DECAY OF POSITIVE WAVES
FOR $n \times n$ HYPERBOLIC SYSTEMS OF BALANCE LAWS

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Abstract. We prove Oleinik-type decay estimates for entropy solutions of $n \times n$ strictly hyperbolic systems of balance laws built out of a wave-front tracking procedure inside which the source term is treated as a nonconservative product localized on a discrete lattice.

1. Introduction

A classical result proved by Oleinik [18] for strictly convex scalar conservation laws in one space dimension shows that the density of positive waves decays in time like $O(1/t)$, see also [14]. More precisely, if we consider the scalar equation

$$u_t + f(u)_x = 0, \quad u(t = 0, \cdot) = u_0 \in L^\infty(\mathbb{R}),$$

with $f''(u) \geq \kappa > 0$, we have that every entropy-admissible solution satisfies

$$u(t, y) - u(t, x) \leq \frac{y - x}{\kappa t} \quad \text{for all } t > 0, x < y,$$

and therefore has locally bounded variation (see also [8], Theorem 11.2.2). Conversely, if $u = u(t, x)$ is a weak solution satisfying (1.2), then $u$ is entropy admissible.

The same estimate as in (1.2) has been recovered for the Riemann coordinates of a particular $2 \times 2$ system [4] and for $n \times n$ genuinely nonlinear systems belonging to the Temple class [7]. However, one cannot expect such a result to remain valid for general $n \times n$ systems, even assuming that all characteristic fields are genuinely nonlinear. Indeed, interactions among existing shocks may generate rarefactions as time increases. Decay estimates must therefore take into account the generation of new positive waves due to interactions. Results in this direction were proved by Liu [17] in the case of approximate solutions constructed by Glimm’s scheme [9], and by Bressan and Colombo [5] for exact solutions obtained as limits of front tracking approximations for $n \times n$ homogeneous systems, [19]. This in turn yields uniqueness of solutions satisfying the Oleinik entropy condition ([6], [7], [10]). From the point of view of practical applications, such one-sided estimates are very useful, for instance, in the context of multiphase geometric optics computations [12], or local error estimates [20], and asymptotic behaviour of entropy solutions.
In this paper we are interested in extending Oleinik-type estimates on positive waves to quasilinear systems of balance laws. More precisely, we shall deal with the Cauchy problem for the following $n \times n$ system of equations:

$$u_t + f(u)_{x} = g(x, u), \quad x \in \mathbb{R}, t > 0,$$

endowed with a (suitably small) initial data $u_0 \in L^1(\mathbb{R}) \cap BV(\mathbb{R}; \mathbb{R}^n)$. Here $u(t, x) \in \mathbb{R}^n$ is the unknown function, and $f : \Omega \rightarrow \mathbb{R}^n$ is a smooth $C^2$ vector field defined on an open neighborhood $\Omega$ of the origin in $\mathbb{R}^n$. We will assume that the system (1.3) is strictly hyperbolic, with each characteristic field either genuinely nonlinear or linearly degenerate in the sense of Lax [15]. Moreover, we assume the following Carathéodory-type conditions for the source term $g$:

1. $g : \mathbb{R} \times \Omega \rightarrow \mathbb{R}^n$ is measurable w.r.t. $x$, for any $u \in \Omega$, and is $C^2$ w.r.t. $u$, for any $x \in \mathbb{R}$;
2. \[ \|g(x, \cdot)\|_{C^2} \text{ is bounded over } \Omega, \text{ uniformly in } x \in \mathbb{R}; \]
3. there exists a function $\omega \in L^1(\mathbb{R}) \cap L^\infty(\mathbb{R})$ such that $|g(x, u)| \leq \omega(x)$ and $\|\nabla_u g(x, u)\| \leq \omega(x)$ for all $(x, u) \in \mathbb{R} \times \Omega$.

