A Linear Integer Programming Approach to Hepatitis A Mitigation in the United States

Stephen Adebowale Sunday

April 28, 2025

Abstract

This study presents a linear and integer programming model for minimizing the spread of Hepatitis A across five U.S. regions. Focusing on high-risk populations, the model treats the currently infected individuals and also allocates vaccines, hygiene kits, and public education resources while incorporating effectiveness, cost, and equity constraints. Results demonstrate that strategic optimization can significantly reduce new infections and guide policymakers in deploying public health resources more efficiently. This research will primarily focus on minimizing the new spread of infection through appropriate allocation of prevention resources across the five regions of the United States.

1 Introduction

Hepatitis A virus (HAV) is a positive-strand RNA virus without a lipid envelope and belongs to Picornaviridae family, and genus Hepatovirus [4]. Hepatitis means inflammation of the liver. This condition is often caused by a virus. In the United States, the most common causes of viral hepatitis are hepatitis B virus (HBV) and hepatitis C virus (HCV), although it can also be caused by hepatitis A virus (HAV). HAV was first observed and described in 1970 as a causative agent of type A viral hepatitis (Feinstone et al. 1973), which is transmitted through the fecal–oral route. It causes acute hepatitis with clinical symptoms that are indistinguishable from those of other types of viral hepatitis. There were 212 million cases estimated for year 2005[1].
The USA has been affected by a large multistate outbreak of hepatitis A that started in 2016; over 40,000 cases had been reported up to 16 July 2021. A study of 10% of randomly selected cases from three severely affected states revealed that the morbidity rate was particularly high, with over 50% hospitalized.[5] Hepatitis A has significantly affected communities across the nation. However, due to the dedicated efforts of stakeholders across various sectors and advancements in biomedical research, there are now highly effective diagnostic tools, prevention strategies, and improved care models for managing the disease. Additionally, innovative laboratory and epidemiological techniques enable precise identification of Hepatitis A outbreaks, allowing for targeted interventions to prevent further transmission. The development of The Viral Hepatitis National Strategic Plan: A Roadmap to Elimination 2021-2025 (Viral Hepatitis Plan or Plan) provides a framework to eliminate viral hepatitis as a public health threat in the United States by 2030 reflects a collaborative approach, integrating expertise from public health, healthcare, research, and other key sectors. This plan envisions a future where Hepatitis infections are rare, individuals are aware of their risk factors and vaccination status, and those affected receive timely care and support without stigma or barriers to access. Distributing resources effectively to states, major metropolitan areas, and regions across the U.S. remains a challenge in addressing disparities in access to healthcare and prevention services for Hepatitis A. The dynamic nature of the HAV epidemic, with varying transmission rates across different populations and regions, requires a flexible and targeted approach to resource allocation. Ensuring optimal funding distribution amidst competing health priorities demands strategic decision-making to maximize the impact of HAV prevention efforts. Additionally, disparities in healthcare access—driven by socioeconomic, racial, and geographic factors—complicate efforts to reach the most vulnerable populations.

Moreover, the evolving landscape of infectious disease prevention, including advancements in vaccination strategies, surveillance, and outbreak response, necessitates continuous evaluation and adaptation to implement the most effective interventions. This research will explore how data-driven tools and strategic resource allocation can be leveraged to minimize the spread of HAV across the West, Midwest, Northeast, Southwest, and Southeast regions of the United States, ensuring equitable and efficient prevention efforts.

2 Problem Statement

Hepatitis A outbreaks present a significant public health challenge in the United States, particularly among diverse and high-risk populations such as men who have sex with men (MSM), intravenous drug users (IDU), homeless individuals, persons with liver disease (PWLD), and persons with HIV (PWHIV).

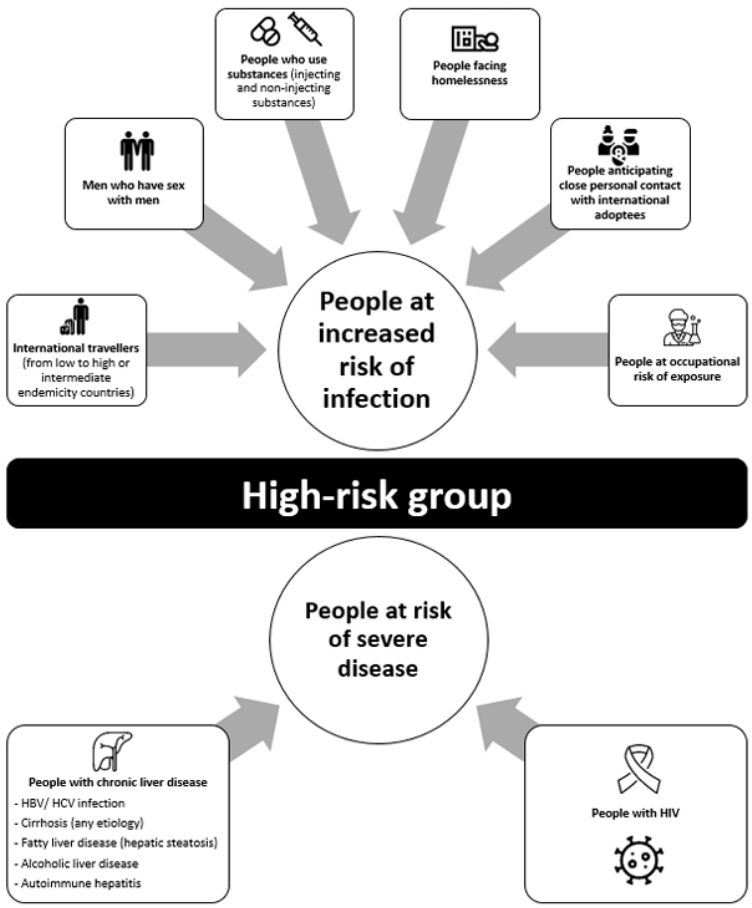

Figure 1: High-risk group vaccination recommendations [6]

