Singular Dirichlet second-order BVPs with impulses

Irena Rachůnková

Department of Mathematical Analysis, Faculty of Science, Palacký University, Tomkova 40, 779 00 Olomouc, Czech Republic

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Abstract

The paper deals with the existence of solutions to singular second-order differential equations with impulse effects and with the Dirichlet boundary conditions. The right-hand side of the differential equation can be singular in its phase variable.

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1. Introduction

For \([a, b] \subset \mathbb{R}\) we denote by \(C^1[a, b]\) the set of functions having continuous first derivatives on \([a, b]\) and by \(L_1[a, b]\) the set of functions Lebesgue integrable on \([a, b]\). Choose \(p \in \mathbb{N}\) and consider the division \(\mathcal{D} = \{t_i\}_{i=1}^p\) of the interval \([0, T] \subset \mathbb{R}\), where \(0 = t_0 < t_1 < \cdots < t_p < t_{p+1} = T\). Further denote by \(C^1_{\mathcal{D}}\) the set of functions \(x: [0, T] \to \mathbb{R}\).
\[ x(t) = \begin{cases} 
  x(0)(t) & \text{for } t \in [0, t_1], \\
  x(1)(t) & \text{for } t \in (t_1, t_2], \\
  \ldots & \ldots \\
  x(p)(t) & \text{for } t \in (t_p, T], 
\end{cases} \tag{1.1} \]

where \( x(i) \in C^1[t_i, t_{i+1}], \) \( 0 \leq i \leq p, \) and denote by \( AC^1 \) the set of functions \( x \in C^1 \) having first derivatives absolutely continuous on \( (t_i, t_{i+1}), 0 \leq i \leq p. \) For \( x \in AC^1 \) we will use the notation

\[ x'(t_i) = \lim_{t \to t_i^-} x'(t), \quad 1 \leq i \leq p + 1, \quad x'(0) = \lim_{t \to 0^+} x'(t). \tag{1.2} \]

In this paper we study the existence of positive solutions of the following singular Dirichlet boundary value problem (BVP) with impulses:

\[ -u''(t) = f(t, u(t), u'(t)), \tag{1.3} \]

\[ u(t_i +) = J_i(u(t_i)), \quad u'(t_i +) = M_i(u'(t_i)), \quad 1 \leq i \leq p, \tag{1.4} \]

\[ u(0) = u(T) = 0, \tag{1.5} \]

where \( u'(t_i), 1 \leq i \leq p, \) are given by (1.2). Here we suppose that \( J_i : \mathbb{R} \to \mathbb{R}, M_i : \mathbb{R} \to \mathbb{R}, \) \( 1 \leq i \leq p, \) are continuous and increasing functions and that \( f \) fulfills the Carathéodory conditions on the set \( [0, T] \times ((0, \infty) \times \mathbb{R}), \) which means that

(i) for each \( (x, y) \in (0, \infty) \times \mathbb{R} \) the function \( f(\cdot, x, y) \) is measurable on \( [0, T]; \)

(ii) for a.e. \( t \in [0, T] \) the function \( f(t, \cdot, \cdot) \) is continuous on \( (0, \infty) \times \mathbb{R}; \)

(iii) for each compact set \( K \subset (0, \infty) \times \mathbb{R} \) the function \( m_K(t) = \sup \{|f(t, x, y)| : (x, y) \in K\} \) is Lebesgue integrable on \( [0, T]. \)

**Definition 1.1.** By a solution of BVP (1.3)–(1.5) we understand a function \( u \in AC^1 \) which satisfies the impulsive conditions (1.4) and the Dirichlet boundary conditions (1.5) and for a.e. \( t \in [0, T] \) fulfills Eq. (1.3). If \( u \) is positive on \( (0, T) \) it is called a positive solution of BVP (1.3)–(1.5).