In addition, we require that a non-resonance condition holds; that is, the characteristic speeds are bounded away from zero: for some $p \in \{1, \ldots, n\}$ and some $c > 0$ one has

$$\lambda_i(u) \leq -c \quad \text{if } i \leq p,$$
$$\lambda_i(u) \geq c \quad \text{if } i > p,$$

for all $u \in \Omega$, where $\lambda_i(u)$ denote the eigenvalues of the Jacobian matrix $Df(u)$.

Under these assumptions, it was proved in [1] that there exists a family of entropy weak solutions to (1.3) continuously depending on the initial data. More precisely, if the $L^1$-norm of $\omega$ is small enough, there exist a closed domain $D \subset L^1(\mathbb{R}; \mathbb{R}^n)$ of functions with sufficiently small total variation, a constant $L$ and a unique semigroup $P : [0, +\infty) \times D \rightarrow D$ with the properties:

(i) For all $u, v \in D$ and $t, s \geq 0$ one has $\|P_t u - P_t v\|_{L^1} \leq L(\|t-s\| + \|u-v\|_{L^1})$.

(ii) For all $u_0 \in D$ the function $u(t, \cdot) = P_t u_0$ is a weak entropy solution of the Cauchy problem (1.3), $u(t = 0, \cdot) = u_0$.

Under the above assumptions, we aim to show that, for genuinely nonlinear characteristic fields, an Oleinik type estimate on the decay of positive waves holds, which takes into account not only new waves generated by interactions but even the contribution of the source term. A careful statement of these results requires some notation (3, 5, 6).

As usual, let $A(u) = Df(u)$ be the Jacobian matrix of $f$, and call $\lambda_i(u)$, $l_i(u)$, $r_i(u)$ respectively the eigenvalues and the left and right eigenvectors of $A(u)$. Let $u : \mathbb{R} \rightarrow \Omega$ have bounded variation in $x$ and satisfy (1.3) with $g \equiv 0$. The distributional derivative $\mu = D_x u$ is a vector measure. For $i = 1, \ldots, n$ we can now define $\mu^i$ as

$$\int \phi \, d\mu^i = \int \phi \tilde{l}_i \cdot D_x u, \quad \phi \in C_c^0,$$

where $\tilde{l}_i(x) = l_i(u(x))$ at points where $u$ is continuous, while $\tilde{l}_i(x_\alpha)$ is some vector that satisfies

$$|\tilde{l}_i(x_\alpha) - l_i(u(x_\alpha))| = O(1) \cdot |u(x_\alpha^+) - u(x_\alpha^-)|,$$
$$\tilde{l}_i(x_\alpha) \cdot (u(x_\alpha^+) - u(x_\alpha^-)) = \sigma^i_\alpha.$$
where $\sigma^i_\alpha$ denotes the strength of the $i$-th wave generated by the resolution of the corresponding discontinuity in $x_\alpha$.

We denote by $\mu^+i$, $\mu^-i$ the positive and negative parts of $\mu$; then we have

$$\mu^i = \mu^+i - \mu^-i,$$

$$|\mu^i| = \mu^+i + \mu^-i.$$

The total strength of waves in $u$ is defined as

$$V(u) = \sum_{i=1}^n V_i(u), \quad V_i(u) = |\mu^i|(|\mathbb{R}|),$$

while the interaction potential is defined in terms of product measures on $\mathbb{R}^2$:

$$Q(u) = \sum_{i<j} (|\mu^i| \times |\mu^j|) \left( \{(x,y) : x < y \} \right) + \sum_{i \in \mathcal{G}N} (|\mu^-i| \times |\mu^i|) \left( \{(x,y) : x \neq y \} \right),$$

where $\mathcal{G}N$ denotes the set of genuinely nonlinear families.

Now we are ready to state our main result in the case $g \neq 0$:

**Theorem 1.1** (Decay of positive waves). Let the system $\{L_i\}$ be strictly hyperbolic and let the $i$-th characteristic field be genuinely nonlinear. Then there exists a constant $C$, depending solely on $f$, such that for every $0 \leq s < t$ and every solution $u$ with small total variation obtained as a limit of wave-front tracking approximations, the measure $\mu^+_i$ of $i$-waves in $u(t, \cdot)$ satisfies

$$\mu^+_i(J) \leq C \cdot \left( \frac{\meas(J)}{t-s} + Q(s) - Q(t) + V(u_0) \cdot \|\omega\|_{L^1} \right)$$

for every Borel set $J \subset \mathbb{R}$.