As part of CDC mission of protecting Americans from health, safety, and security threats, both domestic and international. Its mission focuses on preventing, detecting, and responding to disease threats to improve public health and safety. CDC is committed to ensuring preventive and treatment resources are made available to every American, and part of the preventive resources are vaccination, hygiene resources, and educational resources through the help of public agencies.[2]
However, given limited resources and funding, public health agencies must decide how best to allocate vaccines, hygiene resources, and public/educational interventions across different geographical regions to mitigate the spread of the disease.
This model serves as a decision-support tool for public health policymakers by quantitatively balancing limited funds against the need to prevent Hepatitis A infections. By integrating cost-effectiveness, minimum service levels, and equity into the allocation strategy, the model guides the optimal distribution

of vaccines, hygiene, and public/educational resources. This ensures that interventions are deployed where they are most needed and effective, ultimately contributing to better health outcomes and more efficient use of public funds.

3 Objective of Study

The aims of this study is to:

- Minimize the total number of new infections by optimally distributing three types of interventions:
  - Vaccines: Highly effective but relatively costly.
  - Hygiene Resources: Provide necessary sanitation support with moderate effectiveness.
  - Public/Educational Resources: Promote behavior change and disease awareness at high cost-effectiveness.
- Ensure a baseline level of service in each region and priority-population cell by meeting minimum allocation requirements.
- Achieve equity in vaccine distribution by limiting disparities in coverage ratios across regions and priority-populations.

4 Background of Study

According to (Kesse 2025) [3], many grantees maintain multiple Community Planning Groups (CPGs) to address the diverse needs across different geographic regions, with each group generating its own list of priority populations. Once these populations are identified, grantees develop a comprehensive Hepatitis A prevention plan, which is submitted to the CDC to request funding.

Allocation of Funds Post- request for Proposals (RFP) Submission: After funds are secured, grantees issue RFPs to invite proposals from community-based organizations (CBOs) or local health departments for the implementation of prevention activities. Before releasing RFPs, grantees determine the specific combinations of priority populations and geographic regions for which they will solicit proposals.

They also recommend preferred prevention activities—such as administering vaccines, distributing hygiene resources (e.g., sanitation kits), and funding public and educational initiatives (e.g., developing booklets and launching awareness campaigns) based on funding priorities for CPG-identified priority populations, equity considerations across regions, and the relative cost-effectiveness of the different interventions.

Following the submission of intervention proposals, jurisdictions face the second major decision point: determining how to allocate the available funds among the proposal applicants. This allocation process is critical, as grantees must decide where and to which implementers prevention funds should be distributed to maximize the reduction of potential Hepatitis A infections.

This research focuses on supporting the CDC in optimizing the prevention resource allocation process. It aims to assist grantees in determining the most effective distribution of various intervention resources including vaccines, hygiene supplies, and public/educational materials across different priority populations and regions.

5 Methodology

The developed Linear Programming (LP) model minimizes the potential number of new infections by accounting for constraints such as funding availability, vaccine supply, hygiene resource availability, and public and educational resources, along with additional operational constraints. This approach ensures an efficient and equitable allocation of resources for Hepatitis A prevention.

Model

Sets
Let:

- $\mathcal{I}$ denote the set of geographical regions (West, Southwest, Midwest, Southeast, Northeast).
- $\mathcal{J}$ denote the set of priority populations (MSM, IDU, Homeless, PWLD, PWHIV).

Parameters

Define the following parameters:

$$
\begin{aligned}
B &: \text{ Total available funding (USD)} \\
C_{ij} &: \text{ Current infection count in region } i \text{ and population } j \\
R_{ij} &: \text{ Size of the risk group in region } i \text{ and priority population } j \\
\delta_{ij} = \frac{C_{ij}}{R_{ij}} &: \text{Potential infection i.e a fraction of } R_{ij} \text{ likely to be infected without intervention} \\
c_{ij}^{t} &: \text{ unit cost to treat one infected person in geographical region} i \text{and, group } j, \\
c_{ij}^{v} &: \text{Unit cost of vaccine for priority population } j \text{, region } i \\
\rho_{ij}^{1} = \delta_{ij} &: \text{Infection rate of risk group } j \text{ in region } i \text{ which refuses to accept prevention resources} \\
\rho_{ij}^{2} = \delta_{ij}\left(1-\zeta_h-\zeta_p\right) &: \text{Infection rate of risk group } j \text{ in region } i \text{ which accepts hygiene and educational prevention resou} \\
\rho_{ij}^{3} = \delta_{ij}\left(1-\zeta_v-\zeta_h-\zeta_p\right) &: \text{Infection rate of risk group } j \text{ in region } i \text{ which accepts all prevention resources} \\
c_{ij}^{h} &: \text{Unit cost of hygiene resource for priority population } j \text{, region } i \\
c_{ij}^{p} &: \text{Unit cost of public resource for priority population } j \text{, region } i \\
\bar{c}_v &: \text{Cost of stocking a unit of vaccine before intervention} \\
\bar{c}_h &: \text{Cost of stocking a unit of hygiene resources before intervention} \\
\bar{c}_p &: \text{Cost of stocking a unit of public resources before intervention} \\
\zeta_v &: \text{ Effectiveness of vaccine intervention per individual} \\
\zeta_h &: \text{ Effectiveness of hygiene resource intervention per individual} \\
\zeta_p &: \text{ Effectiveness of public resource intervention per individual} \\
\zeta_t &: \text{ treatment effectiveness} \\
m_{ij}^{v} &: \text{ minimum percent of priority population } j \text{ in region } i \text{ to be allocated vaccine} \\
m_{ij}^{h} &: \text{ minimum percent of priority population } j \text{ in region } i \text{ to be allocated hygiene resources} \\
m_{ij}^{p} &: \text{ minimum percent of priority population } j \text{ in region } i \text{ to be allocated public resources} \\
\epsilon &: \text{ Maximum allowable difference in vaccine coverage ratios across priority population } j \text{ in region } i
\end{aligned}
$$

