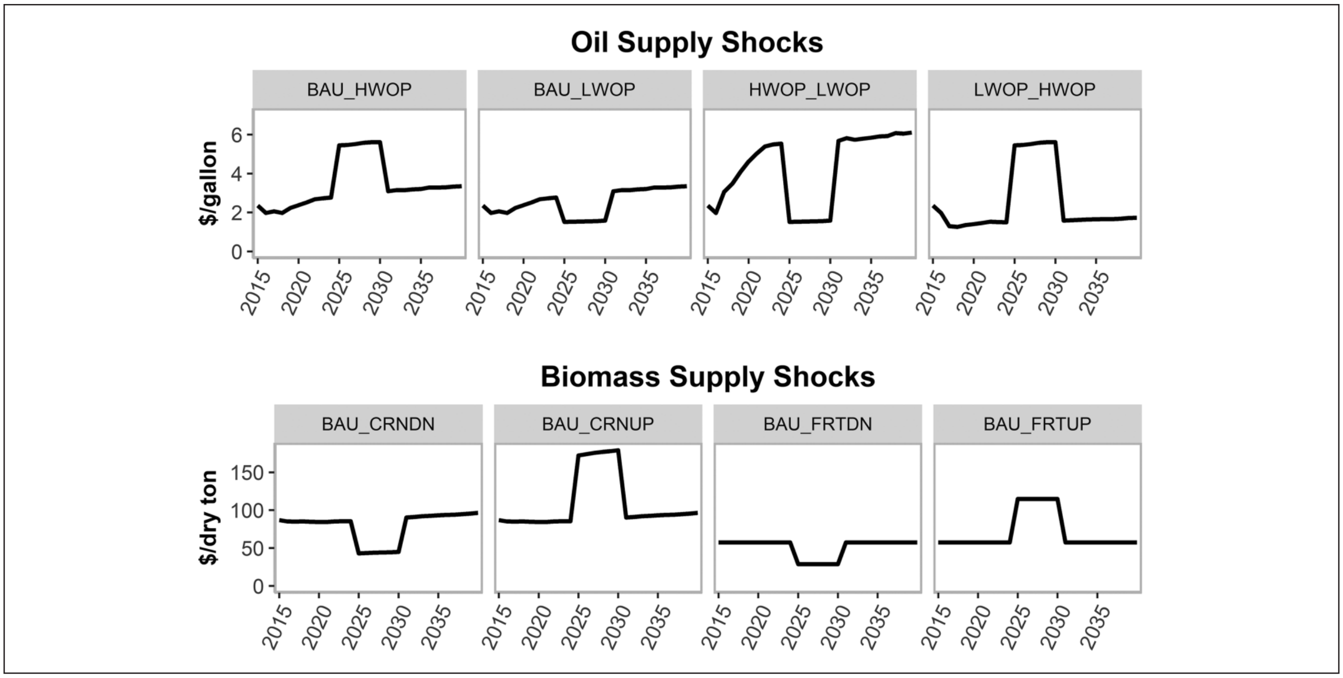

Figure 2. Shocked wholesale gasoline and biomass feedstock reference supply price trajectories.

potential ethanol consumption given the projected LDV fleet is assumed instead. Maximum ethanol consumption would be achieved if flexible fuel vehicles (FFVs) always consumed E85 and other LDVs always used the most ethanol-intensive blend that is compatible with their engines. Based on vehicle stock projections from the AEO2017 reference case, the modeled 2022 blending target is 19 billion gallons of renewable fuel, of which at least four billion gallons must be cellulosic biofuel. The target is kept constant for the remainder of the modeling period (2023–2040). The shadow value of the biofuel blending constraint can be interpreted as the price of a renewable identification number (RIN) which is the marginal cost of compliance with the RFS for obligated parties (petroleum refiners and importers). A positive RIN price indicates that the blending constraint is binding. If ethanol is cheaper than gasoline and it is economical for market participants to use more than what is mandated by the RFS, the RIN price drops to zero.

BioTrans allows depiction and evaluation of two types of strategies used by farmers and biorefiners to manage risks associated with biomass supply shocks: engineering solutions and portfolio diversification (*5*). Particular attention is given here to the value of building flexibility into the supply chain to be able to accommodate changes in the optimal mix of biomass feedstocks or blended fuels depending on the relative prices of gasoline and ethanol.

