

# From Measurement to Policy Design: A Convex Optimization Framework for Broadband Affordability

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Universal service has two core parts: an operator must fund the construction of networks to households, then households must be willing and able to pay for service. Federal programs have funded the first component at scale. The second component, broadband affordability (whether addresses within a network’s coverage area can afford the service it provides), has received neither comparable funding nor systematic measurement. Broadband affordability is a three-dimensional design problem. Policymakers must balance three constraints. (1) An affordability threshold that defines the maximum net out-of-pocket cost for broadband service that a household can bear (typically expressed as a fraction of household income). (2) The retail price for broadband service, which may be market-set or regulator-set, such as through a price cap or other policy intervention. (3) A subsidy budget that supplies public funds to bridge the gap between the retail price and the affordability threshold. Fixing one constraint determines the bounded space of the other two, and fixing any two determines the third. Yet, policymakers have historically separated them, through legislation, regulation, or litigation, without a structured framework for understanding the tradeoffs among the three constraints. To address this, we introduce the Threshold, Price, and Subsidy (TPS) framework, which characterizes the complete set of feasible <affordability threshold, retail price, subsidy budget> policy combinations for a given jurisdiction. We model broadband affordability as a constrained optimization problem over the three constraints. We operationalize the framework using American Community Survey (ACS) household income estimates, computing affordability at census-block-group granularity. As federal deployment programs expand broadband access, the TPS framework helps ensure that availability translates into affordability.

## 1 INTRODUCTION

Broadband has become essential infrastructure for work, healthcare, and education, yet for millions of American households, it is a persistent financial struggle, even in areas served by multiple providers. Affordability strongly determines broadband adoption, often deciding whether households subscribe to service at all [45]. As of 2024, 18 million of the 28.2 million American households without high-speed broadband service remain offline primarily because they cannot afford an in-home internet connection [15].

Recognizing the importance of affordability, the Federal Communications Commission (FCC) introduced a broadband affordability benchmark in 2016, defining affordable service as costing no more than 2% of a household’s monthly income [18]. Broadband remains unaffordable for many of the lowest-income households, even under this benchmark [24]. For example, some low and moderate-income communities spend 2.43% of household income on broadband, above the FCC’s 2% threshold and 4.8 times the 0.51% spent in wealthier areas [24]. This represents an “affordability gap,” which we define to be the amount by which the price of available service exceeds some threshold price that defines affordable service, such as the FCC’s benchmark. Lowering the threshold classifies more households as facing unaffordable broadband prices. Raising it classifies fewer.

Policymakers have sought to address such affordability gaps through several interventions. New York enacted the Affordable Broadband Act (ABA) [39], requiring providers to offer qualifying low-income households plans at \$15 per month for 25 Mbps service or \$20 per month for 200 Mbps. The federal Affordable Connectivity Program (ACP) offered a \$30 subsidy to eligible low-income households [22], and the White House announced that several providers had agreed to offer \$30 plans to qualifying households [22, 38]. With \$30 plans and a \$30 subsidy, service became

free for eligible households. The ACP’s budget consisted of the price, subsidy, and eligibility cutoff (which fixed how many households qualified). Although Congress lost the will to sustain this investment in 2024 [26], this example suggests that states might design sustainable affordability policies that make the same three-way link, replacing ACP’s eligibility cutoff with an affordability threshold.

Interventions thus far interact with at most two of the three constraints: New York’s ABA set a price cap, the ACP funded a subsidy (paired with voluntary \$30 price commitments), and the FCC named a threshold. Each takes an independent and ad hoc approach. No approach incorporates all three aspects: New York and the ACP derived its numbers from an affordability threshold, and the FCC never attached its threshold to a price or subsidy.

This fragmented approach suffers from three structural limitations. First, a policy intervention that fixes one constraint in isolation may ignore the interdependence among the three: fixing an affordability threshold and a retail price jointly determines the subsidy budget required to achieve any coverage target (the share of households for which service becomes affordable). States that treat these constraints as independent choices cannot know what fiscal commitment the policy implies prior to enacting policy. Second, evaluating any policy requires joining what service costs with what each household can pay: no public data source integrates the two. The FCC’s National Broadband Map (NBM) reports which providers serve each location, but it carries no pricing or household income data, so it is not an accurate measure of whether service is affordable at a location. Third, without a systematic framework, policymakers lack a basis for comparing alternative policy designs: what subsidy budget does a retail price imply, what coverage does a fixed budget buy, and what is the marginal fiscal cost of each additional covered household?

To address these limitations, we introduce the Threshold, Price, and Subsidy (TPS) framework, which characterizes the complete set of feasible  $\langle \text{affordability threshold, retail price, subsidy budget} \rangle$  policy combinations for a given jurisdiction: combinations whose subsidy budget closes every household’s affordability gap at that threshold and price. The framework has a direct policy implication: fix any one of the three constraints, and the full range of feasible combinations for the other two follows.

**Contributions.** This paper makes two contributions. (1) Framework. We introduce the TPS framework, which characterizes the feasible set of  $\langle \tau, P, S \rangle$  combinations (affordability threshold, retail price, subsidy budget) for a jurisdiction. Fixing any constraint bounds the values of the other two, and for a fixed threshold the required subsidy budget is increasing and convex in the retail price. (2) National-scale operationalization. We operationalize the framework with American Community Survey (ACS) household income data, computing affordability at census-block-group (CBG) granularity (tract-level income assigned to CBGs, the finest granularity at which ACS income is reliable) and determining the residential addresses at risk of unaffordable broadband within each CBG. At the FCC’s 2% threshold, a \$50 retail price implies a \$4.172 billion annual subsidy budget for fully closing the broadband affordability gap.

Section 2 traces how the three constraints emerged one intervention at a time and why no prior program has set all three constraints together. Section 3 motivates the framework by documenting the limitations of existing state policy approaches, the absence of a public data source that joins service cost with household income, and the absence of a framework for comparing alternative policy designs. We present the TPS framework and the convexity optimization problem in Section 4. Finally, Section 5 applies the TPS framework nationwide using ACS income data. We locate the addresses at risk of unaffordable broadband, trace the price/subsidy frontier (the required subsidy budget at each retail price, nationally and per state), and compute the coverage any subsidy budget buys.