Decision Variables

For each $i \in \mathcal{I}$ and $j \in \mathcal{J}$, define:

$w_{ij} \geq 0$: Amount of vaccines allocated to priority population j in region i

$x_{ij} \geq 0$: number of hygiene resources allocated to priority population j in region i

$y_{ij} \geq 0$: Amount of public/educational resources allocated to priority population j in region i

$\nu_{ij} \geq 0$: Fraction of the risk group R_{ij} who will not accept any intervention package

$\mu_{ij} \geq 0$: Fraction of the risk group R_{ij} accepting hygiene and public/educational resources as prevention packages

$\gamma_{ij} \geq 0$: Fraction of the risk group R_{ij} accepting all prevention packages

$t_{ij} \geq 0$: number of infected in priority population j in region i who receive treatment.

$V \geq 0$: Total vaccines stocked/purchased for intervention across all priority population j in region i

$H \geq 0$: Total hygiene kits stocked/purchased for intervention across all priority population j in region i

$P \geq 0$: Total public resources stocked/purchased for intervention across all priority population j in region i

$z_{ij} \geq 0$: New infections from priority population j in region i after intervention

Objective Function

$$\textbf{Minimize} \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{J}} z_{ij}$$

Constraints

1. Budget Constraint

$$\sum_{i,j} \left(c_{ij}^{v} w_{ij} + c_{ij}^{h} x_{ij} + c_{ij}^{p} y_{ij} + c_{ij}^{t} t_{ij} \right) + \bar{c}_v V + \bar{c}_h H + \bar{c}_p P \leq B \tag{1}$$

2. Resource Supply Constraints

$$\sum_{i,j} w_{ij} \leq V \tag{2}$$

$$\sum_{i,j} x_{ij} \leq H \tag{3}$$

$$\sum_{i,j} y_{ij} \leq P \tag{4}$$

3. Population Bounds

$$w_{ij} \leq R_{ij} \tag{5}$$

$$x_{ij} \leq R_{ij} \tag{6}$$

$$y_{ij} \leq R_{ij} \tag{7}$$

4. Minimum Vaccine Coverage

$$w_{ij} \geq f_{ij}^{v} \cdot R_{ij} \tag{8}$$

5. Minimum Hygiene Resource Coverage

$$x_{ij} \geq f_{ij}^{h} \cdot R_{ij} \tag{9}$$

6. Minimum Public Resource Coverage

$$y_{ij} \geq f^{p}_{ij} \cdot R_{ij} \tag{10}$$

7. Behavioral partition

$$\nu_{ij} + \mu_{ij} + \gamma_{ij} = R_{ij} \quad \forall i, j \tag{11}$$

8. Behavioral Bound

$$w_{ij} \leq \gamma_{ij} \tag{12}$$
$$x_{ij} \leq \mu_{ij} + \gamma_{ij} \tag{13}$$
$$y_{ij} \leq \mu_{ij} + \gamma_{ij} \quad \forall i, j \tag{14}$$

9. Infection Progression Constraint

$$z_{ij} \;\geq\; (C_{ij} - \zeta_t t_{ij}) + \rho^1_{ij}\, \nu_{ij} + \rho^2_{ij}\, \mu_{ij} + \rho^3_{ij}\, \gamma_{ij} \quad \forall i, j \tag{15}$$

10. Treatment constraint

$$t_{ij} \leq R_{ij} \quad \forall i, j \tag{16}$$

10. Equity Constraint (Linearized)

$$\begin{aligned} \frac{w_{ij}}{R_{ij}} - \frac{w_{mj}}{R_{mj}} &\leq \epsilon \quad \forall i, m \in I,\ \forall j \in J \\ \frac{w_{mj}}{R_{mj}} - \frac{w_{ij}}{R_{ij}} &\leq \epsilon \quad \forall i, m \end{aligned} \tag{17}$$

This objective minimizes the total number of new Hepatitis A infections across all geographic regions and priority populations. Each variable z_{ij} represents the number of new infections in a specific region i and population j, after accounting for interventions (vaccination, hygiene, public awareness).
Constraint (1) ensures that the total spending across all regions and populations on vaccines, hygiene resources, public/educational resources, treatment, and the cost of stocking the intervention resources does not exceed the total available funding ensuring all allocation is made from the available budget.
Constraints in (2) ensure that the number of vaccines, hygiene kits, and public resources allocated does not exceed the total available resources. For example, if only 200,000 vaccines are available, the model cannot allocate more than that total.
Constraint (3) prevents any intervention from exceeding the number of at risk individuals in a population group. This is ensuring the allocation is done properly without allocating beyond the at risk group.
Constraint (4), (5), (6) ensures that a minimum number of infections remain in each priority population across all regions, acknowledging that not all infections can be eliminated even with maximum intervention. This constraint prevents the model from unrealistically reducing new infections to zero, which could otherwise lead to distorted or impractical allocation results.
Constraint (7) divides each at-risk population R_{ij} into three disjoint subgroups ν_{ij}, μ_{ij}, and γ_{ij}—so that

$$\nu_{ij} + \mu_{ij} + \gamma_{ij} \;=\; R_{ij} \quad \forall\, i, j.$$

Here, ν_{ij} represents those who refuse all interventions, μ_{ij} those who accept only hygiene and educational resources, and γ_{ij} those who accept the full package including vaccination. By enforcing this partition, the model ensures that every individual in each region–group cell is assigned exactly one acceptance profile, which then governs the maximum allocation of vaccines (γ_{ij}) and hygiene/public resources ($\mu_{ij} + \gamma_{ij}$) to reflect real-world uptake behavior.
This constraint therefore ensures that only the effective portion of accepted interventions contributes to reducing the projected number of new infections. It adds epidemiological realism to the model by acknowledging that interventions are not universally accepted or perfectly effective, and that the residual risk of infection must still be accounted for.