Selected Supply Shocks

Previous research concerned with representing risk surrounding key parameters for biofuel market participants (e.g., oil price, corn yield, ethanol production) has typically used Monte Carlo analysis based on random draws from the observed probability distributions for those parameters (*6,7*). Instead, the approach used here simulates selected multi-year price excursions under limited foresight and alternative supply chain configurations. Supply curves are shifted upward or downward during the shock years without changing the maximum available quantity. The shocked reference price paths are illustrated in Figure 2.

Figure 2 displays the simulated oil (upper panels) and biomass (lower panels) supply shocks. Outside of the shock period (2025–2030), oil price levels correspond to projections from one of three AEO2017 cases: reference (BAU), high world oil price (HWOP), and low world oil price (LWOP). The oil shocks are each depicted as a deviation from one of those reference price paths to another, for a 6-year duration.

In all the biomass supply shocks, the point of departure is a BAU case based on the 2016 Billion Ton Report (*8*) supply quantities and prices (for a US$60/dry ton biomass payment to farmers). The shocks are introduced as biomass feedstock supply curve shifts that result in supply price changes for the affected feedstocks. In the BAU_CRNUP and BAU_CRNDN shocks, both the corn and corn stover supply curves are shifted by multiplicative factors of 2 and 0.5, respectively. In the BAU_FRTUP and BAU_FRTDN shocks, the same multiplicative factors are used to introduce supply curve shifts for forest residues. BAU_CRNUP could be consistent with an extended period of drought or other event causing a multi-year increase in supply prices; similarly, BAU_CRNDN could correspond to a string of exceptionally large harvests that would result in price reductions. For forest residues, it is more difficult to envision large, multi-year changes in availability at the national level. However, there could be significant increases in the supply price of forest residues faced by biofuel producers due to competition from other uses (e.g., strong world demand for pellets produced in the U.S.).

The eight shocks described above are simulated in a limited foresight implementation of BioTrans. Foresight and expectations are important in a long-run dynamic model with durable capital investments; we adopt an approach between perfect foresight and complete myopia. The model is solved in 6-year overlapping windows and the window is rolled forward one year in each successive model solve. This is consistent with market participants formulating their investment and operation plans with reasonably-accurate near-term information that is updated each year. Shocks, however, are surprises: information about the shocks only becomes available in the 2025–2030 solution period, after they have started.

Selected Flexibility Levers

We describe the flexibility levers and discuss their impact on reference (undisrupted) model outcomes prior to the hypothesized 2025–2030 disruption period.

Ethanol Blending Flexibility (E05–E15). The "rigid" option includes two fuel blends in its choice set: E10 and E85, where the latter can only be used by FFVs. The "flexible" option includes two additional gasoline–ethanol blends: E05, and E15. E15 is assumed to be compatible with gasoline-based LDVs whose model year is 2001 or newer and only can be dispensed through flexible pumps. E05 is compatible with all gasoline-based LDVs and can be retailed through the same pumps used for E10. Adjusting ethanol content downwards from E10 to E05 is modeled as cheaper/easier than adjusting it up from E10 to E15. Petroleum refineries, which would likely have to increase use of aromatics to maintain octane ratings if ethanol content was reduced (*9*), are not explicitly modeled in BioTrans.

In 2024, total LDV fuel consumption ranges between 100 billion and 130 billion gallons of gasoline equivalent (gges) depending on the reference oil price path: BAU, HWOP, or LWOP. E85 consumption is higher under the HWOP oil prices regardless of supply chain configuration. The only noticeable change in the reference (undisrupted) outcomes brought about by the ability to change ethanol content in the E05–E15 range is the consumption of 4 billion gges of E15 consumption in the HWOP case.

Biorefinery Feedstock Flexibility. In this study, two levels of feedstock flexibility at biorefineries were considered: "rigid" and "flexible." In the rigid configuration, four biomass-to-biofuel conversion pathways are included with each dedicated to a single feedstock: dry milling of corn, biochemical conversion of stover to cellulosic ethanol, biochemical conversion of switchgrass to cellulosic ethanol and, thermochemical conversion of forest residue to cellulosic ethanol. In the flexible configuration, thermochemical biorefineries can use any mix of stover, switchgrass, and forest residue. Both configurations lead to similar levels and types of installed biorefinery capacity by 2024 (the year before the start of the simulated shocks) but there are differences in their regional distribution. When thermochemical biorefineries only use forest residue, most are built in the regions with the largest potential supply of that feedstock. With feedstock flexibility, thermochemical biorefinery capacity is concentrated in the regions with the cheapest supply of cellulosic feedstock.