Of course, we tacitly assume (P1)–(P3) and $\{L_i\}$ throughout this paper.

2. **Wave-front tracking with zero-waves**

In this section we briefly recall the construction of wave-front tracking approximations as stated in [1]. We start with the definition of the $h$-Riemann solver. For small $h > 0$ we introduce the map

$$\Phi_h(x_\alpha, u) \doteq f^{-1} \left[ f(u) + \int_{0}^{h} g(x_\alpha + s, u) ds \right]$$

(note that $f$ is invertible due to $\{L_i\}$), which approximates the flow of the stationary equation associated to $\{L_i\}$. Consider now the Riemann problem with initial states

$$u(0, x) = \begin{cases} u_l & \text{if } x < x_o, \\ u_r & \text{if } x > x_o. \end{cases}$$

To locally render the source term’s effects, a stationary discontinuity is introduced along the line $x = x_o$, that is, a wave whose speed is equal to zero; it will be referred to as a zero-wave. An $h$-Riemann solver for $\{L_i\}$–(2.1) has been defined in [1] as a self-similar function $u(t, x) = R_h((x-x_o)/t; u_l, u_r)$ as follows:

(a) there exist two states $u^-, u^+$ that satisfy $u^+ = \Phi_h(x_o, u^-)$;

(b) $u(t, x)$ coincides, on the set $\{t \geq 0, x < x_o\}$, with the solution to the homogeneous Riemann problem with initial values $u_l, u^-$ and, on the set $\{t \geq 0, x > x_o\}$, with the solution to the homogeneous Riemann problem with initial values $u^+, u_r$.
(c) the Riemann problem between \( u_l \) and \( u^- \) is solved only by waves with negative speed (i.e., of the families \( 1, \ldots, p \));
(d) the Riemann problem between \( u^+ \) and \( u_r \) is solved only by waves with positive speed (i.e., of the families \( p + 1, \ldots, n \)).

This clearly shares a lot of common features with the nonconservative Riemann problems studied in [16]. Now let \( \epsilon, h > 0 \) be given: an \((\epsilon, h)\)-approximate solution of (1.3) is constructed as follows. First of all, the source term is localized by means of a Dirac comb along zero-waves located on the lattice \( x = jh, \ j \in (-\frac{1}{\epsilon h}, \frac{1}{\epsilon h}) \cap \mathbb{Z} \):

\[
(2.2) \quad u_t + f(u)_x = h \sum_j g(x, u) \cdot \delta(x - jh),
\]

where \( \delta \) stands for the Dirac measure concentrated on \( x = 0 \).

Given the initial data \( u_o \), we deduce a piecewise constant approximation \( u(0, \cdot) \) without increasing its \( BV \)-norm, and \( u(t, x) \) is constructed, for small \( t \), by applying the \( h \)-Riemann solver at every point \( x = jh \), and by solving the remaining discontinuities in \( u(0, \cdot) \) using a classical homogeneous Riemann solver (rarefaction waves are discretized following [3]: for a fixed small parameter \( \nu \), each rarefaction of size \( \sigma \) is divided, at its starting time, into \( m = \lceil \frac{\sigma}{\nu} \rceil + 1 \) wave fronts of size \( \sigma/m \leq \nu \)).

At every interaction point, a new Riemann problem arises. Notice that because of their null speed, zero-waves cannot interact with each other. In order to keep finite the total number of wave fronts, two distinct procedures are used for solving a Riemann problem: an accurate method, which possibly creates several new fronts, and a simplified method, which minimizes the number of new wave fronts. For a detailed description, as well as the proof of the stability of the algorithm, we refer the reader to [1, 3].