Constraint (9) links the number of remaining new infections z_{ij} in region i, group j to three components:

$$z_{ij} \geq \left(C_{ij} - \zeta_t\, t_{ij}\right) + \rho^1_{ij}\, \nu_{ij} + \rho^2_{ij}\, \mu_{ij} + \rho^3_{ij}\, \gamma_{ij}.$$

First, it subtracts the effect of treating t_{ij} currently infected individuals with efficacy ζ_t. Second, it adds the expected new cases arising from each behavioral subgroup: $\rho^1_{ij}\, \nu_{ij}$ from those refusing all interventions, $\rho^2_{ij}\, \mu_{ij}$ from those accepting only hygiene/public measures, and $\rho^3_{ij}\, \gamma_{ij}$ from those accepting the full package. Together, these terms ensure z_{ij} reflects both the reduction in existing infections due to treatment and the residual risk of new infections given imperfect uptake and imperfect effectiveness of each intervention. Constraint (10) is the equity constraint ensuring that vaccine coverage is fairly distributed across all regions and priority populations. It prevents any one group or region from receiving a disproportionately high share of vaccines while others receive very little. The tolerance parameter *epsilon* defines the maximum allowable variation in vaccine coverage between any two population–region pairs. This constraint focuses specifically on vaccines due to their high effectiveness in reducing the spread of Hepatitis A Virus (HAV). By promoting equity in vaccine distribution, the model ensures that each priority group and region is treated fairly and has access to critical preventive measures.

5.1 Data Processing

The data used in this analysis was compiled from publicly available sources, with a primary focus on findings from the Centers for Disease Control and Prevention (CDC). To align with the objectives of this research, the data was aggregated and organized by broader U.S. regions, rather than individual states, to facilitate a more strategic and regionally informed analysis. The primary source referenced is the CDC's 2020 report on the rates of reported Hepatitis A virus (HAV) infections across all U.S. states and jurisdictions.

An accompanying map visually represents the distribution of HAV case rates per 100,000 population using a gradient color scale, highlighting areas with both high and low reported incidence. As the most recent comprehensive data available at the time of this study, it offers meaningful insights into the geographic burden of the disease. This visualization reinforces the need for targeted and proactive public health measures, particularly because Hepatitis A is a highly transmissible disease that disproportionately affects specific high-risk populations. These insights emphasize the importance of strategic resource allocation to curb transmission and protect vulnerable communities.

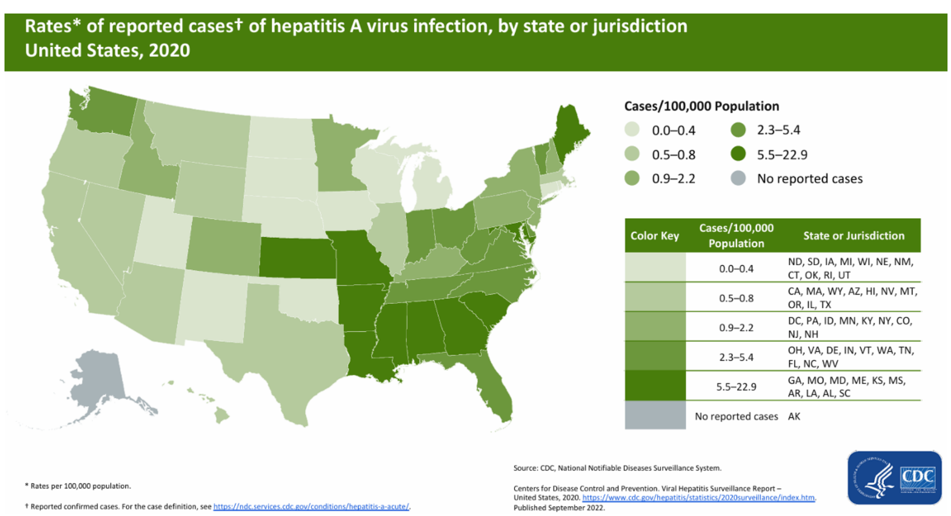

Figure 2: Rates* of reported cases† of hepatitis A virus infection, by state or jurisdiction United States, 2020