Advanced Logistics Design. The "flexible" option for biomass logistics is the Advanced Logistics Design (*10*). With advanced logistics, cellulosic feedstocks are preprocessed into a more flowable material (e.g., pellets) that is cheaper to transport longer distances by rail and store. The lower transportation cost per unit also allows for taking advantage of economies of scale in biorefinery sizing. Cumulative biorefinery investment cost by 2024 decreases by approximately 9% in the advanced logistics case, relative to the "rigid" conventional logistics design, because of the larger biorefinery sizes. Consistent with the idea that advanced logistics makes biorefineries less dependent on their local supply by creating a larger pool of eligible resources, interregional transportation of biomass feedstocks is allowed in this configuration. The "rigid" option (conventional logistics design) involves transportation of cellulosic feedstocks in bales or raw format by truck to nearer destinations and smaller biorefineries. Therefore, under the "rigid" scenarios, only transportation within the census division in which the feedstock is harvested is allowed. The logistics for corn are assumed to already be mature and optimized but, to explore differences in optimal supply chain configuration and response to shocks with national versus regional biomass feedstock markets, corn is also restricted to only be transported within the census division in which it is harvested in the conventional logistics design.

The largest savings associated with the adoption of advanced biomass logistics accrue to forest residues. Advanced logistics result in a lower forest residue supply price at the roadside because the ability to ship forest residues across census divisions mobilizes cheap supplies from regions where otherwise it would not be collected. Additional savings in transportation and storage costs more than offset the cost of pre-processing forest residues at depots. Simulated forest residue price at the biorefinery gate is US$135/dry ton versus US$106/dry ton under conventional and advanced logistics, respectively.

A transition to advanced biomass logistics, by reducing transportation and storage costs and enabling biorefinery scale economies, would likely impact average distance traveled both by biomass from forest/field to biorefinery and by ethanol from biorefinery to demand center. Figure 3 shows volume-weighted average distances traveled by biomass in

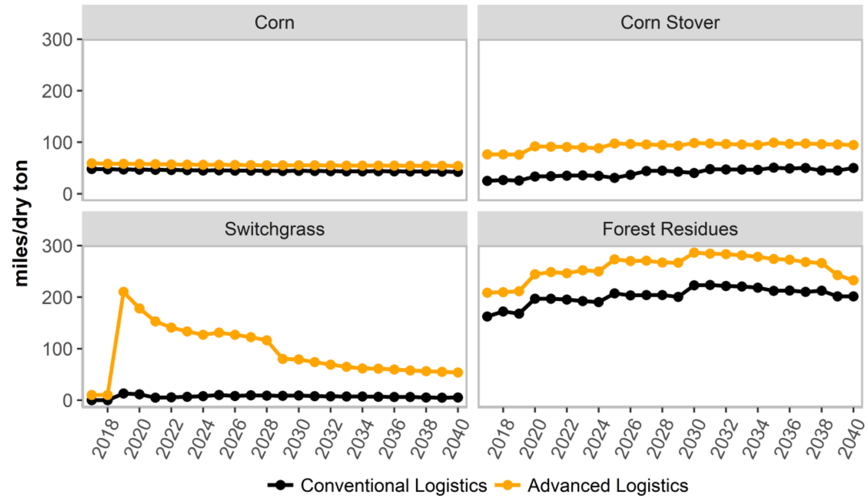

Figure 3. Average distance traveled by biomass under alternative logistics designs (2017–2040).

Table 1. Net Private Cost (or Benefit) of Selected Supply Shocks Under Different Biofuel Supply Chain Configuration (Million 2010 US dollars)

Shock type	All rigid	Biorefinery feedstock flexibility	Advanced logistics design	Ethanol blend flexibility	All flexible
BAU_HWOP	−118,605.8	−118,537.2	−118,481.4	−118,030.5	−117,671.0
BAU_LWOP	70,561.2	70,398.0	70,472.1	70,534.5	70,568.2
LWOP_HWOP	−276,892.5	−275,393.5	−275,849.7	−276,922.4	−275,607.1
HWOP_LWOP	174,717.2	174,546.9	174,603.3	173,257.0	173,166.4
BAU_CRNUP	−23,435.9	−22,727.5	−22,179.4	−23,373.6	−21,999.0
BAU_CRNDN	13,208.9	13,958.3	13,047.8	13,091.8	14,251.1
BAU_FRTUP	−4750.0	−1.6	−4683.8	−4861.2	−739.0
BAU_FRTDN	2617.0	4.2	2851.4	2508.6	2823.8

the conventional versus advanced logistics designs from 2017 to 2040; note that 2017 is the year in which the advanced logistics design is first available in the BioTrans simulations.