The fact that BVP (1.3)–(1.5) is singular means that the right-hand side \( f \) of the differential equation does not fulfill the Carathéodory conditions on the whole region where we seek for solutions, i.e. on \( [0, T] \times [0, \infty) \times \mathbb{R}. \) Here, the Carathéodory conditions can be broken in the phase variable \( x. \) Particularly, for a.e. \( t \in [0, T] \) and all \( y \in \mathbb{R} \) the function \( f(t, x, y) \) can be unbounded for \( x \to 0^+. \) Such singular problems without impulse effects have been solved before for example in \([1–4,6,8–15,17–23].\) But as far as we know the solvability of singular problems with impulses has not been studied yet. In this paper we want to fill in this gap and extend the existence results on the case of singular problems with impulses. Our main goal is to
find conditions for $f, J_i, M_i, 1 \leq i \leq p$, which guarantee the existence of at least one solution of problem (1.3)–(1.5). The proofs are based on the method of a priori estimates, on the regularization technique, on the topological degree arguments and on the Vitali convergence theorem.

In what follows, we assume that $C^1[a, b]$ and $L_1[a, b]$ are, respectively, equipped with the norm

$$||x||_{C^1} = \max\{|x(t)| + |x'(t)| : t \in [a, b]\}, \quad \text{and} \quad ||y||_{L_1} = \int_a^b |y(t)| \, dt.$$  

Then $C^1[a, b]$ and $L_1[a, b]$ become Banach spaces. For any measurable set $\mathcal{M} \subset \mathbb{R}$, $\mu(\mathcal{M})$ denotes the Lebesgue measure of $\mathcal{M}$.

**Definition 1.2.** A collection $\mathcal{A} \subset L_1[a, b]$ is called uniformly absolutely continuous on $[a, b]$ if for every $\varepsilon > 0$ there exists $\delta > 0$ such that if $\varphi \in \mathcal{A}$ and $\mathcal{M} \subset [a, b]$ with $\mu(\mathcal{M}) < \delta$, then

$$\int_{\mathcal{M}} |\varphi(t)| \, dt < \varepsilon.$$  

**Theorem 1.3** (Vitali convergence theorem, [5, pp. 178–180]). Let $[a, b] \subset \mathbb{R}$ and let $\{f_n\}$ be a sequence in $L_1[a, b]$ which is convergent to $f$ for a.e. $t \in [a, b]$. Then the following statements are equivalent:

(a) $f \in L_1[a, b]$ and $\lim_{n \to \infty} ||f_n - f||_{L_1} = 0$.
(b) The set $\{f_n : n \in \mathbb{N}\}$ is uniformly absolutely continuous on $[a, b]$.

2. Main assumptions

In the study of problem (1.3)–(1.5) we will work with the following assumptions:

(H$_1$) The impulse functions $J_i : \mathbb{R} \to \mathbb{R}$, $M_i : \mathbb{R} \to \mathbb{R}$, $1 \leq i \leq p$, are continuous and increasing and

$$J_i(0) = 0, \quad M_i(0) = 0, \quad 1 \leq i \leq p. \quad (2.1)$$

(H$_2$)

$$\lim_{x \to \infty} \frac{J_i(x)}{x} < \infty, \quad 1 \leq i \leq p, \quad (2.2)$$

$$\lim_{x \to \infty} \frac{M_1(x)}{x} > 0, \quad \lim_{x \to \infty} \frac{M_i(x)}{x} \geq 1, \quad 2 \leq i \leq p, \quad (2.3)$$
\[
\lim_{x \to -\infty} \frac{x}{M_p(x)} > 0, \quad \lim_{x \to -\infty} \frac{x}{M_i(x)} > 1, \quad 1 \leq i \leq p - 1. \tag{2.4}
\]

(H3) The function \( f \) satisfies the Carathéodory conditions on the set \( [0, T] \times ((0, \infty) \times \mathbb{R}) \) and there exists a function \( \psi \) Lebesgue integrable on \( [0, T] \) such that
\[
0 < \psi(t) \leq f(t, x, y) \tag{2.5}
\]
for a.e. \( t \in [0, T] \) and each \( x \in (0, \infty), y \in \mathbb{R} \).