The approximate solution can have four types of jumps: shocks (or contact discontinuities), rarefaction fronts, non-physical waves and zero-waves: \( J = S \cup R \cup N \cup \mathbb{Z} \). A priori bounds on the functions \( u^\epsilon, h \) are obtained by slightly modifying the Glimm’s functionals [9] in order to keep track of the zero-waves,

\[
(2.3) \quad V(t) = \sum_{\alpha \in J} |\sigma_{\alpha}| = \sum_{\alpha \in S \cup R \cup N \cup \mathbb{Z}} |\sigma_{\alpha}|,
\]

\[
(2.4) \quad Q(u(t)) = \sum_{\alpha, \beta \in \mathbb{A}} |\sigma_{\alpha} \sigma_{\beta}| \leq V(t)^2,
\]

measuring respectively the total wave strengths and the interaction potential in \( u(t, \cdot) \). In particular, if \( \alpha \in \mathbb{Z} \), then the strength of the wave located in \( x_\alpha = j_\alpha h \) can be measured by means of

\[
(2.5) \quad \sigma_{\alpha} = \int_0^h \omega(j_\alpha h + s) ds.
\]

In (2.4) we have denoted by \( \mathbb{A} \) an extended set of approaching waves. As usual, we call \( k_{\alpha} \), the family of the front located at \( x_\alpha \), with size \( \sigma_{\alpha} \). More precisely, a pair of wave-fronts of families \( k_{\alpha}, k_{\beta} \), located at \( x_\alpha < x_\beta \), belongs to \( \mathbb{A} \) in any of the following cases:

- if neither of the two is a zero-wave, either \( k_{\alpha} > k_{\beta} \), or else \( k_{\alpha} = k_{\beta} \) and at least one of them is a genuinely nonlinear shock. [9];
- if \( \alpha \) is a zero-wave and \( \beta \) is a physical one, \( k_{\beta} \leq p \);
- if \( \beta \) is a zero-wave and \( \alpha \) is a physical one, \( k_{\alpha} > p \).
Notice that for some $C > 1$,
\[
\frac{1}{C} \left[ \|\omega\|_{L^1(I)} + \text{Tot.Var}.u(t, \cdot) \right] \leq V(t) \leq C \left[ \|\omega\|_{L^1(I)} + \text{Tot.Var}.u(t, \cdot) \right],
\]
where the interval $I$ is defined by
\[
I = \bigcup_{\alpha \in \mathbb{Z}} [j_\alpha h, (j_\alpha + 1)h] = \bigcup_{j \in (-\frac{1}{h}, \frac{1}{h}) \cap \mathbb{Z}} [jh, (j + 1)h].
\]
Passing to the limit as $\epsilon \to 0$, $h > 0$ fixed, one has:

(i) the total variation of $u^{\epsilon, h}(t, \cdot)$ remains uniformly bounded;
(ii) the maximum size of rarefaction fronts approaches zero;
(iii) the total strength of all non-physical waves approaches zero.

By (i), Helly’s theorem guarantees the existence of a subsequence strongly convergent in $L^1_{loc}$. By (ii) and (iii), this limit provides a weak solution to (2.2) in agreement with nonconservative theories, [16]. At this stage, we can again extract a subsequence $u^{h_i}$ that converges to some function $u$ in $L^1_{loc}$ and solves (1.3) in the usual weak distributional sense.

In the sequel, we will need a semicontinuity property of Glimm’s functionals. For $h > 0$ fixed, let the total strength of waves $V_h$ and the interaction potential $Q_h$ be as in [1], Section 4.1; that is, they are defined as in (1.5)-(1.6), but including the zero-waves. We have
\[
V_h(u) = V(u) + \|\omega\|_{L^1},
\]
(2.7)
\[
Q(u) \leq Q_h \leq Q(u) + \|\omega\|_{L^1} \cdot V(u).
\]
Proceeding as in [3], we recover the lower semicontinuity of the functionals $Q_h$ and
\[
Y_h(u) = V_h(u) + C_o Q_h(u), \quad C_o > 0, \quad \text{on a domain } D \text{ of the form }
\]
\[
D = \left\{ u \in L^1 \cap \text{BV}(\mathbb{R}; \mathbb{R}^n), Y_h(u) \leq \gamma \right\}, \quad \gamma \text{ small enough}
\]
(see [3], Theorem 10.1):