Figure 3 shows that corn travels an average of 50 miles from farm to biorefinery and this distance does not change markedly across the two logistics designs. On the other hand, cellulosic feedstocks travel significantly larger distances in the advanced logistics configuration. Switchgrass only becomes available in 2019, which explains the zero distances for years 2017 and 2018. In the 2020s, as switchgrass planted acreage increases, average distance traveled decreases.

Advanced logistics result in cellulosic feedstocks traveling longer distances. On the other hand, transitioning to advanced logistics leads to a substantial reallocation of dry mill capacity within the Midwestern census divisions that reduces the average distance traveled by corn ethanol from 917 to 714 miles. More than half of the corn ethanol produced is transported across census divisions in the advanced logistics scenario. In contrast, most cellulosic ethanol is consumed in the same census division as it is produced, and the advanced logistics case decreases the average shipping distance modestly from 756 to 660 miles.

Results

The set of cases to be discussed in this document includes 40 shocked cases (eight shocks times five supply chain configurations) plus the 15 corresponding unshocked baseline cases (three baseline oil market futures times five supply chain configurations) needed to determine the cost of the shocks. Table 1 summarizes the net private cost of each shock under the various supply chain configurations. Net private cost is a welfare measure that adds up the differences in producer and consumer surplus components along with the differences in transportation and conversion costs between the two solutions.

Each cell in Table 1 represents the cost of a shock (relative to the market outcomes of a model run with the same supply chain configuration and no shock). Reading vertically down a column shows the large variation in shock costs by type and size. Comparing results horizontally within a row serves as an indication of variability in the net welfare effect of a shock under alternative supply chain configurations. Comparing shock costs across configurations is not straightforward because many of the model variables take different base values in 2024 across the various supply chain alternatives. These differences in "starting points" lead to instances in which a more flexible configuration results in a worse net private welfare outcome during a shock. For instance, the LWOP_HWOP shock is slightly more damaging for the *Ethanol Blend Flexibility* than the *All Rigid* case. Ethanol blending flexibility enables the system to better adapt to the market conditions in earlier years, less ethanol consumption during low oil price periods up until 2024, but makes a sudden increase in gasoline prices costlier.

The BAU_HWOP and BAU_CRNDN shocks are the only shocks where the gain, or avoided cost, enabled by the most flexible configuration is larger than the sum of gains from each individual lever. In response to those shocks, the flexibility levers act synergistically. In many of the other shocks, there is a single flexibility lever that is more effective than the others and even more effective than the combination of all three levers. This result shows the importance of evaluating flexibility levers in the context of the full biofuel-petroleum fuel system.

Oil Supply Shocks

For oil supply shocks, the main takeaway is that the flexibility levers, as depicted, are not very effective in mitigating the cost of damaging upward oil supply shocks (BAU_HWOP, LWOP_HWOP) or amplifying the benefits from downward oil supply shocks (BAU_LWOP, HWOP_LWOP). The difference in net private cost across supply chain configurations is less than 1% for those shocks. During supply shocks that increase the cost of ethanol relative to gasoline, there is limited ability to adjust ethanol content down due to the biofuel blending mandate constraint. In contrast, RIN prices drop down to zero at the beginning of the BAU_HWOP shock and for most years of the LWOP_HWOP shock, indicating that it is optimal to use more biofuel than the mandated level during major oil price increases. Increases in ethanol use during those shocks are typically achieved through a combination of increases in sugarcane ethanol imports and investments in additional domestic ethanol production capacity. Availability of additional domestic biofeedstock supplies and E15/E85-compatible retail fuel infrastructure limit the magnitude of the ethanol use increase in response to BAU_HWOP and LWOP_HWOP shocks.

Simulated oil supply shocks result in large changes in the price of wholesale gasoline. The average changes in gasoline prices during the shock period range between –US$3.71/gallon in the HWOP_LWOP shock and US$6.45/gallon in the LWOP_HWOP shock. The average annual fuel expenditure for FFV owners in 2025–2030 across all shocks is 3%–8% lower (depending on supply chain configuration) than for conventional vehicle owners. For conventional vehicle owners, adding flexibility levers reduces average expenditures by 2% relative to the most rigid configuration.

Biomass Supply Shocks

Biomass supply shocks lead to moderate changes in ethanol price. The average changes in ethanol price during the shock period range between –US$0.22/gallon in the BAU_CRNDN shock and US$0.55/gallon in the BAU_CRNUP shock. Biomass supply shocks affecting the feedstock used to produce the majority of biofuel (corn) have a larger impact on ethanol prices than the forest residue supply shocks.