## 2 BACKGROUND

The federal policy goal of ensuring the “universal service” of critical communications technologies has at least three components: service *availability*, *quality*, and *affordability*, echoing 47 U.S.C. § 254(b)(1)’s mandate that “quality services should be available at just, reasonable, and affordable rates” [56]. Availability and quality govern whether

(and what quality of) service reaches a location, while affordability governs whether the household can pay for it. U.S. federal deployment programs fund the first two. The Rural Digital Opportunity Fund (RDOF) program committed \$20.4 billion and the 2021 Infrastructure Act’s Broadband Equity, Access, and Deployment (BEAD) program another \$42.45 billion to extend infrastructure to unserved addresses and enforce a 100/20 Mbps quality standard [20, 51, 57]. But the June 2025 BEAD restructuring sharpened the gap between programs aimed at availability and quality versus those aimed at affordability: it barred states from setting low-cost plan rates, lowered income eligibility from 200% to 135% of the Federal Poverty Level (FPL), and eliminated the middle-class affordability requirement [40]. Even where deployment succeeds, low-income households may still not be able to afford broadband prices [24].

Closing the affordability gap requires an assessment of three policy constraints: an affordability threshold, retail prices, and a subsidy budget. For eighty years, universal service policy has strived for this three-constraint structure without explicitly setting all three at once. From the Communications Act of 1934 to the FCC’s 2016 Lifeline Modernization Order, federal policy added one constraint at a time: a subsidy, then a retail price, then an affordability threshold, each through a separate statute or order.

**Lifeline became the first explicit subsidy.** The Communications Act of 1934 directed the FCC to make service available “to all the people of the United States . . . at reasonable charges” [55]: the affordability principle, with no constraint attached. The principle predates the statute: AT&T had marketed “universal service” since 1907 and accepted regulatory obligations in the 1913 Kingsbury Commitment [3], settling an antitrust investigation. For the next half-century, implicit cross-subsidies inside the regulated AT&T monopoly funded universal service. The 1984 AT&T divestiture ended those cross-subsidies, and the FCC’s 1985 Lifeline program became the first explicit subsidy  $S$ : a fixed dollar transfer, currently \$9.25 per month, targeted through an income-based eligibility rule, with the price left to the market [23].

**1992 capped basic-tier cable rates.** Congress extended this trajectory in 1992. After the 1984 Cable Act’s deregulation produced runaway cable-rate escalation, the Cable Television Consumer Protection and Competition Act of 1992 [12] re-imposed targeted rate regulation under what is now 47 U.S.C. § 543. The statute capped “basic tier” cable prices in markets without “effective competition.” The basic-tier cap made the retail price  $P$  an instrument of federal communications policy, and it remains an important legal template for regulating a modern broadband retail price [36].

**Section 254 makes affordability a mandate.** The Telecommunications Act of 1996 codified universal service in modern form. Section 254 required that subsidies be explicit, competitively neutral, and tied to “an evolving level of telecommunications services,” and § 254(b)(1) wrote affordability directly into the statute [14]. Section 254 codified four standing programs under this mandate: Lifeline for low-income households, a high-cost fund for rural and expensive-to-serve areas, E-rate for schools and libraries, and a rural health care fund for clinics and hospitals [16]. Over time, the FCC incorporated broadband into the scope of these programs, and then, in 2016, set the affordability threshold  $\tau$  at 2% of monthly household income [18].

**The framework takes the threshold as input.** The FCC tracks affordability by measuring how far low-income households’ voice and broadband spending exceeds 2% of disposable household income, benchmarked against the next-highest income group. It set the 2% level by analogy to the United Nations’ 5%-of-disposable-income target for entry-level broadband in developing countries and to International Telecommunication Union data showing that a fixed broadband connection already consumed 2.47% of monthly disposable income for the poorest 20% of U.S. households [54]. The FCC conceded that 2% was “a clear yardstick for charting changes, not as an inherently meaningful level” [18].

**No instrument alone suffices.** Of the three constraints, two operate as direct policy instruments, and either alone leaves the affordability gap open. Rate regulation can cap the retail price  $P$  that providers may charge. By contrast, similar to Lifeline, direct subsidies (the subsidy budget  $S$ ) give consumers a discount on the market price for broadband. The two act on opposite sides of the affordability gap: rate regulation can control the market price, but

Table 1. No enacted program sets all three constraints together: eligibility rules stand in for affordability thresholds, and the one proposal engaging all three (Virginia’s Joint Commission on Technology and Science, JCOTS) remains a recommendation. We let  $\tau$  denote the affordability threshold,  $P$  the retail price,  $S$  the subsidy budget, LCSO the low-cost service option, and FPL the Federal Poverty Level. The BEAD LCSO row reflects guidance predating the June 2025 restructuring.

| Program              | Threshold ( $\tau$ )            | Retail Price ( $P$ )       | Subsidy ( $S$ )        |
|----------------------|---------------------------------|----------------------------|------------------------|
| Lifeline             | unset (eligibility: 135% FPL)   | unset (market)             | \$9.25/mo              |
| ACP                  | unset (eligibility: 200% FPL)   | voluntary \$30 commitments | \$30/mo                |
| NY ABA               | unset (categorical eligibility) | \$15 / \$20                | none                   |
| BEAD LCSO            | set per state plan              | recommended \$30           | infrastructure subsidy |
| JCOTS (VA, proposed) | <\$18K disposable income        | \$30                       | \$360/yr tax credit    |
| FCC 2% benchmark     | 2% of income                    | unset                      | unset                  |

that price may still be out of reach for many of the lowest-income households. A subsidy reaches the lowest-income households but cannot control the price. Therefore, affordability is the relationship between the subsidy, price, and threshold.

**Scholars split between rate regulation and subsidy.** Controversy exists among scholars and advocacy organizations over which policy instrument should have primary responsibility for addressing broadband affordability. Professor Narechania argues for a scheme of broadband rate regulation modeled after the framework applied to cable television in the 1992 Act [36]. His proposed basic-service tier benchmarks the regulated price to what a competitive market would otherwise yield. He identifies at least two contexts in which such a regulated price would apply. The first is monopoly markets, which encompass roughly one in five American households. The second is federal subsidy programs in which a single provider receives funds to serve unserved and underserved areas. The Information Technology and Innovation Foundation takes the opposing view: Congress should fund a targeted affordability subsidy rather than regulate prices since deployment is largely complete [31].

**ACP tested subsidy at scale.** The Emergency Broadband Benefit (EBB) and its successor, ACP, paired a federal subsidy of up to \$30 per month with voluntary price commitments, making broadband effectively free for many eligible households (however eligibility is defined) [22, 38, 60]. ACP served roughly 23 million households before its funding lapsed in 2024, and evaluations document measurable declines in adoption after it ended [26]. The program revealed both the reach of a subsidy and the fragility of one that lacks an enforceable price cap or a durable funding commitment.