**Theorem 2.1** (Lower semicontinuity of the Glimm functionals). There exists a choice of the constants $C_o, \gamma > 0$ such that, if $Y_h(u) = V_h(u) + C_o Q_h(u) < \gamma$, then for any sequence of functions $u_\nu \in D$, $u_\nu \to u$ in $L^1$ as $\nu \to \infty$, one has
\[
Q_h(u) \leq \liminf_{\nu \to \infty} Q_h(u_\nu),
\]
(2.8)
\[
Y_h(u) \leq \liminf_{\nu \to \infty} Y_h(u_\nu).
\]
Moreover, for every finite union of open intervals $J = I_1 \cup \ldots \cup I_S$, one has
\[
\mu^{\pm}(J) + C_o Q_h(u) \leq \liminf_{\nu \to \infty} (\mu^{\pm}(J) + C_o Q_h(u_\nu)), \quad i = 1, \ldots, n.
\]
(2.10)

3. PROOF OF THEOREM [1.1]

I. By Lipschitz continuous dependence of the trajectories it is not restrictive to assume $s = 0, t = T$. We will consider a particular converging sequence $u^{\nu, h}$ of $(\epsilon_\nu, h)$-approximate solutions with the following properties:

(i) each rarefaction front $x_\alpha$ travels with the characteristic speed of the state on the right:
\[
\dot{x}_\alpha = \lambda_{k_\alpha}(u(x_\alpha+));
\]
(ii) each shock $x_{\alpha}$ travels with a speed strictly contained between the right and the left characteristic speeds:
\[
\lambda_{k_{\alpha}}(u(x_{\alpha}+)) < \dot{x}_{\alpha} < \lambda_{k_{\alpha}}(u(x_{\alpha}-));
\]
(iii) calling $N_{\nu}$ the number of jumps in $u_{\nu}^{\epsilon,h} = u_{\nu}^{\epsilon,h}(0, \cdot)$, as $\nu \to \infty$ one has
\[
\epsilon_{\nu} \to 0, \quad \epsilon_{\nu} N_{\nu} \to 0;
\]
(iv) the interaction potential satisfies
\[
Q_{h}(u_{\nu}^{\epsilon,h}(0, \cdot)) \to Q_{h}(u_{0}) \quad \text{as } \nu \to \infty.
\]
Such a sequence can be constructed as explained in [3] (proof of Lemma 10.2, p. 205).

Let $u = u(t, x)$ be a piecewise constant $(\epsilon, h)$-approximate solution constructed via front-tracking approximation (we shall drop the $\epsilon, h$ superscripts since there is no ambiguity). As usual, by (generalized) $i$-characteristic we mean an absolutely continuous curve $x = x(t)$ such that, [3],
\[
\dot{x}(t) \in [\lambda_{i}(u(t, x+)), \lambda_{i}(u(t, x-))], \quad \text{a.e. } t \geq 0.
\]

By $t \mapsto y^{i}(t; \bar{x})$ we denote the minimal $i$-characteristic passing through $\bar{x}$ at time $T$. Because of (1.4) the presence of zero-waves does not affect the usual construction.

Now let $I = [a, b]$ be any half-open interval, and define
\[
I(t) = [y^{i}(t; a), y^{i}(t; b)] \equiv [a(t), b(t)].
\]

We seek an estimate of the number of positive $i$-waves in the approximate solution $u(T, \cdot)$ contained in $I$. We recall that $k_{\alpha}$ stands for the family of the front located at $x_{\alpha}$, with size $\sigma_{\alpha}$. For a genuinely nonlinear family, the size of the jump can be measured by
\[
\sigma_{\alpha} \equiv \lambda_{k_{\alpha}}(u(x_{\alpha}+)) - \lambda_{k_{\alpha}}(u(x_{\alpha}-)),
\]
while the size of a zero-wave is still given by (2.5). Define
\[
m(t) \equiv b(t) - a(t).
\]