(H4) A function \( h \) satisfies the Carathéodory conditions on the set \( [0, T] \times [0, \infty) \), \( h \) is nonnegative and nondecreasing in its second argument and
\[
\lim_{z \to \infty} \frac{1}{z} \int_0^T h(t, z) \, dt = 0, \tag{2.6}
\]
a function \( q \) is nonnegative and essentially bounded on \( [0, T] \) and a function \( \omega \) is positive, nonincreasing on \( (0, \infty) \) and
\[
\int_0^T \omega(s) \, ds < \infty. \tag{2.7}
\]

(H5) For a.e. \( t \in [0, T] \) and for each \( x \in (0, \infty), y \in \mathbb{R} \)
\[
f(t, x, y) \leq h(t, x + |y|) + q(t)\omega(x), \tag{2.8}
\]
where functions \( h, q, \omega \) satisfy (H4).

**Remark 2.1.** Since \( \omega \) in (H4) is positive and nonincreasing, assumption (2.7) implies that \( \int_0^V \omega(s) \, ds < \infty \) for each \( V \in \mathbb{R}_+ \).

3. **A priori estimates**

In order to construct auxiliary regular problems and to use convergence theorems we need a priori estimates of solutions both below and above. Such types of estimates are proved in lemmas of this section.

**Lemma 3.1.** Suppose that (H1) holds and that \( u \in AC^1_{\mathbb{R}} \) fulfils (1.4), (1.5) and
\[
0 < -u''(t) \quad \text{for a.e. } t \in [0, T]. \tag{3.1}
\]
Then $u$ is positive on $(0, T)$ and there exists $\xi \in (0, T)$ such that

$$u'(\xi) = 0, \quad u' > 0 \text{ on } [0, \xi), \quad u' < 0 \text{ on } (\xi, T].$$  \hspace{1cm} (3.2)

**Proof.** Let $u \in AC^1_{[0]}$ fulfill (1.4), (1.5) and (3.1). Then

$$u' \text{ is decreasing on } (t_i, t_{i+1}], \quad 0 \leq i \leq p.$$  \hspace{1cm} (3.3)

(i) Suppose $u'(0) \leq 0$. Then, by (3.3), $u'(t) < 0$ for $t \in (0, t_1]$ and $u'(t_1) = M_1(u'(t_1)) < M_1(0) = 0$. Therefore $u'(t_1) < 0$ and, by (3.3), $u'(t) < 0$ for $t \in (t_1, t_2]$. Repeating these arguments we get

$$u'(t) < 0 \quad \text{for } t \in (0, T].$$  \hspace{1cm} (3.4)

Then, according to (1.5), $u(t) < 0$ for $t \in (0, t_1]$ and $u(t_1) = J_1(u(t_1)) < J_1(0) = 0$. Therefore $u(t_1) < 0$ and, by (3.4), $u(t) < 0$ for $t \in (t_1, t_2]$. Repeating it we get $u(t) < 0$ for $t \in (0, T]$, contrary to (1.5). Therefore we have proved

$$u'(0) > 0.$$  \hspace{1cm} (3.5)

(ii) Suppose $u'(T) \geq 0$. Then, by (3.3), $u'(t) > 0$ for $t \in (t_p, T)$ and $u'(t_p) > 0$, which gives $M_p(u'(t_p)) > 0 = M_p(0)$. Since $M_p$ is increasing, we get $u'(t_p) > 0$. By (3.3) we conclude that $u'(t) > 0$ for $t \in (t_{p-1}, t_p]$. Repeating these arguments we get

$$u'(t) > 0 \quad \text{for } t \in [0, T].$$  \hspace{1cm} (3.6)