**No program sets all three constraints together.** Prior programs have largely focused on one or two of these constraints, leaving the rest to market mechanisms (Table 1). The gaps in these programs can be traced to the constraints that they left unset. Lifeline fixes the subsidy budget  $S$  alone and targets it through a binary income cutoff, so a flat benefit over-subsidizes households near the threshold and under-subsidizes the lowest-income households [22]. ACP paired its subsidy with voluntary \$30 price commitments that made service nominally free for many enrolled households. But none of the three margins was binding. The price commitments were unenforceable, so retail prices remained at provider discretion. Eligibility stopped at 200% of the FPL Guidelines by statute [10], so a household just above the line paid full price no matter what share of its income that price consumed. Finally,  $S$  was a fixed \$14.2 billion appropriation rather than a function of the eligible population [22], which is why the program exhausted its funds and ended in June 2024. New York’s ABA fixes the retail price  $P$  through a price cap at \$15–\$20 with no public subsidy, so the lowest-income households may still pay more than the 2% threshold allows [39]. The FCC’s 2% benchmark fixes the threshold  $\tau$  alone, naming which households count as burdened without constraining prices or funding the gap.

**Federal price authority remains legally unsettled.** An unstable classification determines whether the FCC may regulate broadband rates at all. The 2005 *Brand X* decision let the FCC treat broadband as a lightly regulated Title I

“information service” [49]. The agency reclassified it as a Title II common-carrier service in 2015 [17], reversed itself in 2017 [19], and was reclassified in 2024. In 2025, the Sixth Circuit vacated that 2024 order, holding that broadband is an information service outside Title II’s rate authority [59]. The court owed the agency no deference: the Supreme Court had overruled *Chevron* [50], under which courts had deferred to agency readings of ambiguous statutes. Two decades of whipsaw thus left Title II rate regulation foreclosed for now, though the Sixth Circuit acknowledged that Section 706 gives the FCC some regulatory authority to encourage broadband deployment [13, 59]. Indeed, that statute itself expressly authorizes “price cap regulation.” The D.C. Circuit’s 2019 *Mozilla* decision had already held that the FCC could not bar states from regulating broadband, clearing the path for the state interventions below [58]. **States are now testing the constraints.** New York fixed the price through statute, and the Second Circuit upheld the ABA in 2024, confirming state authority to regulate broadband retail rates [30, 39]. Virginia’s Joint Commission on Technology and Science (JCOTS) recommended a hybrid that engages all three constraints at once: an income cutoff (under \$18K disposable income), a \$30 price cap on providers, and a refundable \$360-per-year tax credit for the lowest-income households [29]. California reached a comparable price cap through a merger condition rather than a statute, requiring a \$20 monthly plan for qualifying households as a condition of the Verizon–Frontier acquisition [7]. In 2025, Tennessee moved the opposite way, enacting a statute that bars state and local governments from regulating broadband rates at all [52].

### 3 MOTIVATION

The policy objective is the longstanding federal goal traced in Section 2: affordable universal broadband service for all households. The need for a systematic affordability design framework arises from the one-constraint-at-a-time programs cataloged in Section 2, which compound into the three structural limitations identified in Section 1: state policy approaches that ignore constraint interdependence, data sources that cannot support affordability analysis at the prices households actually pay, and analytical frameworks that do not characterize the full policy design space. The paragraph below documents the first limitation. The two subsections that follow elaborate the second and third. Specifically, each intervention cataloged in Section 2 and Table 1 occupies a single design point in the  $\langle \tau, P, S \rangle$  space, chosen without a model of the space: New York fixed the retail price alone, Lifeline the subsidy alone, and neither evaluated its choice against the trade-offs among the three constraints.

#### 3.1 Public Broadband Data Are Unverified and Omit Prices

Federal programs, including RDOF and BEAD, have committed over \$62 billion to expanding broadband availability [20, 57]. These allocations rely on address-level availability data. Evaluating affordability additionally requires the prices and plans available to an address, which no public source reports.

The FCC’s Form 477 and its successor, the NBM [1, 11], guide funding and coverage decisions. Two limitations persist across both. First, data self-reported by Internet Service Providers (ISPs) often lack independent verification, and academic audits and journalistic investigations have both documented addresses reported as “served” where no service exists [4, 5, 27, 35] and unexplained flips in technology types [6, 34, 64]. When the FCC published the first NBM, state broadband offices and other stakeholders filed hundreds of bulk challenges that refuted ISP-reported availability at millions of locations [47]. Within a year the FCC had processed 4.8 million availability challenges [48]. Second, neither Form 477 nor the NBM reports plan prices: both capture availability and quality, but omit what a household would pay. The TPS framework uses the retail price as a variable, so income data alone locates the CBGs where broadband would be unaffordable at a given price (Section 5).

### 3.2 No Framework Spans the Full Design Space

Existing literature has examined affordability from several angles, but no existing approach characterizes the full broadband affordability design space or enables systematic trade-off analysis. Evaluations of specific programs analyze the effects of a given policy at the single point it occupies in the design space. Econometric studies of Lifeline’s effect on subscription [2, 25] and analyses of ACP enrollment and performance [28, 61] each evaluate one enacted  $\langle \tau, P, S \rangle$  design point.

Price and availability analyses characterize the current broadband market without modeling policy interventions [9, 62]. These analyses document potential affordability gaps and their correlation between income and geography [33, 63], identifying the problem the TPS framework solves. Knowing that CBGs have higher average plan prices does not necessarily tell a policymaker what retail price makes broadband affordable for households in those tracts, or what subsidy budget closes the remaining gap at a given price.

The closest antecedents evaluate a single price, subsidy design point for one jurisdiction [44] or analyze pricing and subsidy instruments jointly in theory [46]. None characterizes the complete set of feasible  $\langle \tau, P, S \rangle$  combinations. The TPS framework does so at CBG granularity, the finest the public income data reliably supports. We set  $\tau$  to the FCC’s 2% benchmark in Section 5, though any other threshold works the same way, as Section 2 discusses. Critics raise two objections: a single national ratio cannot capture the local prices and incomes that determine whether a plan is affordable for a given household [53], and a benchmark defined on disposable income (after taxes) rather than discretionary income (after taxes and essential expenses) overstates what low-income households can spend. Under a uniform 2% threshold, the ceiling is \$40 a month for a household earning \$2,000 and \$100 for one earning \$5,000 whereas the poorer household has little to nothing left after essentials. As Section 5 shows, the dollar amount the threshold affords varies more than fivefold across congressional districts. Such variation is the argument for treating the threshold as an explicit design constraint, an important consideration the TPS framework utilizes.