By (3.3) and the Lipschitz continuity of the map $u \mapsto \lambda_{i}(u)$ we deduce that
\[
\dot{m}(t) = \lambda_{i}(u(t, b(t))) - \lambda_{i}(u(t, a(t))) = M(t) + O(1)(\epsilon + K(t))
\]
for a.e. $t$. The Landau symbol stands for a quantity whose modulus is uniformly bounded. We see that
\[
M(t) \equiv \sum_{k_{\alpha} = i, x_{\alpha} \in I(t)} \sigma_{\alpha} = \mu_{i}^{+}(I(t))
\]
is the total number of (signed) $i$-waves in $u(t, \cdot)$ contained in $I(t)$, while
\[
K(t) \equiv \sum_{k_{\alpha} \neq i, x_{\alpha} \in I(t)} |\sigma_{\alpha}| = \sum_{k \neq i} |\mu_{k}^{+}||I(t)| + \int_{I(t)} \omega(x)dx
\]
stands for the total strength of waves of families $\neq i$ inside $I(t)$, zero-waves included. To estimate the contribution of the term $K(t)$ in (3.4) we introduce
\[
\Phi(t) \equiv \sum_{k_{\alpha} \neq i} \phi_{k_{\alpha}}(t, x_{\alpha}(t)) \cdot |\sigma_{\alpha}| \leq V_{h}(u(t)),
\]
where
\[
\phi_j(t, x) = \begin{cases} 
1 & \text{if } x < a(t), \\
\frac{b(t) - x}{m(t)} & \text{if } x \in [a(t), b(t)], \\
0 & \text{if } x \geq b(t),
\end{cases}
\]
or
\[
\phi_j(t, x) = \begin{cases} 
0 & \text{if } x < a(t), \\
\frac{x - a(t)}{m(t)} & \text{if } x \in [a(t), b(t)], \\
1 & \text{if } x \geq b(t),
\end{cases}
\]
in the cases \( j < i \) or \( j > i \), respectively. Roughly speaking, \( \Phi(t) \) represents the accumulated strength of the waves that do not approach the interval \( \mathcal{I}(t) \). By strict hyperbolicity, we can expect it to grow with time. Observe that \( \Phi \) is piecewise Lipschitz continuous with a finite number of discontinuities occurring at interaction times, where it may decrease by at most
\[(3.5) \quad \Phi(\tau+) - \Phi(\tau-) = \mathcal{O}(1)[Q(u(\tau-)) - Q(u(\tau+))].\]

Following [3], we assume that, for some \( c_o > 0 \),
\[(3.6) \quad |\lambda_i(u) - \lambda_i(v)| \leq c_o, \quad |\lambda_i(u) - \lambda_{k_0}(v)| \geq 2c_o,\]
for every two states \( u, v \) and every \( k_0 \neq i \). Outside interaction times, \( \Phi \) is non-decreasing; indeed, we have
\[
\dot{\Phi}(t) = \sum_{k_\alpha \neq i} |\sigma_\alpha| \cdot \frac{d}{dt} \phi_{k_\alpha}(t, x_\alpha(t))
\]

\[
= \sum_{k_\alpha < i, x_\alpha \in \mathcal{I}(t)} |\sigma_\alpha| \cdot \left( \frac{\dot{b} - \dot{x}_\alpha}{m} - \frac{(b - x_\alpha)\dot{m}}{m^2} \right)
+ \sum_{k_\alpha > i, x_\alpha \in \mathcal{I}(t)} |\sigma_\alpha| \cdot \left( \frac{\dot{x}_\alpha - \dot{a}}{m} - \frac{(x_\alpha - a)\dot{m}}{m^2} \right)
\geq \sum_{k_\alpha \neq i} |\sigma_\alpha| \cdot \frac{c_o}{m(t)}
\]

thanks to the system’s strict hyperbolicity and the non-resonance condition (1.4). In particular, observe that \( c_o \leq c \) in (3.6). The above estimate yields a bound valid for all but finitely many times \( t \):
\[(3.7) \quad K(t) \leq \frac{1}{c_o} \Phi(t)m(t).\]

We notice again, as in [1, 2], that there is a need for a completely different theory in order to tackle resonant cases, see also [13].