Then, according to (1.5), $u(t) < 0$ for $t \in (t_p, T)$ and $u(t_p) < 0$. Therefore $J_p(0) = 0 > u(t_p) = J_p(u(t_p))$, and having in mind that $J_p$ is increasing, we get $u(t_p) < 0$, which together with (3.6) gives $u(t) < 0$ on $(t_p-1, t_p]$. Repeating it we deduce that $u(t) < 0$ for $t \in [0, T)$, contrary to (1.5). Therefore we have proved

$$u'(T) < 0.$$  \hspace{1cm} (3.7)

(iii) Condition (H1) implies that

$$\text{if } x \in \mathbb{R} \setminus \{0\}, \text{ then } \sgn(M_i(x)) = \sgn x, \quad 1 \leq i \leq p.$$  \hspace{1cm} (3.8)

(a) Suppose that there is $i_0 \in \{1, \ldots, p\}$ such that $u'(t_{i_0}) = 0$. Then, by (H1), $u'(t_{i_0}) = M_{i_0}(0) = 0$. By virtue of (3.3) and (3.8), we have $u'(t) > 0$ for $t \in [0, t_{i_0})$, $u'(t) < 0$ for $t \in (t_{i_0}, T]$. Therefore, (3.2) is satisfied with $\xi = t_{i_0}$.

(b) Let $u'(t_i) \neq 0, 1 \leq i \leq p$. Then, by (3.8), $\sgn u'(t_i) = \sgn u'(t_i), 1 \leq i \leq p$. Thus, by (3.3), (3.5) and (3.7), there exists $\xi \in \bigcup_{i=0}^{p} (t_i, t_{i+1})$ satisfying (3.2). \hfill \Box

**Definition 3.2.** Suppose that $u \in AC^1_{[0]}$ and $\xi \in (0, T)$ are from Lemma 3.1. Then $\xi$ is called a critical point of $u$. 
Lemma 3.3. Suppose that (H_1) holds and that \( \psi \in L_1[0, T] \). Then there exists a constant \( \gamma > 0 \) such that for any function \( u \in AC_1^1 \) having a critical point \( \zeta = \zeta(u) \) and fulfilling (1.4), (1.5) and
\[
0 < \psi(t) \leq -u''(t) \quad \text{for a.e. } t \in [0, T],
\]
the following estimates hold:

(I) if \( \zeta \in \mathcal{D} \), i.e. \( \zeta = t_{j+1} \) for some \( j = j(u) \in \{0, \ldots, p-1\} \), then
\[
u(t) \equiv \begin{cases}
\frac{t-t_i}{t_{i+1} - t_i} & \text{for } t \in (t_i, t_{i+1}], \quad 0 \leq i \leq j, \\
\frac{t_{i+1} - t}{t_{i+1} - t_i} & \text{for } t \in (t_i, t_{i+1}], \quad j + 1 \leq i \leq p;
\end{cases}
\]

(II) if \( \zeta \in (0, T) \setminus \mathcal{D} \), i.e. \( \zeta \in (t_j, t_{j+1}) \) for some \( j = j(u) \in \{0, \ldots, p\} \), then
\[
u(t) \equiv \begin{cases}
\frac{t-t_i}{t_{i+1} - t_i} & \text{for } t \in (t_i, t_{i+1}], \quad 0 \leq i \leq j - 1, \\
\frac{t-t_j}{\zeta - t_j} & \text{for } t \in (t_j, \zeta], \\
\frac{t_{j+1} - t}{t_{j+1} - \zeta} & \text{for } t \in (\zeta, t_{j+1}], \\
\frac{t_{i+1} - t}{t_{i+1} - t_i} & \text{for } t \in (t_i, t_{i+1}], \quad j + 1 \leq i \leq p.
\end{cases}
\]