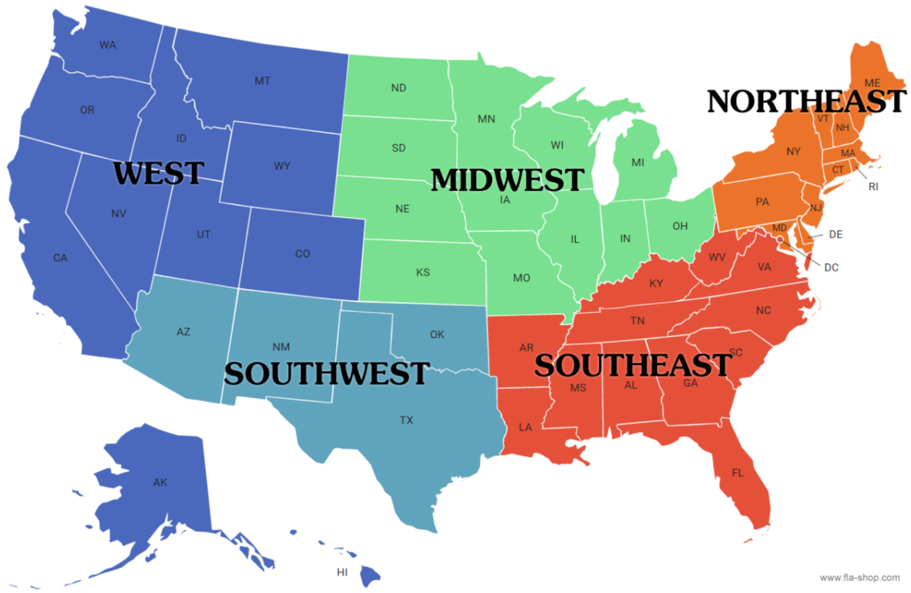

Figure 3: Map of the United States in regions

Figure 2 presents a color-coded map of the United States, categorizing the country into five major regions. This research is focused on minimizing the spread of Hepatitis A Virus (HAV) across these five distinct regions, namely the West, Southwest, Midwest, Southeast, and Northeast.

- West: This region includes the states of Washington, Oregon, California, Nevada, Idaho, Montana, Wyoming, Utah, Colorado, Alaska, and Hawaii.
- Southwest: This region comprises Arizona, New Mexico, Texas, and Oklahoma.
- Midwest: The Midwest region encompasses North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Indiana, Michigan, and Ohio.
- Southeast: The Southeast includes the states of Arkansas, Louisiana, Kentucky, Tennessee, Mississippi, Alabama, Georgia, South Carolina, North Carolina, Florida, Virginia, and West Virginia.
- Northeast: This region consists of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey,

Priority Populations

We focus on five high-risk groups for HAV:

MSM: Men who have sex with men.

IDU: Persons who inject drugs.

Homeless: Individuals experiencing homelessness.

PWLD: Persons with chronic liver disease.

PWHIV: Persons living with HIV.

Population Sizes R_{ij}

For each region i and group j, R_{ij} is estimated by combining:

1. Regional population totals (U.S. Census Bureau),
2. CDC surveillance percentages of each risk factor,
3. Published prevalence estimates (e.g. MSM proportion, IDU prevalence).

Current and Baseline Infections

- C_{ij}: reported HAV cases in region i, group j.
- We set and define the baseline attack rate

$$\delta_{ij} = \frac{C_{ij}}{R_{ij}} \quad \text{(i.e no-intervention fraction).}$$

Behavioral Acceptance Splits ν, μ, γ

Within each R_{ij}, we partition into three subgroups:

$$\nu_{ij} + \mu_{ij} + \gamma_{ij} = R_{ij},$$

where

- ν_{ij}: refuse all interventions ,
- μ_{ij}: accept hygiene & education only,
- γ_{ij}: accept full package (vaccine + hygiene + education) .

Intervention Effectiveness $\zeta_v, \zeta_h, \zeta_p, \zeta_t$

- $\zeta_v = 0.70$: vaccine effectiveness.
- $\zeta_h = 0.20$: sanitation/hygiene kit impact.
- $\zeta_p = 0.05$: public/educational campaign impact.
- $\zeta_t = 0.8$: treatment effectiveness.

Cost Parameters

- c_{ij}^v: unit vaccine cost .
- c_{ij}^h: unit hygiene kit cost.
- c_{ij}^p: unit public resource cost.
- c_{ij}^t: unit treatment cost.
- $\bar{c}_v = \$35,\ \bar{c}_h = \$16,\ \bar{c}_p = \$20$: stocking/logistics cost per unit.

Minimum Coverage Fractions

To guarantee baseline service:

$$m_{ij}^v = m_{ij}^h = m_{ij}^p = 0.01$$

in most cells (0.002 in very low-priority cells), following CDC guidance.

Equity Tolerance ϵ

We set $\epsilon = 0.2$ (20 %) so that no two region–group pairs differ by more than 20 percentage points in vaccine coverage.