## 4 THE TPS FRAMEWORK

This section presents the model underlying the TPS framework. We begin with a static model of the three policy constraints (the affordability threshold  $\tau$ , the retail price  $P$ , and the subsidy budget  $S$ ), demonstrating how fixing any one determines the trade-off between the other two. We then show that, given any affordability threshold, the trade-off between the retail price and the required subsidy budget is strictly convex. Measured as the number of households whose service becomes affordable under the policy intervention, this shapes how policymakers should reason about the cost of expanding affordability coverage. We close by outlining a dynamic, time-indexed extension as future work.

### 4.1 Static Model

We define the three policy constraints. Let  $\tau$  denote the affordability threshold, the maximum share of monthly income a household can bear for broadband. For a household  $i$  with monthly income  $m_i$ , the dollar amount  $\tau \cdot m_i$  is its affordability ceiling. Let  $P$  denote the retail price for broadband service: the minimum of a price cap if it exists and market price. Let  $S$  denote the total subsidy budget, the pool of public funds available to bridge the gap between the price for broadband and the affordability ceiling. For household  $i$ , let  $\text{price}_i$  denote the market price of the broadband plan available to it. The household pays the minimum of the market price and the retail price  $P$ . The affordability gap, the difference between this payment and what the household can bear ( $\tau \cdot m_i$ ), is:

$$g_i = \min(\text{price}_i, P) - \tau \cdot m_i$$

A household needs a subsidy only when  $g_i > 0$ , i.e., when the price exceeds what the household can reasonably afford. Since the three data inputs (address-level plan prices, tract-level household incomes, and address counts) are available at different granularities, we join them at CBG level: we assign each tract’s income estimate to the CBGs within it, and sum address counts up to the same level, treating each residential address as one household. Let  $H_n$  denote the number of households in CBG  $n$ ,  $f_n(\text{price})$  the distribution of address-level prices within CBG  $n$ , and  $m_n$  its assigned household income (Section 5 instantiates  $m_n$  as the tract’s 20th-percentile income). The total subsidy required to achieve the affordability threshold  $\tau$  under retail price  $P$  is:

$$S = \sum_{n \in \mathcal{N}} H_n \int_{\text{price: } \min(\text{price}, P) - \tau m_n > 0} [\min(\text{price}, P) - \tau \cdot m_n] \cdot f_n(\text{price}) d(\text{price})$$

Here,  $\mathcal{N}$  denotes the jurisdiction’s set of CBGs.

This formulation supports at least two natural policy scenarios: (1) a fixed budget  $S$  is available, and for the threshold  $\tau$ , policymakers wish to find the retail price  $P$  that maximizes affordability coverage (Section 5 realizes this trade-off on national income data), or (2) based on some  $P$  (a potential commitment to market prices, or an evaluation of some feasible price cap), policymakers must determine the funding  $S$  needed to close the affordability gap across all addresses. In both cases,  $\tau$  serves as the normative anchor (the politically negotiated definition of what share of income is acceptable to spend on connectivity), and policymakers typically determine it first. Formally, given any two of the three constraints, the framework computes the minimum feasible value of the third. This is the constrained optimization that the convexity result below makes tractable.

Two important modeling assumptions emerge from the static case. First, the subsidy must be non-negative: when household  $i$ ’s affordability ceiling already covers what it would pay ( $\tau \cdot m_i \geq \min(\text{price}_i, P)$ ), the model excludes it from the subsidy pool. Second, the static model assumes no strategic interaction between policy instruments and ISP pricing. If ISPs set prices in response to consumer willingness to pay, the introduction of a subsidy creates an incentive to raise prices. Policymakers who wish to maintain a subsidy’s effectiveness over time must place restraints on ISP pricing, as adopted in EBB, which prevented providers from raising prices above market rates to capture the maximum reimbursement [21]. This reinforces that  $S$ ,  $P$ , and  $\tau$  interact as a single policy bundle.

## 4.2 Relationship among the Constraints

Fixing any one of the three constraints ( $P$ ,  $\tau$ , or  $S$ ) determines the relationship between the other two. The examples below illustrate these trade-offs for a single household, writing  $s_i = \max(g_i, 0)$  for that household’s subsidy.

**Case 1: fixing the price.** Suppose the market price is  $\text{price}_i = \$70$ , but policymakers choose to cap the price at  $P = \$50$ . The household’s monthly income is \$2,000. The required subsidy is  $s_i = \min(\$70, \$50) - \$2,000 \cdot \tau$ : at  $\tau = 0.01$  the subsidy is \$30, and at  $\tau = 0.02$  it falls to \$10. With a fixed price, a higher threshold shifts the cost to households, reducing the required subsidy.

**Case 2: fixing the threshold.** For the same household, the market price remains  $\text{price}_i = \$70$ , and policymakers might cap the price at  $P$ . Fixing  $\tau = 0.02$  makes the subsidy  $s_i = \min(\$70, P) - \$40$ : a price cap of \$50 requires \$10 and one of \$60 requires \$20. With the threshold fixed, lowering  $P$  below market prices directly reduces what the household pays and the required subsidy. The lower the price, the lower the required subsidy.

**Case 3: fixing the subsidy budget.** Now let monthly income be \$1,500 and fix the household’s subsidy at  $s_i = \$40$ . The market price remains  $\text{price}_i = \$70$ , and a price cap is an optional intervention. Rearranging gives  $\min(\$70, P) = \$40 + \$1,500 \cdot \tau$ : at  $\tau = 0.01$  the price cap must be \$55, and at  $\tau = 0.02$  any price of \$70 or above satisfies the budget. With a fixed subsidy, a higher threshold permits a higher price because the household pays more. If policymakers enact no price cap, fixing the subsidy implicitly sets a burden share for each household: the household pays  $\text{price}_i - s_i$ ,

a share  $(\text{price}_i - s_i)/m_i$  of income that grows as income falls, requiring lower-income households to dedicate a greater proportion of their income to connectivity than wealthier ones.

### 4.3 Inherent Convexity

The trade-off between the retail price and total subsidy budget is *strictly convex* when household incomes are continuously distributed within the jurisdiction. This follows directly from the distribution of affordability gaps across all households. Recall each household's affordability gap:

$$g_i = \min(\text{price}_i, P) - \tau \cdot m_i$$

For any given policy intervention  $\tau, P$ :

- Households with  $g_i \leq 0$  already have affordable service (no subsidy needed).
- Households with  $g_i > 0$  require a subsidy equal to their gap  $g_i$ .

Two key facts generate convexity.

**Small-gap households save little subsidy budget.** As policymakers lower the price, the first households whose service becomes affordable are those with the *smallest gaps*, the highest-income households among those subsidized. Removing these households from the subsidy pool saves little to no subsidy.

**Remaining gaps grow as coverage expands.** As coverage expands, the policy must reach households with progressively *larger gaps* (lower incomes or higher effective prices). Each additional household requires strictly more subsidy than the previous marginal household.