For corn supply shocks (BAU_CRNUP and BAU_CRNDN), the most flexible configuration produces the best outcome from a social welfare perspective. Combining the three flexibility levers leads to an 8% increase in the net benefit of the BAU_CRNDN shock and a 6% decrease in the cost of the BAU_CRNUP shock. The depicted flexibility levers are most consequential in response to supply shocks affecting cellulosic biomass feedstocks. Biorefinery feedstock flexibility mutes the effect from forest residue supply shocks because forest residue is not used in large amounts when biorefiners can choose among multiple feedstocks, *but* the prevailing logistics design is conventional. For BAU_FRTDN, the advanced logistics configuration leads to the highest net benefit.

Variability in farmer revenue from sales of corn or cellulosic feedstocks for ethanol production decreases significantly in the *All Flexible* configuration relative to the *All Rigid* configuration. The coefficient of variation of farmer revenue decreases from 18.4% to 16.9% for corn and from 30.9% to 21.7% for cellulosic feedstocks when comparing the most flexible to the most rigid supply chain configuration. Weighting the probability of all the simulated shocks equally, the highest average farmer revenues correspond to the most rigid supply chain design. These results regarding farmer revenue are due to the very high equilibrium prices of corn and forest residue during the BAU_CRNUP and BAU_FRTUP shocks respectively in the *All Rigid* configuration.

Normalized Shock Costs

Taking into account the differences in scale of biofuel versus gasoline use is important for interpreting the results from Table 1. Average volumetric ethanol content of fuels by 2024 (the year before the start of the simulated shocks) ranges between 13% in cases with LWOP oil prices and 16.8% in cases with HWOP oil prices. The implied shocks to fuel supply price are therefore greater for gasoline than for ethanol (since biomass only represents a fraction of ethanol costs). Shocks on petroleum supply affect a much larger fraction of total light-duty fuel supply and lead to much larger changes,

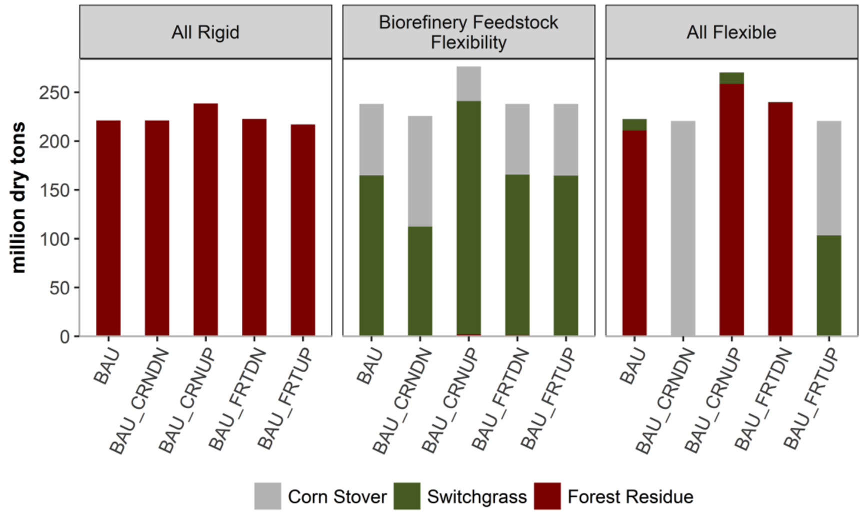

Figure 4. Simulated cellulosic feedstock mix during biomass supply shocks under three alternative supply chain configurations (average, 2025–2030).

in absolute value, in net private welfare than the biomass supply shocks.

Biorefinery Feedstock Flexibility

As our representation of dry mills does not allow the use of any feedstock other than corn, this flexibility lever should primarily be of use in adjusting to supply shocks affecting cellulosic feedstocks (corn stover, switchgrass, and forest residues). Figure 4 shows the annual average mix of cellulosic feedstocks during biomass supply shocks for three alternative supply chain configurations: *All Rigid*, *Biorefinery Feedstock Flexibility*, and *All Flexible*.

Regardless of the biomass supply shock, the *All Rigid* configuration does not allow thermochemical biorefineries to use any other feedstock than forest residue; thus, forest residue is used 100% of the time. With feedstock flexibility, the selected feedstock mix under undisrupted baseline circumstances (BAU case) differs from the *All Rigid* configuration and is made up of corn stover and switchgrass. Large, cost-reducing adjustments take place in response to shocks affecting corn and corn stover: reliance on corn stover increases during the BAU_CRNDN shock. In response to the BAU_CRNUP shock, switchgrass substitutes for much of the stover use. The absence of forest residue from the feedstock mix in the *Biorefinery Feedstock Flexibility* configuration results from transport costs of forest residue being much more expensive than either stover or switchgrass under conventional biomass logistics. The cost of transporting forest residue 50 miles with conventional logistics is US$16.8/dry ton versus US$10.4/dry ton for stover and switchgrass.