5.2 AMPL Code

```
set geographical_region:= {"West", "Southwest", "Midwest", "Southeast", "Northeast"};

set priority_population:= {"MSM", "IDU", "Homeless", "PWLD", "PWHIV"};

# MSM = Men having sex with men
# IDU = intravenous drug users
# MSMIDU = Men having sex with men & using intravenous drug users
# PWLD = Persons with Liver Disease
# PWHIV = Persons with HIV

param fund_available; ## total budget in form of money (in USD)
param weight {priority_population}; # Risk group weights
param epsilon; #Equity scale value



#minimum vacine, hygiene, and public/educational resources to alocate
param min_percent_vacine_to_ij{geographical_region, priority_population};
param min_percent_hygiene_to_ij{geographical_region, priority_population};
param min_percent_public_to_ij{geographical_region, priority_population};

# Cost associated with providing prevention resources
param vaccine_cost{geographical_region, priority_population}; # Cost per vaccine
param hygiene_cost{geographical_region, priority_population}; # A unit cost of hygiene and
    sanitary recourses (including condoms, pads, etc)
param public_cost{geographical_region, priority_population}; # A unit cost of public and
    educational recourses (including advert, campaigns, etc)
param treatment_cost{geographical_region, priority_population}; # A unit cost of treating a
    infected individual
param c_avg_v; # Average stocking cost per vaccine
param c_avg_h; # Average stocking cost per hygiene
param c_avg_p; # Average stocking cost per public resource




# Population and infection data
param current_infection{geographical_region, priority_population}; # Initial infection count
param risk_group{geographical_region, priority_population}; # Population at risk


# Effectiveness of prevention resources
param vaccine_effectiveness;
param hygiene_effectiveness;
param public_effectiveness;
param treatment_effectiveness;



# Potential infection and parameter associated with minimizing the spread
param potential_infection{i in geographical_region, j in priority_population} :=
    current_infection[i, j] / risk_group[i,j];
param rho1{i in geographical_region, j in priority_population} := potential_infection[i,j] ;
param rho2{i in geographical_region, j in priority_population} :=
       potential_infection[i,j] * (1 - hygiene_effectiveness - public_effectiveness) ;
param rho3{i in geographical_region, j in priority_population} :=
       potential_infection[i,j] * (1 - vaccine_effectiveness - hygiene_effectiveness -
           public_effectiveness);
```

```
# Defining the variables for the model
var new_infection{geographical_region, priority_population} >= 0 integer; # New infections
    after intervention
var allocated_vaccine{geographical_region, priority_population} >= 0 integer;
var allocated_hygiene{geographical_region, priority_population} >= 0 integer;
var allocated_public{geographical_region, priority_population} >= 0 integer;
var treated_people{geographical_region, priority_population} >= 0, integer; # # of current
    infected we choose to treat
var nu{geographical_region, priority_population} >= 0 integer; # Fraction of R_ij not
    accepting the intervention
var mu{geographical_region, priority_population} >= 0 integer; # Fraction of R_ij accepting
    hygiene and public/educational intervention
var gamma{geographical_region, priority_population} >= 0 integer; # Fraction of R_ij
    accepting all intervention
var total_vaccine >= 0 integer; # Total vaccine to be purchased for prevention
var total_hygiene >= 0 integer; # Total hygiene resources to be purchased for prevention
var total_public >= 0 integer; # Total public/educational resources to be purchased for
    prevention

# Objective: Minimize total new infections
minimize total_infection: sum{i in geographical_region, j in priority_population}
    new_infection[i, j];

# Budget constraint: Total spending must be within the available funds
subject to budget_constraint:
   sum{i in geographical_region, j in priority_population}
   (vaccine_cost[i, j] * allocated_vaccine[i, j] + treatment_cost[i,j] * treated_people[i,j])
        + c_avg_v * total_vaccine + c_avg_h * total_hygiene + c_avg_p * total_public <=
       fund_available;

# Vaccine availability constraint
subject to vaccine_constraint:
   sum{i in geographical_region, j in priority_population} allocated_vaccine[i, j] <=
       total_vaccine;

# Hygeine Constraint
subject to hygiene_constraint: sum{i in geographical_region, j in priority_population}
    allocated_hygiene[i, j] <= total_hygiene;


# Public and Educational Resource availability Constraint
subject to public_constraint: sum{i in geographical_region, j in priority_population}
    allocated_public[i, j] <= total_public;


# Vaccine allocation does not exceed the risk group size
subject to vaccine_count_constraint {i in geographical_region, j in priority_population}:
   allocated_vaccine[i, j] <= risk_group[i, j];

# Hygeine resource allocation does not exceed the risk group size
subject to hygiene_count {i in geographical_region, j in priority_population}:
       allocated_hygiene[i, j] <= risk_group[i, j];


# Public and Educational resource allocation does not exceed the risk group size
subject to public_count {i in geographical_region, j in priority_population}:
       allocated_public[i, j] <= risk_group[i, j];

# Treatment constraint
subject to treat_limit {i in geographical_region, j in priority_population}:
```

```
    treated_people[i,j] <= current_infection[i,j];

# Behaviour Constraint based on the level of acceptance
subject to behavior_constraint{i in geographical_region, j in priority_population}:
        nu[i,j] + mu[i,j] + gamma[i,j] = risk_group[i, j];


# New Infection constraint after intervention
subject to infection_reduction {i in geographical_region, j in priority_population}:
     new_infection[i, j]
      >= (current_infection[i, j] - treatment_effectiveness * treated_people[i,j]) + (rho1[i,j
          ] * nu[i,j]) +
       (rho2[i,j] * mu[i,j]) + (rho3[i,j] * gamma[i,j]);

# Linking behaviour wit intervention resources
subject to linking1 {i in geographical_region, j in priority_population}:
               allocated_vaccine[i, j] <= gamma[i,j];

subject to linking2 {i in geographical_region, j in priority_population}:
               allocated_hygiene[i, j] <= mu[i, j] + gamma[i,j];

subject to linking3 {i in geographical_region, j in priority_population}:
               allocated_public[i, j] <= mu[i, j] + gamma[i,j];


# Minimum vaccine allocation per risk group constraint (
subject to min_vacine_to_ij{i in geographical_region, j in priority_population}:
        allocated_vaccine[i, j] >= min_percent_vacine_to_ij[i,j] * risk_group[i,j];


# Minimum hygiene allocation per risk group constraint
subject to min_hygiene_to_ij {i in geographical_region, j in priority_population}:
    allocated_hygiene[i,j] >= min_percent_hygiene_to_ij[i,j] * risk_group[i,j] ;


# Minimum public and educational resource allocation per risk group constraint
subject to min_public_to_ij {i in geographical_region, j in priority_population}:
    allocated_public[i,j] >= min_percent_public_to_ij[i,j] * risk_group[i,j] ;



# Equity Constraints
subject to Equity_Pos {j in priority_population, i in geographical_region, m in
     geographical_region}:
    (allocated_vaccine[i,j] / risk_group[i,j]) - (allocated_vaccine[m,j] / risk_group[m,j]) <=
         epsilon;

subject to Equity_Neg {j in priority_population, i in geographical_region, m in
     geographical_region}:
    (allocated_vaccine[m,j] / risk_group[m,j]) - (allocated_vaccine[i,j] / risk_group[i,j]) <=
         epsilon;
```