Let  $S(P)$  denote the total subsidy budget required at retail price  $P$ , i.e., the sum of subsidies across all households, and assume a price cap binds for subsidized households ( $P \leq \text{price}_i$ , the case that Section 5 evaluates). When  $P$  is high, many households require subsidies. A small reduction in  $P$  lowers costs for all of them, leading to a large reduction in  $S(P)$ . When  $P$  is already low, only a few households remain in need of subsidy. Further reductions in  $P$  affect fewer households, leading to a smaller reduction in  $S(P)$ . Thus, the marginal savings from lowering the price diminish as the price falls:

$$\frac{d^2 S}{dP^2} > 0$$

With finitely many households, the frontier is piecewise linear and convex, so the marginal gap is non-decreasing. Under a continuous-income idealization it is strictly convex and the marginal gap strictly increases.

**Policy implication.** A \$5 reduction in the price yields large subsidy savings when the price is high (many marginal households have small gaps), but much smaller savings when the price is already low (remaining households have large gaps). Ignoring this curvature leads to systematic misestimation of policy costs, underestimating the expense of reaching the lowest-income households.

### 4.4 Future Work: Dynamic Extensions

The static model treats prices, incomes, and the three constraints as fixed. In practice, all evolve over time. A central policy concern is whether subsidies or price caps cause ISPs to adjust prices strategically: the EBB [60], the predecessor to ACP, included a price-freeze requirement for this reason. Future work extends the model to a time-indexed setting that estimates ISP price responses from longitudinal price data and distinguishes subsidies delivered directly to consumers (e.g., vouchers or tax rebates [29]) from subsidies delivered through ISPs, which may shape ISP pricing differently. The next section traces the static frontier nationwide from public income data.

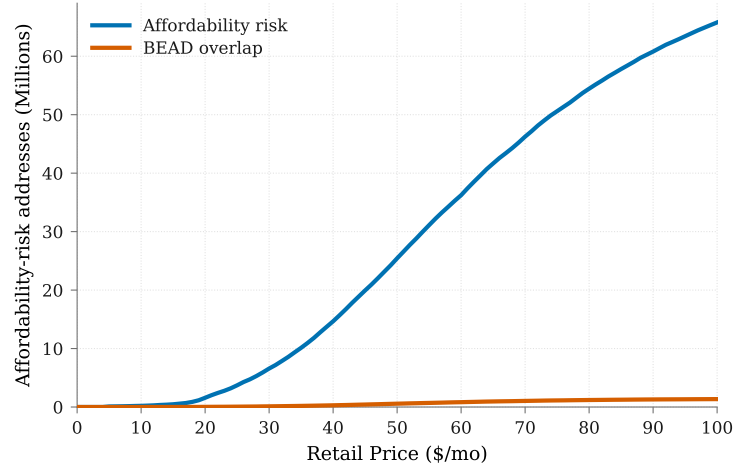


Fig. 1. Affordability-risk addresses as the retail price varies from \$0 to \$100.  $\tau$  is held fixed at 2%. BEAD-eligible addresses (orange) peak at 3.243% of the affordability-risk addresses.

## 5 NATIONWIDE AFFORDABILITY FROM INCOME DATA ALONE

This section maps nationwide affordability-risk addresses: locations where broadband would be unaffordable at given prices, based on U.S. Census data on household incomes (aggregated at the census tract level). Converting this risk assessment into confirmed gaps, where market prices verify what households face, requires address-level prices (Section 5.4).

### 5.1 Identifying Affordability-Risk CBGs

We operationalize the affordability threshold at  $\tau = 0.02$  of household income (Section 2), applied to the 20th-percentile disposable monthly household income from the ACS 2019–2023 5-year tract estimates. We assign each tract’s income to its constituent CBGs [8]. We measure income at the tract level because ACS income estimates are not accurate at CBG granularity. We define an *affordability-risk CBG* at a price as a CBG whose affordability ceiling  $\tau m_n$  falls below  $P$ : broadband at that price would cost more than low-income households in the CBG can afford (given our  $\tau$ ). A residential address within such a CBG is an *affordability-risk address*. We vary the price from \$0 to \$100 and report every result as a function of  $P$ . Every figure in this section holds the threshold fixed at  $\tau = 0.02$  and states which of the remaining two constraints varies and which we hold fixed. Section 5.3 varies the threshold itself.

**Risk grows with the retail price.** Figure 1 traces the affordability-risk addresses as the retail price varies from \$0 to \$100. The number of affordability-risk addresses rises steeply through the range where most advertised plans sit, and reaches 65.8 million addresses across 198,876 CBGs at \$100. We compare the affordability-risk addresses against BEAD eligibility since BEAD is the largest federal broadband commitment to date and targets locations without adequate infrastructure: if affordability-risk addresses also received BEAD funding, deployment funding would address the broadband affordability gap as a side effect. Instead, the overlap peaks at 3.243% of affordability-risk addresses, so affordability-risk addresses outnumber the BEAD-eligible subset at least thirtyfold at every price, and the NBM classifies the rest as “served”. Their problem is affordability, not availability: deployment funding can build networks, but it cannot close the gap between the retail price and what these households can afford. No federal program matches its scale to the affordability-risk households: Lifeline’s fixed \$9.25 monthly benefit covers a shrinking share of the gap as the price rises, and the ACP, which came closest, lapsed in 2024 [22, 23].

**Share and count rank states differently.** The geographic distribution of affordability risk can be read two ways. By *address share*, measured at the \$30 price, the deepest gaps occur in rural areas of Mississippi (27.8%), Louisiana