Proof. Let \( u \in AC_1^1 \) satisfy (1.4), (1.5) and (3.9). Denote \( u(t_i) = c_i, \quad 0 \leq i \leq p + 1 \). Then, by Lemma 3.1,
\[
c_0 = c_{p+1} = 0, \quad c_i > 0, \quad J_i(c_i) > 0, \quad 1 \leq i \leq p.
\]
Let \( G_i(t, s) \) be Green’s function of the problem
\[
-v''(t) = 0, \quad v(t_i) = v(t_{i+1}) = 0, \quad 0 \leq i \leq p,
\]
i.e.
\[
G_i(t, s) = \begin{cases}
\frac{(s - t_i)(t_{i+1} - t)}{t_{i+1} - t_i}, & t_i \leq s \leq t \leq t_{i+1}, \\
\frac{(t - t_i)(t_{i+1} - s)}{t_{i+1} - t_i}, & t \leq t < s \leq t_{i+1}.
\end{cases}
\]
Define \( J_0(c_0) = c_0 \) and let for \( 0 \leq i \leq p, u_{(i)} \in C^1[t_i, t_{i+1}] \) correspond to \( u \) in the sense of (1.1), i.e.
\[
u(0)(0) = 0 = u(0), \quad u_{(i)}(t) = u(t) \quad \text{on } (t_i, t_{i+1}], \quad u_{(i)}(t_i) = u(t_{i+}). \]
We have
\[-u''(t) = -u''(t) \text{ a.e. on } (t_i, t_{i+1}), \quad 0 \leq i \leq p,\]
\[u(i)(t) = f_i(c_i), \quad u(i)(t_{i+1}) = c_{i+1}, \quad 0 \leq i \leq p.\]

Now, let us choose an arbitrary \( i \in \{0, \ldots, p\}. \) Hence, for \( t \in [t_i, t_{i+1}], \) we get
\[u(i)(t) = \frac{t - t_i}{t_{i+1} - t_i} c_{i+1} + \frac{t_{i+1} - t}{t_{i+1} - t_i} f_i(c_i) - \int_{t_i}^{t_{i+1}} G(t, s)u''(s) \, ds,
\]
which, by virtue of (3.12) and (3.9), yields
\[u(i)(t) \geq \int_{t_i}^{t_{i+1}} G(t, s)\psi(s) \, ds \text{ for } t \in [t_i, t_{i+1}]. \tag{3.14}\]

Put
\[
\Phi_i(t, s) = \frac{G_i(t, s)}{(t - t_i)(t_{i+1} - t)} \text{ on } [t_i, t_{i+1}] \times [t_i, t_{i+1}]. \tag{3.15}\]

Then,
\[\Phi_i > 0 \text{ on } (t_i, t_{i+1}) \times (t_i, t_{i+1}) \tag{3.16}\]
and for \( s \in (t_i, t_{i+1}) \)
\[
\lim_{t \to t_{i+1}^-} \Phi_i(t, s) = \frac{1}{t_{i+1} - t_i} \frac{\partial G_i(t, s)}{\partial t} \bigg|_{(t,s) = (t, s)} = \frac{t_{i+1} - s}{(t_{i+1} - t_i)^2} > 0,
\]
\[
\lim_{t \to t_i^+} \Phi_i(t, s) = \frac{-1}{t_{i+1} - t_i} \frac{\partial G_i(t, s)}{\partial t} \bigg|_{(t,s) = (t, s)} = \frac{s - t_i}{(t_{i+1} - t_i)^2} > 0.
\]

Therefore, by (3.16), we can extend the function \( \Phi_i \) at \( t = t_i, t = t_{i+1} \) such that for each \( s \in (t_i, t_{i+1}) \) the function \( \Phi_i(\cdot, s) \) is continuous and positive on \([t_i, t_{i+1}].\)

Put
\[
F_i(t) = \int_{t_i}^{t_{i+1}} \Phi_i(t, s)\psi(s) \, ds \text{ for } t \in [t_i, t_{i+1}]. \tag{3.17}\]