In the most flexible configuration, the cost of transporting forest residue becomes comparable to the other cellulosic feedstocks (approximately US$6/dry ton to transport preprocessed material for 50 miles) due to the advanced logistics design. Without shock, the least expensive way to operate the thermochemical biorefineries is by using forest residue almost exclusively. Reliance on forest residue is maintained during the BAU_CRNUP and BAU_FRTDN shocks. However, both unexpected increases in the supply cost of forest residue or decreases in the cost of corn stover result in drastic changes in feedstock mix. In response to the BAU_CRNDN shock, corn stover is used as the unique feedstock in thermochemical biorefineries instead of forest residue. When forest residue supply becomes more expensive, it is completely replaced by a mixture of corn stover and switchgrass (BAU_FRTUP). For perennial energy crops like switchgrass, there is a multi-year lag from planting to harvesting which is not captured in the model. Thus, the surge in switchgrass use during the BAU_FRTUP shock would require a large amount of the crop to have been planted years earlier without being tied to a particular use by a long-term contract. Only with advanced logistics and mature regional or national markets for switchgrass does the existence of those "free" switchgrass supplies appear plausible.

Figure 4 shows that total cellulosic feedstock use increases during the BAU_CRNUP shock regardless of supply chain configuration. During the BAU_CRNUP shock, the cellulosic portion of the RFS blending mandate is not binding and the cellulosic RIN price plunges to zero (even though the overall renewable fuel blending mandate remains binding). In those instances, it is optimal to increase the fraction of total ethanol use satisfied with cellulosic ethanol instead of corn ethanol or sugarcane ethanol imports. A total of 83% of the instances in which the cellulosic RIN price is zero arise in supply chain configurations with biorefinery feedstock flexibility or advanced

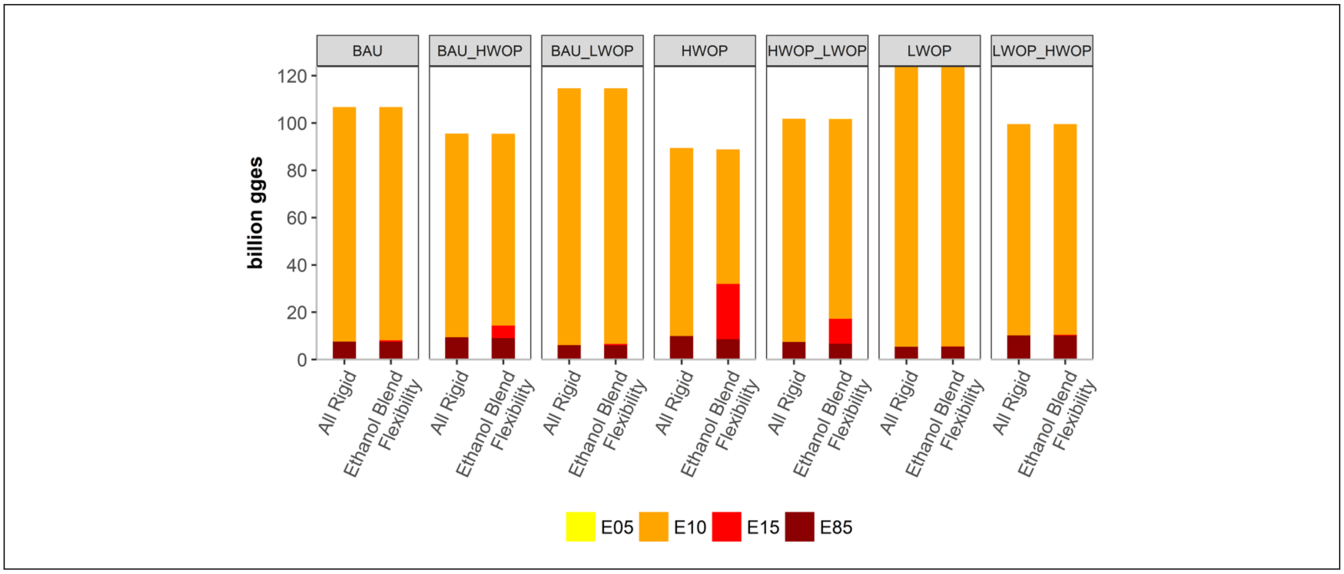

Figure 5. Simulated LDV fuel mix during oil supply shocks under alternative supply chain configurations (average, 2025–2030).

logistics design. Flexibility levers make cellulosic ethanol better able to compete with or complement corn ethanol.