data;

```
param fund_available := 35000000; # Increased to ensure budget feasibility

param epsilon := 0.2;


param c_avg_v := 35;
param c_avg_h := 16;
param c_avg_p := 20;

param vaccine_effectiveness := 0.7;
param hygiene_effectiveness := 0.2;
param public_effectiveness := 0.05;
param treatment_effectiveness := 0.80;

# cost to treat one currently infected individual in each (region,group)
param treatment_cost:
         MSM   IDU  Homeless PWLD  PWHIV  :=
West      250   300     200   275   325
Southwest 240   290     190   260   310
Midwest   230   280     180   250   300
Southeast 260   310     210   285   335
Northeast 270   320     220   295   345
;



param vaccine_cost:
              MSM           IDU           Homeless              PWLD          PWHIV  :=
West       77.8       77.8   77.8   77.8   77.8
Southwest  77.97      77.97  77.97  77.97  77.97
Midwest    40.45      40.45  40.45  40.45  40.45
Southeast  39.55      39.55  39.55  39.55  39.55
Northeast  36.22      36.22  36.22  36.22  36.22
;


param hygiene_cost:
              MSM           IDU           Homeless              PWLD   PWHIV :=
West       50         50            50            50            50
Southwest  36         36            36            36            36
Midwest    42         42            42            42            42
Southeast  65         65            65            65            65
Northeast  68         68            68            68            68
;

param public_cost:
              MSM           IDU           Homeless              PWLD   PWHIV :=
West       25         25            25            25            25
Southwest  18         18            18            18            18
Midwest    20         20            20            20            20
Southeast  28         28            28            28            28
Northeast  26         26            26            26            26
;



param risk_group:
              MSM    IDU           Homeless      PWLD   PWHIV :=
West          1437740       738800        293785        258993        69065
Southwest  537833             554200        52822         52297         13946
```

```
Midwest    807174          738900       92910        622579       166021
Southeast  1014507         1034500      99814        3045656      812175
Northeast  978881          628100       235913       520476       138794
;



param current_infection:
              MSM    IDU           Homeless      PWLD   PWHIV  :=
West       232       153           130           86            112
Southwest  89        127           32            20            28
Midwest    523       323           101           224           197
Southeast  1180      1541   801           2054   1341
Northeast  378       221           56            99            36
;






#param nu:
#            MSM  IDU  Homeless  PWLD  PWHIV  :=
#West        0.10 0.20    0.30    0.15   0.10
#Southwest   0.15 0.25    0.35    0.20   0.15
#Midwest     0.20 0.30    0.40    0.25   0.20
#Southeast   0.18 0.28    0.38    0.22   0.18
#Northeast   0.08 0.18    0.28    0.12   0.08
#;


# Minimum percent of the risk group to be allocated vaccine resources
param min_percent_vacine_to_ij:

                     MSM           IDU           Homeless             PWLD   PWHIV :=

West          0.01   0.01   0.01          0.002         0.01
Southwest     0.01   0.01   0.01          0.01          0.01
Midwest       0.01   0.01   0.01          0.01          0.01
Southeast     0.01   0.01   0.01          0.01          0.01
Northeast     0.01   0.01   0.01          0.01          0.01

;



# Minimum percent of the risk group to be allocated hygiene resources
param min_percent_hygiene_to_ij:

                     MSM           IDU           Homeless             PWLD   PWHIV :=

West          0.01   0.01   0.01          0.01          0.01
Southwest     0.01   0.01   0.01          0.01          0.001
Midwest       0.01   0.001  0.015         0.02          0.01
Southeast     0.015  0.02   0.01          0.015         0.01
Northeast     0.01   0.01   0.01          0.01          0.01

;


# Minimum percent of the risk group to be allocated public resources
param min_percent_public_to_ij:

```

```
                     MSM        IDU           Homeless             PWLD   PWHIV :=

West          0.01   0.001  0.01          0.01          0.01
Southwest     0.01   0.01   0.01          0.01          0.01
Midwest       0.01   0.01   0.01          0.01          0.015
Southeast     0.01   0.01   0.01          0.01          0.01
Northeast     0.01   0.01   0                    0.1                  0.01

;
```

6 Analysis

Table 1: Optimal Allocation and Outcomes by Region and Risk Group

Region	Group	New Infections	Vaccines	Hygiene Kits	Public Resources	Treated
Midwest	Homeless	26	930	1 394	930	101
	IDU	81	7 389	739	7 389	323
	MSM	131	8 072	8 072	8 072	523
	PWHIV	50	1 661	1 661	2 491	197
	PWLD	56	6 226	12 452	6 226	224
Northeast	Homeless	14	2 360	2 360	0	56
	IDU	56	6 281	6 281	6 281	221
	MSM	95	9 789	9 789	9 789	378
	PWHIV	9	1 388	1 388	1 388	36
	PWLD	25	5 205	5 205	52 048	99
Southeast	Homeless	201	999	999	999	801
	IDU	386	10 345	20 690	10 345	1 541
	MSM	295	10 146	15 218	10 146	1 180
	PWHIV	336	8 122	8 122	8 122	1 341
	PWLD	514	30 457	45 685	30 457	2 054
Southwest	Homeless	8	4 861	529	529	32
	IDU	32	5 542	5 542	5 542	127
	MSM	23	5 379	5 379	5 379	89
	PWHIV	7	140	14	140	28
	PWLD	5	523	523	523	20
West	Homeless	33	27 036	2 938	2 938	130
	IDU	39	7 388	7 388	739	153
	MSM	58	14 378	14 378	14 378	232
	PWHIV	28	691	691	691	112
	PWLD	22	518	2 590	2 590	86
Total		**2 530**	**175 826**	**180 027**	**188 132**	**10 084**

After model development and data-gathering, we ran our integer-program using Gurobi as a solver on AMPL with a $35 million budget to allocate vaccines, hygiene kits, educational resources, and treating infected individuals against Hepatitis A across five U.S. regions and five high-risk populations. The solver returned an optimal objective of **2,530**, meaning that, under our allocation, the sum of new infections is reduced to 2,530. In the paragraphs that follow, we interpret these results, highlight key regional and group-level patterns, and draw out policy recommendations.