Then, by virtue of (3.9), the function \( F_i \) is continuous and positive on \([t_i, t_{i+1}]\) and so we can find \( \delta_i > 0 \) such that \( F_i(t) \geq \delta_i \) for \( t \in [t_i, t_{i+1}]. \)

Therefore, by (3.14), (3.15) and (3.17)
\[
u(i)(t) \geq (t - t_i)(t_{i+1} - t) \int_{t_i}^{t_{i+1}} \Phi_i(t, s)\psi(s) \, ds
\]
\[
= (t - t_i)(t_{i+1} - t) F_i(t) \geq (t - t_i)(t_{i+1} - t)\delta_i \text{ for } t \in [t_i, t_{i+1}].
\]
So,

\[
\max\{u(i)(t): t \in [t_i, t_{i+1}]\} \geq \frac{1}{3}(t_{i+1} - t_i)^2 \delta_i = \gamma > 0.
\]

If we put \( \gamma = \min\{\gamma_i, 0 \leq i \leq p\} \), we have

\[
\max\{u(i)(t): t \in [t_i, t_{i+1}]\} \geq \gamma, \quad 0 \leq i \leq p.
\] (3.18)

Now, we are going to prove assertion (I).

Suppose that \( u \) has a critical point \( \xi \) and \( \xi = t_{j+1} \) for some \( j \in \{0, \ldots, p - 1\} \). Choose an arbitrary \( i \in \{0, \ldots, j\} \). Then, by (3.9), (3.2) and (3.13), \( u(i) \) is concave and increasing on \([t_i, t_{i+1}]\). Moreover \( u(i)(t_i) \geq 0 \) and \( u(i)(t_{i+1}) \geq \gamma \), by (3.18). Hence we conclude that

\[
u(t) = u(i)(t) \geq \frac{t - t_i}{t_{i+1} - t_i} \gamma \quad \text{for} \ t \in (t_i, t_{i+1}), \quad 0 \leq i \leq j.
\]

Now consider the case \( j + 1 \leq i \leq p \). For such an \( i \) the function \( u(i) \) is concave and decreasing on \([t_i, t_{i+1}]\), \( u(i)(t_i) \geq \gamma \), \( u(i)(t_{i+1}) \geq 0 \). Therefore the estimate

\[
u(t) = u(i)(t) \geq \frac{t_{i+1} - t}{t_{i+1} - t_i} \gamma \quad \text{for} \ t \in (t_i, t_{i+1}), \quad j + 1 \leq i \leq p
\]

is true.

To prove assertion (II) we assume that \( \xi \in (t_j, t_{j+1}) \) for some \( j \in \{0, \ldots, p\} \) and get (3.11) by means of the concavity and monotonicity arguments as in the proof of (3.10).

Lemma 3.4. Let \( \psi \in L_1[0, T] \). Suppose that \( (H_1), (H_2) \) and \( (H_4) \) with \( \tilde{h} \) instead of \( h \) hold. Then there exists constants \( A^*, B^* \) such that for any function \( u \in AC^1_{\tilde{h}} \) satisfying (1.4), (1.5), (3.9) and

\[-u''(t) \leq \tilde{h}(t, u(t) + |u'|) + q(t)u(u(t)) \quad \text{for a.e.} \ t \in [0, T],
\] (3.19)

the estimates

\[
\sup\{u(t): t \in [0, T]\} < A^*, \quad \sup\{|u'(t)|: t \in [0, T]\} < B^*
\] (3.20)

are valid.

Proof. Let \( u \in AC^1_{\tilde{h}} \) satisfy (1.4), (1.5), (3.9), and (3.19). According to Lemma 3.1 and Definition 3.2 \( u \) has a critical point \( \xi \in (0, T) \) satisfying (3.2). We distinguish two cases: (i) \( \xi \) belongs to the division \( \mathcal{D} \) and (ii) \( \xi \) does not belong to \( \mathcal{D} \).