Concerning the term \( M(t) \), observe that it can change only when an interaction occurs within the interval \([a(t), b(t)]\). In this case, one has
\[
M(\tau+) - M(\tau-) = \mathcal{O}(1)[Q(u(\tau-)) - Q(u(\tau+))].
\]

This yields an estimate of the form
\[(3.8) \quad M(T) - M(t) = \mathcal{O}(1) \sum_{\tau \in \mathcal{T}}[Q(u(\tau-)) - Q(u(\tau+))],\]
where the summation extends over all times $\tau \in [0, T]$ and where an interaction occurs inside $[a(\tau), b(\tau)]$. Inserting the estimates $(3.7) - (3.8)$ in $(3.4)$, we obtain

$$\dot{m}(t) + C\dot{\Phi}(t)m(t) \geq M(T) - C\left(\epsilon + \sum_{\tau \in T} |\Delta Q(\tau)|\right),$$

for some constant $C$ and a.e. $t$. We now observe that $m$ is a continuous, piecewise linear function of $t$, and $\Phi$ is uniformly bounded. It can decrease only at interaction times, where $(3.5)$ holds. Hence its total variation is uniformly bounded, and for some constant $K_\alpha$ we have the estimate

$$\int_0^T \dot{\Phi}(t)dt \leq K_\alpha.$$  

As in [3], from $(3.9)$ we deduce the decay estimate:

$$(3.11) \quad M(T) \leq 2e^{CK_\alpha} \left(\frac{b-a}{T}\right) + 2C\epsilon + 2C \sum_{\tau \in T} |\Delta Q(\tau)|.$$

### II.

Repeating the above process for any finite number $S$ of disjoint half-open intervals $I_s = [a_s, b_s]$, we obtain

$$\sum_{s=1}^S M_s(T) \leq C' \left(\sum_{s=1}^S \frac{b_s - a_s}{T} + S\epsilon + |Q(u(0)) - Q(u(T))|\right),$$

for some constant $C'$ independent of $S$ and of the particular $(\epsilon, h)$-approximate solution. Here we have used the notation

$$M_s(T) \equiv \sum_{k_a = i, x_a \in [a_s, b_s]} \sigma_{a_s} = \mu^+_T([a_s, b_s])$$

to denote the sum of (signed) strength of all $i$-waves in $u(T, \cdot)$ contained in the interval $[a_s, b_s]$.  

### III.

Let us consider now any open interval $[a, b]$. Let $N$ be the number of $i$-shocks of the first generation in the front-tracking $(\epsilon, h)$-approximate solution $u$, as defined in [3], Chapter 7. We can thus construct half-open intervals $I_s = [a_s, b_s]$, $s = 1, \ldots, S \leq N + 1$, such that the following holds (see [3], Chapter 10):

- Every $i$-rarefaction front in $u(T, \cdot)$ contained in $[a, b]$ falls inside one of the intervals $I_s$.
- No $i$-shock front of the first generation falls inside any of the intervals $I_s$.

Calling $\mu_T^+$ the measure of positive $i$-waves in $u(T, \cdot)$, the above properties imply that

$$\mu_T^+([a, b]) = \sum_{s} M_s(T) + O(1) \cdot |Q_h(u(0)) - Q_h(u(T))| + O(1) \cdot r(\epsilon),$$

where $Q_h$ is the interaction potential introduced in [1], Section 4.1.

Indeed, the only negative $i$-waves contained in $\bigcup_s I_s$ must have generation order $\geq 2$, originating from interactions during the time interval $[0, T]$. The total strength of these negative $i$-waves is bounded by the decrease in the interaction potential $Q$. The last term on the right-hand side of $(3.10)$ tends to zero as $\epsilon$ does, and comes from the difference between $Q(u)$ and $Q_h(u)$: in the latter there are no non-physical fronts and all the countable $h$-Riemann problems are solved (whereas before only zero-waves inside the interval $(-1/\epsilon, 1/\epsilon)$ were considered).
Therefore one recovers (4.1) in the case $C$ for some constant $C''$ independent of $\epsilon$.