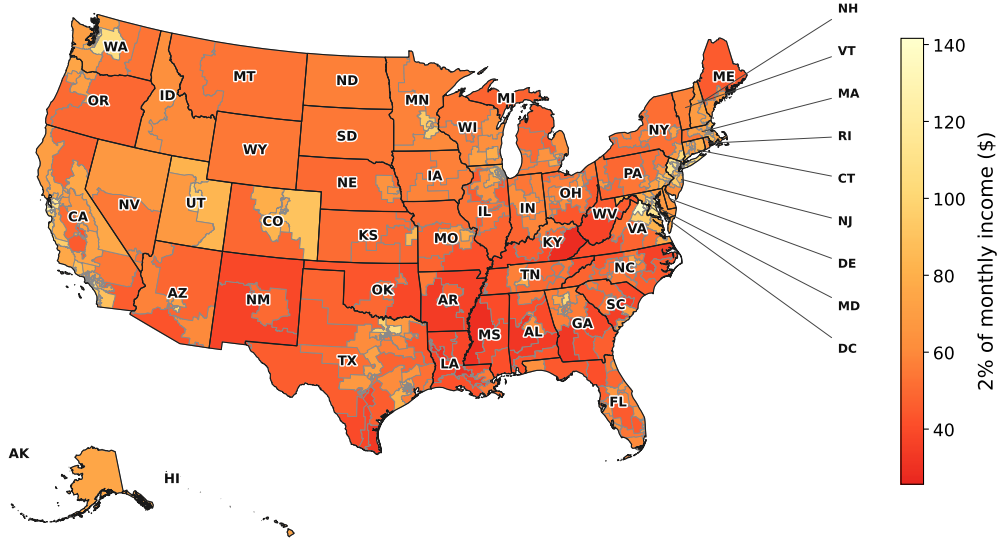


Fig. 2. Each U.S. congressional district shaded by the median affordability ceiling (2% of its CBGs’ 20th-percentile monthly household income) across its CBGs. Darker districts have lower affordability ceilings. The scale runs from \$25.66 to \$141.61/month.  $\tau$  is held fixed at 2%. The price and subsidy are not included, since the map reports the ceiling each district faces before policymakers choose either.

(24.5%), New Mexico (20.9%), and Alabama (19.0%). These regions carry the largest fractions of affordability-risk addresses, a concentration the congressional-district map makes visible (Figure 2), while the share of affordability-risk addresses shows how deeply the problem runs within a state. By *absolute count*, the most affordability-risk addresses are located in some of the most populous states: Texas, Florida, North Carolina, Ohio, and California. Count shows how many constituents the problem reaches. Across both measures, broadband affordability spans constituencies from both political parties: many of the hardest-hit states elect predominantly Republican delegations, and the largest affordability-risk counts are located in states both parties hold.

**Districts reveal the ceiling by geography.** Figure 2 shows the affordability ceiling across 435 congressional districts and the District of Columbia: broadband priced above that ceiling would cost more than what low-income households in the district can afford (given our  $\tau$ ). This ceiling varies more than fivefold, from \$25.66 in the poorest district to \$141.61 in the most affluent. The lowest-income districts (deepest red in Figure 2) form a contiguous band across the Deep South and Appalachia, running from the Mississippi Delta through Louisiana, Arkansas, and Alabama into eastern Kentucky and West Virginia. The Texas border, New Mexico, and Native American districts across the Southwest are also among the lowest-income districts. We report each district’s ceiling in dollars rather than a pass or fail flag at a fixed price to ensure that a reader can test any retail price directly.

## 5.2 Realizing the Frontier from Income Data

Public income data (i.e., ACS) that locates the affordability-risk addresses realizes the price/subsidy tradeoff of Section 4. We evaluate the case where the price cap binds: market prices meet or exceed  $P$ , so every household pays  $P$ . The subsidy required to hold every household’s payment at or below its affordability ceiling is:

$$S(P) = \sum_{n \in N} H_n \cdot \max(0, P - \tau m_n)$$

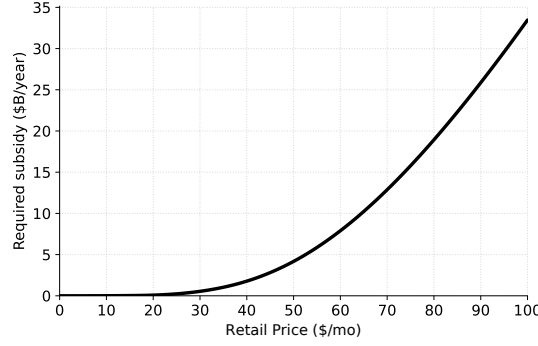


Fig. 3. The national price/subsidy frontier is convex. Total annual subsidy budget  $S(P)$  as the retail price varies from \$0 to \$100.  $\tau$  is held fixed at 2%. Counts are residential addresses. The marginal cost of a \$5 price increase grows by two orders of magnitude from the bottom of the range to the top.

where  $\mathcal{N}$  is the jurisdiction’s set of CBGs,  $H_n$  is the count of residential addresses in CBG  $n$ ,  $m_n$  is the 20th-percentile monthly household income from the ACS estimates, and  $\tau m_n$  is the affordability ceiling at  $\tau = 0.02$ . Each CBG contributes the gap between the retail price  $P$  and its ceiling, weighted by its locations. CBGs whose ceiling meets the price contribute nothing. Prices and incomes are monthly, so  $S(P)$  is a monthly floor. We report totals annualized. We evaluate  $S(P)$  over all CBGs nationwide, varying the retail price from \$0 to \$100. Figure 3 plots the national frontier and confirms the convexity result of Section 4 on real income data. A retail price at or below a household’s affordability ceiling eliminates its subsidy entirely, so at the left end of the frontier the price cap carries the whole burden and the required subsidy budget approaches zero. The marginal cost grows as the price rises: a \$5 increase adds under \$20 million per year at the bottom of the range and \$3.946 billion per year at the top. Therefore, no retail price maximizes the subsidy relief bought per dollar of price reduction. Across the \$0–\$100 range the subsidy budget rises by \$335 million per year for each dollar of retail price. The frontier’s marginal cost crosses that average at \$52, just above the \$50 price sampled below. The crossing depends on where the price range ends: extending it to \$200 raises the average to \$623 million per dollar and, since marginal cost increases with price, moves the crossing to \$77. For any retail price a policymaker considers, the curve returns the annual subsidy budget that price implies.

Figure 4 samples each state’s frontier at a mid-range price (\$30) and a near-market price (\$50), close to the prices ISPs typically advertise, so it leaves most of the affordability gap to the subsidy. Reading a state across the panels traces its frontier. Comparing states within a panel shows the geographic skew at that price. A \$15 price requires under \$3 million per year in every state, peaking at \$2.465 million in Texas. At the near-market price, requirements span two orders of magnitude, from \$3.29 million in Alaska to \$415.3 million in Texas. States with large affordability-risk address counts carry the largest totals.

**Partial budgets buy partial coverage.** The frontier returns the budget for full coverage. Inverting it answers the budget-constrained question. We evaluate two allocation orderings. Need-first funds the largest affordability gaps before smaller ones. Smallest-gap-first, the ordering Figure 5 plots, funds the opposite way and gives the per-dollar efficiency bound. At the mid-range price, the neediest tenth of addresses absorbs \$145 million per year under need-first, more than the \$109 million that brings half of all affordability-risk addresses to affordability under smallest-gap-first. Smallest-gap-first covers the most locations per dollar (half for \$109 million, 90% for \$396 million). The two orderings bracket any real allocation. Funding need-first also sharpens the case for the price cap: a price reduction shrinks every affordability-risk household’s gap at once, at zero public cost.