Case (i): Suppose that there is \( j \in \{0, \ldots, p - 1\} \) such that \( \xi = t_{j+1} \). Define

\[
u'(t_i) = \rho_i, \quad 0 \leq i \leq p + 1.
\] (3.21)
Then
\[ u'(t_{i+}) = M_i(\rho_i), \quad 1 \leq i \leq p, \] (3.22)
and by (3.2) and (H₁)
\[
\begin{cases}
\rho_i > 0, \ M_i(\rho_i) > 0 & \text{for } 1 \leq i \leq j, \ \rho_0 > 0, \\
\rho_{j+1} = 0, \ M_{j+1}(\rho_{j+1}) = 0, \\
\rho_i < 0, \ M_i(\rho_i) < 0 & \text{for } j + 2 \leq i \leq p, \ \rho_{p+1} < 0.
\end{cases}
\] (3.23)

Further, due to (3.3),
\[ \rho_0 > \rho_1, \quad M_i(\rho_i) > \rho_{i+1}, \quad 1 \leq i \leq p \] (3.24)
and
\[
\begin{cases}
\sup\{|u'(t)|: t \in (0, t_1)\} = u'(0) = \rho_0, \\
\sup\{|u'(t)|: t \in (t_i, t_{i+1})\} = u'(t_{i+}) = M_i(\rho_i), \quad 1 \leq i \leq j, \\
\sup\{|u'(t)|: t \in (t_j, t_{j+1})\} = |u'(t_{j+1})| = |\rho_{j+1}|, \quad j + 1 \leq i \leq p.
\end{cases}
\] (3.25)

**Part 1**: First, we are going to find bounds for \( u \) and \( |u'| \) on \([0, t_{j+1}]\). Define
\[ \gamma = \max\{t_{i+1} - t_i, 0 \leq i \leq j\}, \quad M_0(\rho_0) = \rho_0, \]

\[ Q = \sup \text{ess}\{q(t): t \in [0, T]\}, \quad \bar{\omega} = \frac{1}{\gamma} \int_0^\gamma \omega(t) \, dt. \] (3.26)

Here \( \gamma > 0 \) is from Lemma 3.3.

According to Lemma 3.1, \( u \) is increasing on \((t_i, t_{i+1}), 0 \leq i \leq j, \) and \( u(t_0) = u(0) = 0, \) which together with (3.25) yields
\[
\begin{cases}
\sup\{u(t): t \in (0, t_1)\} = u(t_1) \leq \gamma \rho_0 = \gamma r_1 > 0, \\
\sup\{u(t): t \in (t_i, t_{i+1})\} = u(t_{i+1}) \leq J_i(\rho_i) + \gamma M_i(\rho_i) = r_{i+1} > 0, \\
\text{for } 1 \leq i \leq j.
\end{cases}
\] (3.27)