**IV.** For $h > 0$ fixed, we now consider a sequence of $(\epsilon, h)$-approximate solutions satisfying the properties (i)-(iv) stated at the beginning of this section. It is clearly not restrictive to take $C'' \geq C_o$ in (3.14), where $C_o$ is the (big) constant in Theorem 24. Using (2.8), (2.10), (3.14), (3.1) and (3.2), we obtain

$$\mu^+ (\epsilon, h) \leq C'' \left( \frac{b - a}{T} + (N + 1) r(\epsilon) + [Q_h(u(0)) - Q_h(u(T))] \right)$$

for some constant $C''$ independent of $\epsilon$.

Using (2.8), (2.10), (3.14), (3.1) and (3.2), we obtain

$$\mu^+ (\epsilon, h) \leq \liminf_{\nu \to \infty} \left( \mu^+ (\epsilon, h) + C'' Q_h(u(0)) - C'' Q_h(u(T)) \right)$$

$$\leq C'' \liminf_{\nu \to \infty} \left( \frac{b - a}{T} + (N + 1) r(\epsilon) + Q_h(u(0)) - C'' Q_h(u(T)) \right)$$

$$\leq C'' \frac{b - a}{T} + C'' [Q_h(u(0)) - Q_h(u(T))]$$

Since the last term is independent of $h$, this proves (4.7) in case $J$ is an open interval. The same arguments can be used in the case where $J$ is a finite collection of open intervals. Since $\mu^+$ is a bounded Radon measure, the estimate (1.7) holds for every Borel set $J$, and we are done.

\[ \Box \]

4. A SHORT COMMENT

All these computations heavily rely on the restrictive assumption that the source term is dominated by a function $\omega \in L^1(\mathbb{R})$ (the $L^\infty(\mathbb{R})$ bound being just a consequence of the smoothness of $g$). In the case of a convex scalar law, \[11\],

$$u_t + f(u)_x = g(u), \quad u_0 \in L^1(\mathbb{R}),$$

the stability of the approximation procedure for (1.3) can be obtained requiring only $\omega \in L^\infty(\mathbb{R})$. Hence one can follow the same canvas, and (3.4) simplifies a lot thanks to the obvious bound $K(t) \leq \|\omega\|_{L^\infty} m(t)$. Thus (3.9) boils down to

$$\dot{m}(t) + \|\omega\|_{L^\infty} m(t) \geq M(T),$$

which leads, in sharp contrast, to an exponential bound of the type $\mu^1 = u_x$:

$$\mu^1 (\epsilon, h) \leq C e^{\|\omega\|_{L^\infty} t \cdot \frac{\text{meas}(J)}{t}}, \quad t > 0.$$

This agrees of course with simple computations, since in this context Oleïnik’s estimates can be derived from the Riccati differential equation:

$$z_t - g'(u) z + f''(u) z^2 = 0, \quad z(0) = \sup_{\mathbb{R}} \left\{ \max_{\mathbb{R}} (0, (u_0)_x) \right\} \in \mathbb{R}.$$

Therefore one recovers (4.1) in the case $C = 1/\kappa$ and $\omega \equiv \text{Lip}(g)$, since we have

$$z(t) = \frac{1}{z(0) + \kappa (\frac{\text{Lip}(g)}{\text{Lip}(g)} - \frac{1}{k} \frac{Lip(g)}{\kappa t})} \leq \frac{e^{\text{Lip}(g) t}}{\kappa t}, \quad t > 0.$$
All in all, the $L^1(R)$ bound on $\omega$ expresses somehow the fact that the source has negligible effects outside a compact interval in $\mathbb{R}$, as pointed out in [8], p. 329. Hence, by the strict hyperbolicity ensured by (1.3)–(3.6), waves exit this region after some time and then are ruled only by the convective process.

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