The frontier is the TPS framework’s output realized from public income data alone: for any retail price, it returns the annual subsidy budget that retail price implies given some threshold for affordability (here, the FCC’s income

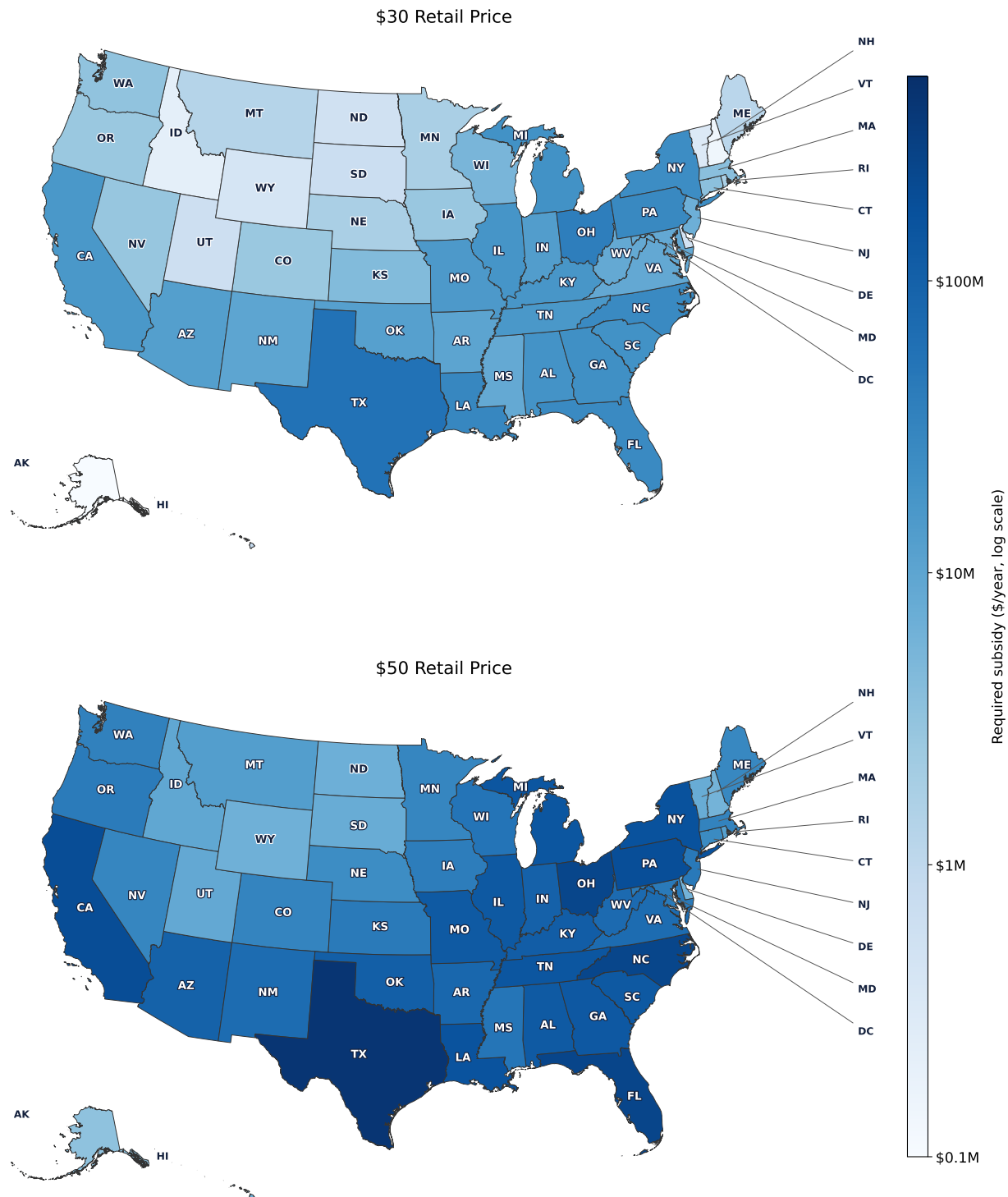


Fig. 4. Statewide required annual subsidy budget at two sample retail prices: \$30 and \$50.  $\tau$  is held fixed at 2%. We sample the price per panel (residential addresses, shared log color scale). Every state is labeled, with the smallest Northeast and Mid-Atlantic states labeled by leader line. At the near-market price, state requirements span two orders of magnitude.

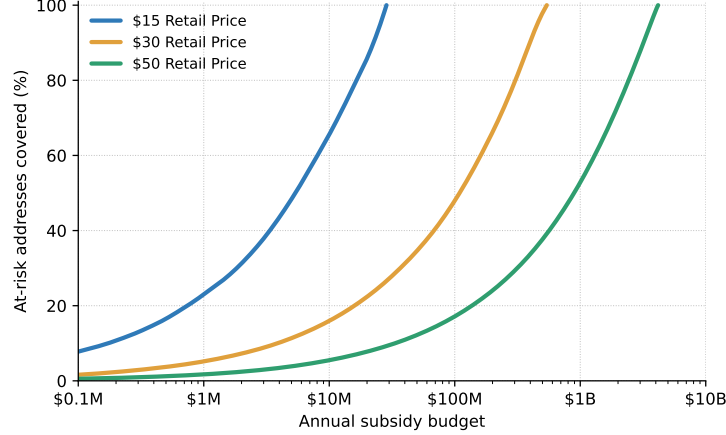


Fig. 5. Partial budgets buy partial coverage. Share of affordability-risk addresses reaching affordability as the annual subsidy budget varies. We plot curves for the smallest-gap-first ordering, the per-dollar efficiency bound.  $\tau$  is held fixed at 2% and the price, one curve per sample price. Each curve’s slope falls as coverage grows: the final tenth of the affordability-risk addresses costs more than the first half.