Advanced Logistics

Advanced logistics for biomass feedstocks might help reduce the costs of a biomass supply shock in two ways: 1) by leading to a network of depots and biorefineries able to produce cellulosic ethanol at a lower price than in the conventional logistics case in undisrupted market conditions and 2) by shipping feedstocks between Census Divisions to arbitrage away price differences that arise during the shock period. In our current implementation, biomass supply shocks are applied uniformly across the country which limits the potential for large interregional price differentials opening up during supply shocks. Regional variation in the welfare consequences of a shock for farmers remains when, as it happens in the BAU_FRTUP case, alternative feedstocks with different geographical distribution substitute the one experiencing the shock.

The national average cellulosic ethanol price in 2025–2030 is lower in the *Advanced Logistics Design* configuration than in the *All Rigid* alternative, both with and without biomass supply shocks. In the unshocked BAU case, the simulated cellulosic ethanol price is US$2.38/gallon and US$2.84/gallon under advanced and conventional logistics, respectively. The most flexible supply chain configuration (*All Flexible*) leads to even lower prices, particularly in the BAU_FRTUP shock where advanced logistics yields greater value combined with biorefinery feedstock flexibility.

Advanced logistics leads not only to a lower average cellulosic ethanol price across shock events but also to a less variable price. With the *All Rigid* configuration, cellulosic ethanol prices range between US$2.46-3.56/gallon. The range narrows to US$2.30–3.04/gallon with the *Advanced Logistics* configuration.

Prices for corn ethanol during shocks change much less with supply chain configuration because corn cannot be substituted by other feedstocks at dry mills and the only difference between conventional and advanced logistics is the ability to transport corn across census divisions. For instance, in the BAU_CRNDN shock, the average price of corn ethanol is US$2.07/gallon in the *All Rigid* configuration and US$2.05/gallon with *Advanced Logistics Design*. In the BAU_CRNUP shock, the *All Rigid* average corn ethanol price is US$2.89/gallon and US$2.80/gallon lower with advanced logistics.

Ethanol Blend Flexibility

Ethanol blend flexibility is potentially the most-powerful lever of those analyzed here, allowing adjustment of the ethanol–gasoline mix used to satisfy most light-duty transportation demand. Blending flexibility can play a role in response to both oil and biomass supply shocks. There are limits to this flexibility however, including regulatory constraints establishing a minimum volume of biofuel use and retail infrastructure availability for dispensing E15 and E85. Figure 5 summarizes changes in the mixture of gasoline–ethanol blends consumed during oil supply shocks.

The height of the bars in Figure 5 corresponds to total LDV fuel consumption in billion gges. It changes significantly depending on oil price levels (BAU, HWOP, LWOP) outside of the shock period, as base conditions alter total consumption and blend mix used before the shock starts. The flexibility levers considered here do not substantially modify the total fuel consumption level. The renewable fuel blending mandate is binding except in the first two years of the

BAU_HWOP shock and from 2025 to 2029 in the LWOP_HWOP shock. Under those circumstances, gasoline is sufficiently expensive relative to ethanol such that the optimal level of ethanol use is larger than what is required by the mandate.

For oil price shocks taking place under BAU oil prices, supply chain configuration does not play a significant role. The increase or decrease in biofuel consumption that accompanies the BAU_LWOP and BAU_HWOP shocks, respectively, is mostly attained by adjusting the level of E85 consumption. However, E15 sales are also part of the response during a BAU_HWOP shock.

The ability to adjust ethanol content between E05 and E15 plays a key role in response to the downward HWOP_LWOP oil price shock. In response to a very large decrease in oil prices that unexpectedly interrupts a sequence of high prices (HWOP_LWOP shock), total fuel consumption increases, and total ethanol use decreases through a substitution from E15 to E10. This combination of responses results in a decrease in total ethanol consumption from 18.9 billion gallons in 2024 to 17.9 billion gallons in 2025 under the ethanol blend flexibility configuration.