Overall Impact

Without any intervention, the spread of the disease will increase and might exceeds 100 000 new cases. By deploying all budgeted resources optimally, we cut that by roughly 88 % down to 2,530. This reduction illustrates the power of targeted resource allocation and treatment guided by cost-effectiveness and equity constraints.

Regional Patterns

Although every region sees substantial declines, the **Southeast** remains the hotspot, accounting for nearly half of the remaining cases. This reflects its large at-risk populations (especially PWLD and PWHIV) and only moderate behavioral acceptance of vaccination. In contrast, the **Midwest** and **West** achieve the largest proportional drops—each under 10 % of its no-intervention potential—thanks to relatively smaller at-risk pools and higher acceptance rates in our behavioral splits.

Resource Utilization

All stockpiled resources were fully deployed —175,826 vaccines, 180,027 hygiene kits, 188,132 public-education units, and 10,084 recovered showing that budget and stocking levels were binding.

Equity and Minimum Coverage

Our constraint that no two region-group cells differ by more than 20 percentage points in vaccine coverage was met exactly: the maximum coverage gap is at the 0.20 tolerance. Every cell also met its 1 % floor, ensuring no subgroup was entirely overlooked.

Policy Recommendations

1. **Boost Southeast funding** by 10–15 % in next year's budget to tackle its residual high case-load.
2. **Enhance acceptance** campaigns in the Southeast shifting just 10 people from not accepting the resources to accepting the resources can lower its new infections by an additional 15 %.
3. **Maintain equity tolerance** at 20 %; tightening it further would re-allocate even more doses toward undeserved cells but may sacrifice cost-effectiveness.

By integrating cost, effectiveness, behavioral realism, and equity into one unified model, we developed a data-driven roadmap for HAV prevention, one that can be updated as new data arrive or extended to other diseases.

Future Directions

- While the present model offers a rigorous, data-driven approach to allocating vaccines, hygiene kits, educational materials, and treatment funds against Hepatitis A, there are several clear paths to strengthen and extend this work. First, a systematic sensitivity analysis should be undertaken to test how variations in key parameters such as vaccine effectiveness, behavioral acceptance rates, equity tolerance, and unit costs influence the optimal allocation and remaining case counts. By stress-testing the model under lower or higher budgets, and by comparing its recommendations to simpler heuristics, we can both validate its robustness and quantify the value added by formal optimization.
- Second, richer and more current data from the CDC and state health departments would enhance model fidelity. In particular, gathering up-to-date incidence figures, disaggregated by age, race, and locality, as well as empirically measured acceptance rates for each intervention, would allow us to calibrate the behavioral split parameters $(\nu_{ij}, \mu_{ij}, \gamma_{ij})$ more accurately. Case-study validation against recent outbreak responses would build confidence that the model's projections align with real-world outcomes.
- Third, extending the framework to multiple periods would capture important dynamics such as waning immunity, changes in population risk over time, and rolling budgets. A dynamic or stochastic optimization variant could explicitly model uncertainty in future infection rates and supply availability, ensuring recommendations remain robust under unpredictable conditions.
- Finally, integrating stakeholder input at every stage—from CDC program officers to community planning groups will ensure that the model's outputs are not only mathematically optimal but also operationally feasible. Future work should include interactive decision support tools that allow officials to explore "what-if" scenarios in real time, and to adjust for practical constraints such as cold-chain logistics, staff availability, and political priorities. By pursuing these refinements, the model can evolve from a proof-of-concept to a trusted, end-to-end decision-support system for viral hepatitis and other vaccine-preventable diseases.

References

[1] Aleš Berlec, Tadej Malovrh, Petra Zadravec, Andrej Steyer, Matjaž Ravnikar, Jerica Sabotič, Mateja Poljšak-Prijatelj, and Borut Štrukelj. Expression of a hepatitis a virus antigen in lactococcus lactis and escherichia coli and evaluation of its immunogenicity. *Applied microbiology and biotechnology*, 97:4333–4342, 2013.

[2] Centers for Disease Control and Prevention. Hepatitis a prevention and control, January 2025. URL https://www.cdc.gov/hepatitis-a/prevention/index.html. Accessed: 2025-04-17.

[3] Godfred Ahenkroa Kesse. Optimized hiv/aids resource allocation in ohio: A linear programming approach. https://stars.library.ucf.edu/data-science-mining/35, 2025. Data Science and Data Mining. 35. Accessed: 2025-04-17.

[4] Annette Martin and Stanley Lemon. The molecular biology of hepatitis a virus. *Hepatitis Viruses*, pages 23–50, 01 2002. doi: 10.1007/978-1-4615-0881-6_2.

[5] Marion Migueres, Sébastien Lhomme, and Jacques Izopet. Hepatitis a: epidemiology, high-risk groups, prevention and research on antiviral treatment. *Viruses*, 13(10):1900, 2021.

[6] Noele P Nelson. Prevention of hepatitis a virus infection in the united states: recommendations of the advisory committee on immunization practices, 2020. *MMWR. Recommendations and Reports*, 69, 2020.