Table 2. The threshold and the price trade at a fixed rate. Required annual subsidy budget as the affordability threshold varies.  $P$  is held fixed at \$50, so every affordability-risk address reaches its ceiling. We use ACS 2019–2023 income data and residential addresses. The ceiling column reports the median of  $\tau m_n$  across CBGs, where  $m_n$  is the CBG’s assigned 20th-percentile disposable monthly household income. The gap column reports the mean shortfall per affordability-risk address. The 2% row is the configuration used elsewhere in this section.

| Threshold $\tau$ | Ceiling | Risk addresses | Mean gap | Budget $S(\$50)$ |
|------------------|---------|----------------|----------|------------------|
| 1.0%             | \$29.37 | 65.78M         | \$21.20  | \$16.735B        |
| 1.5%             | \$44.06 | 43.17M         | \$16.05  | \$8.313B         |
| 2.0%             | \$58.74 | 25.43M         | \$13.67  | \$4.172B         |
| 2.5%             | \$73.43 | 14.66M         | \$12.63  | \$2.222B         |
| 3.0%             | \$88.12 | 8.83M          | \$11.99  | \$1.271B         |

threshold). Convexity works in opposite directions for the two instruments. Even a modest price cap yields large savings to subsidy programs, but further reductions buy progressively less relief: setting the price at \$50 rather than \$60 cuts the required budget from \$7.893 to \$4.172 billion per year, while the same \$10 reduction from \$30 to \$20 saves \$0.461 billion. A subsidy applied need-first works the other way: the deepest gaps absorb the most budget per location, so coverage grows slowly at first and accelerates as the remaining gaps shrink. The two-orders-of-magnitude spread across states at the near-market price (Figure 4) means the efficient  $\langle \tau, P, S \rangle$  bundle is state-specific.

### 5.3 The Threshold and the Price Trade at a Fixed Rate

The threshold and the retail price enter the budget through a single combination. In  $S(P, \tau) = \sum_{n \in \mathcal{N}} H_n \max(0, P - \tau m_n)$  both appear only as  $P - \tau m_n$ , so a CBG carries affordability-risk addresses exactly when  $m_n < P/\tau$ . Scaling the two together moves the budget proportionally:  $S(cP, c\tau) = c S(P, \tau)$ . The count of affordability-risk addresses depends on the ratio  $P/\tau$  alone. The 65.8 million addresses at a \$50 price and a 1% threshold are the 65.8 million that Section 5.1 reaches at \$100 and 2%. The frontier at any threshold is that of of Section 5.2 rescaled by the same factor on both axes, so the convexity Section 4 proves for any threshold holds at every row of Table 2. That section’s first case gives the direction for a single household. The table gives the national magnitude.

**A lower threshold multiplies count and gap.** Halving the threshold from 2% to 1% quadruples the required budget, and lowering it from 2% to 1.5% doubles it. A lower threshold drops every household’s ceiling, which pulls

new addresses into the affordability-risk set and widens the gap at addresses already there. Between 2% and 1% the count rises from 25.43 to 65.78 million and the mean monthly gap from \$13.67 to \$21.20. The budget is their product, so both increases compound.

**Percent for percent, price moves more.** Cutting the threshold to  $c\tau$  and raising the price to  $P/c$  leave the same addresses at risk, and by the homogeneity  $S(cP, c\tau) = c S(P, \tau)$  the cut costs  $c$  times as much as the rise. At a \$50 price, cutting the threshold from 2% to 1.5% puts the same 43.17 million addresses at risk as holding the threshold at 2% and letting the price rise to \$67, and it costs three-quarters as much. The law also ties the two elasticities together. The budget’s elasticity with respect to the price is the price divided by the mean gap, and its elasticity with respect to the threshold is the mean ceiling divided by that same gap. Because the price is the ceiling plus the gap, the first exceeds the second by exactly one at every price and every threshold: at \$50 and 2% they are +3.66 and −2.66. One percent of the price always moves more money than one percent of the threshold. Raw dollar steps invert that ranking only because half a percentage point is a quarter of a 2% threshold, where \$10 is a fifth of a \$50 price.

**Nothing bounds the threshold.** Of the three constraints, the threshold is the only one with no market or fiscal referent. Providers’ prices and the courts bound the price cap, and appropriations bound the subsidy. An agency can move the threshold in an order, as the FCC did in 2016 with a figure it called a yardstick for charting changes rather than an inherently meaningful level [18]. Enacted programs substitute income-eligibility cutoffs, which do answer to a federal statistic and to a budget (Table 1). Table 2 prices the choice: at a \$50 price, each half point between 1% and 2% is worth \$4.14 to \$8.42 billion a year. That figure is large because a half point is a quarter or a third of the threshold, not because the threshold is the more elastic constraint.

#### 5.4 From Risk to Challenge: The Missing Price Input

We define an *affordability-challenge CBG* as a CBG where both income and price data confirm a gap between what is affordable and available. Affordability-risk CBGs are a predictive estimate. Affordability-challenge CBGs are an empirical finding. The two sets differ: some risk locations are not challenges (where low-cost plans are available), and some locations whose affordability ceiling clears a given retail price may still be challenges (where market prices exceed even that ceiling). Separating the two requires the framework’s second input: the prices available at each address.

No public dataset supplies this input (Section 3), and audits repeatedly show provider self-reports overstate availability [4, 27, 37, 41]. BQT+ [32] is an automated platform that obtains address-level pricing data at scale: it emulates a consumer’s broadband-shopping experience on ISP web interfaces to obtain the set of plans and prices available at a given residential address. BQT+ has supported multiple studies. First, it contextualized crowdsourced speed test data, demonstrating that many low speed-test results reflect the household’s subscribed plan tier rather than inadequate infrastructure [43]. Second, it collected broadband plan data for over one million addresses across thirty cities [42], exposing disparities and monopolistic practices that policymakers used as evidence to address digital discrimination [63]. Third, it evaluated the FCC’s multi-billion-dollar Connect America Fund (CAF) program, revealing that only 33% of targeted addresses received the promised service levels [35]. In future work, we will use BQT+ to query street addresses in the affordability-risk CBGs identified in Section 5.1 and determine which are affordability-challenge locations.

## 6 CONCLUSION

This paper treats broadband affordability as a design problem: three constraints whose feasible combinations a policymaker can characterize before enacting any of them. The TPS framework shows that the three policy constraints (the affordability threshold  $\tau$ , the retail price  $P$ , and the subsidy budget  $S$ ) are interdependent: fixing any one determines the trade-off between the other two. For a fixed threshold and binding price cap (at or below market prices), the

required subsidy  $S(P)$  is increasing and convex in  $P$ . When household incomes are continuously distributed, the price/subsidy frontier  $S(P)$  is strictly convex. This curvature carries a direct policy implication: modest price reductions save the most subsidy per dollar, while more aggressive ones save progressively less. Need-first subsidy allocation has a curvature opposite that of the smallest-gap-first ordering of Section 5: early dollars fund the deepest gaps, so coverage per dollar starts low and rises as the remaining gaps narrow.

Public ACS income data as well as NBM’s public address counts suffice to operationalize the framework nationwide at CBG granularity. As BEAD and other large-scale programs extend broadband infrastructure to unserved areas, affordability shapes whether that infrastructure translates into broadband adoption. The TPS framework prices the affordability gap: it makes the cost of any affordability policy intervention explicit before enactment, returning the feasible  $\langle \tau, P, S \rangle$  combinations for any jurisdiction.

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