Prior to the upward LWOP_HWOP shock, 125 billion gges of E10 and 5 billion gges of E85 are estimated to be consumed in 2024. In response to the sudden increase in gasoline prices, E85 consumption roughly doubles during the shock period accounting for approximately 80% of the vehicle-miles traveled (VMT) demand by FFVs for the duration of the shock. Total ethanol use increases by an additional 2.8 billion gallons in 2025 in the *Ethanol Blend Flexibility* configuration in response to the LWOP_HWOP shock. Such an increase in ethanol supply is achieved through a combination of biorefinery capacity additions (both dry mills and cellulosic biorefineries) and an increase in sugarcane ethanol imports. In the LWOP_HWOP shock, the 2025 supply cost of ethanol jumps to US$6.5/gallon. To accommodate the increase in ethanol supply, retail infrastructure investment also adjusts. For instance, during the LWOP_HWOP shock, investment in dedicated E85 pumps increases but E85 consumption is bounded by the number of FFVs (30 million in 2025), which is an exogenous parameter in BioTrans.

Conclusions and Further Work

This analysis has explored the value of three selected flexibility levers for mitigating the impacts of petroleum and biomass supply shocks on the LDV fuel supply. Although not every lever is useful in response to every shock, a more flexible supply chain slightly reduces average fuel expenditures for consumers and variability of revenues for farmers. The reduction in petroleum shock costs enabled by these particular levers is quite limited and merits further investigation.

The flexibility levers affect the undisrupted base supply chain configuration, changing the optimal regional distribution of installed biorefinery capacity, cellulosic feedstock mix, and fuel blend mix. This leads to different pre-disruption conditions on which a given shock is applied. These differences in starting points influence the effectiveness of a given flexibility lever during a shock and complicate the comparison of shock costs across supply chain configurations.

For oil supply shocks, the main takeaway is that the depicted flexibility levers are not very effective in mitigating the cost of damaging supply shocks (BAU_HWOP, LWOP_HWOP) or amplifying the benefits from positive supply shocks (BAU_LWOP, HWOP_LWOP). The RFS constraint is often binding, limiting downward biofuel blend flexibility and occasionally making upward flexibility unnecessary or unattractive unless oil prices increase greatly. Upward ethanol blend flexibility is also limited by short-run surge supply limits, short-run biomass supply elasticity, available logistics, and conversion capacity. The flexibility levers considered are most useful in response to supply shocks affecting cellulosic biomass feedstocks. Biorefinery feedstock flexibility and advanced logistics help decrease the supply cost of cellulosic ethanol so that it becomes more competitive with corn ethanol.

The supply chain representation in BioTrans does not include some response mechanisms that would help increase the effectiveness of flexibility levers during shocks: first, the analysis does not consider short-run flexibility from inventories of fuel or feedstock; second, no adjustment in corn planted acreage in response to shocks that imply large increases in ethanol demand and prices is allowed; third, drop-in biofuels that could substitute for larger shares of gasoline without requiring modifications to vehicle engines or retail infrastructure are not modeled. Including these mechanisms in BioTrans is among the items suggested for future study.

This analysis has explored potential benefits from flexibility levers along the supply chain, but it does not fully account for all the costs associated with implementing that flexibility. It includes estimated costs for flexible fuel pumps and advanced logistics components. Multi-feedstock biorefineries are presumably more expensive to build and operate than those dedicated to a single feedstock and those premia are not yet included in BioTrans. Similarly, *Ethanol Blend Flexibility* would require changes in operations at petroleum refineries whose cost is not depicted here. A more complete accounting of those additional costs could be a useful extension to this analysis.

The set of selected shocks is meant to be diverse enough to ascertain which types of shocks a given flexibility lever is more effective in mitigating. Without a probability distribution attached to those different types, average revenue and expenditure calculations are effectively assuming equal probabilities for all the simulated shocks which is not necessarily realistic. For petroleum and corn supply shocks, historical data can help in assigning probabilities, as long as we assume that the future will follow a similar pattern to the past. For cellulosic feedstocks, the task is much more difficult because historical data are limited.

All the supply shocks we have simulated are nationwide and applied uniformly to all U.S. regions. Additional insight, and measured flexibility benefits, might arise from regional supply shocks, particularly for biomass supply. If only one region is affected by adverse weather or a pest, the combination of biorefinery feedstock flexibility and advanced biomass logistics might significantly dampen the net private welfare cost of the shock by substituting biomass from unaffected regions for the affected crops.

Another reason that shocks' benefits are small is the way benefits are calculated. In this study welfare value has not been ascribed to the reduction of fuel price shock size *per se*. The social surplus measure focuses on deadweight loss, and import costs, to measure U.S. net private welfare loss. A change in price from the shocks we model leads mostly to offsetting gains and losses for producers and consumers, or vice versa. When elasticities are small, the deadweight loss triangles are small. If petroleum imports are replaced by imported ethanol during a shock and elasticities are small, then the social surplus change may be very small.

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