Integrating (3.19) on \([0, t_{j+1}]\) we obtain, by virtue of (3.21) and (3.22)
\[ \rho_0 + \sum_{i=1}^j M_i(\rho_i) - \sum_{i=1}^j \rho_i \leq \int_0^{t_{j+1}} \left( \hat{h}(t, u(t) + |u'(t)|) + q(t) \omega(u(t)) \right) dt, \]
wherefrom, due to (3.25)–(3.27),
\[ \sum_{i=0}^j M_i(\rho_i) \leq \sum_{i=1}^j \rho_i + \sum_{i=0}^j \int_{t_i}^{t_{i+1}} \hat{h}(t, r_{i+1} + M_i(\rho_i)) dt + Q \int_0^{t_{j+1}} \omega(u(t)) \, dt. \] (3.28)
Applying statement (I) of Lemma 3.3 we get
\[ \int_0^{t_{j+1}} \omega(u(t)) \, dt \leq \sum_{i=0}^{j} \int_{t_i}^{t_{i+1}} \omega \left( \frac{t-t_i}{t_{i+1}-t_i} \right) \, dt = \frac{1}{\gamma} \sum_{i=0}^{j} (t_{i+1}-t_i) \int_0^{\gamma} \omega(t) \, dt. \]
Hence, by (3.26),
\[ \int_0^{t_{j+1}} \omega(u(t)) \, dt \leq T \bar{\omega}. \] (3.29)
Employing (3.28) and (3.29), it follows that
\[ 1 \leq \frac{1}{\sum_{i=0}^{j} M_i(\rho_i)} \left( \sum_{i=0}^{j} \rho_i + \sum_{i=0}^{j} \int_{t_i}^{t_{i+1}} \tilde{h}(t, r_{i+1} + M_i(\rho_i)) \, dt + QT \bar{\omega} \right). \] (3.30)
Assume for the sake of contradiction that
(a1) there is a sequence of functions \{u_m\}, satisfying (1.4), (1.5), (3.9), and (3.19) such that each \( u_m, m \in \mathbb{N} \), has its critical point equal to \( t_{j+1} \);
(a2) if we put (according to (3.21))
\[ u'_m(t_i) = \rho_{i,m}, \quad 0 \leq i \leq j + 1, \ m \in \mathbb{N}, \] (3.31)
then there is a \( k \in \{0, \ldots, j\} \) such that
\[ \lim_{m \to \infty} \rho_{k,m} = \infty. \] (3.32)
Assuming (a1) and (a2) we derive a contradiction in the following way. Let \( k \) be the largest number satisfying (3.32), i.e. if \( k < j \), then \( \{\rho_{i,m}\}, k + 1 \leq i \leq j \), are bounded. First, let us show that (3.32) implies
\[ \lim_{m \to \infty} \rho_{i,m} = \infty, \quad 0 \leq i \leq k. \] (3.33)
Really, if \( k = 1 \) then (3.33) follows from the first inequality in (3.24). If \( k \geq 2 \), then, by the second inequality in (3.24), \( \lim_{m \to \infty} M_{k-1}(\rho_{k-1,m}) = \infty \). By virtue of (H1), it follows that \( \lim_{m \to \infty} \rho_{k-1,m} = \infty \). Continuing inductively we get (3.33). Now, according to (2.27), define
\[ \begin{align*}
  r_{1,m} &= x \rho_{0,m}, \\
  r_{i+1,m} &= J_i(r_{i,m}) + x M_i(\rho_{i,m}), \quad 1 \leq i \leq j, \ m \in \mathbb{N}. 
\end{align*} \] (3.34)
Then, by virtue of (3.26), (3.30) and the assumption (a1), we put \( M_0(\rho_{0,m}) = \rho_{0,m} \) and have
\[ 1 \leq \sum_{i=1}^{j} \rho_{i,m} \frac{\sum_{i=0}^{j} \int_{t_i}^{t_{i+1}} \tilde{h}(t, r_{i+1,m} + M_i(\rho_{i,m})) \, dt + QT \bar{\omega}}{\sum_{i=0}^{j} M_i(\rho_{i,m})}, \] (3.35)
Consider the first member on the right-hand side of (3.35). Note that due to (2.3) and (3.33) we can find $\delta > 0$ and $m_0 \in \mathbb{N}$ such that for $m \geq m_0$

\[
\begin{cases}
M_1(\rho_{1,m}) > \rho_{1,m}\delta, \\
M_i(\rho_{i,m}) > (1 + \delta)\rho_{i,m}, \text{ if } k \geq 2, \ 2 \leq i \leq k.
\end{cases}
\]  

(3.36)

Therefore, using also the first inequality in (3.24), we get

\[
S_m = \frac{\sum_{i=1}^{j} \rho_{i,m}}{\sum_{i=0}^{j} M_i(\rho_{i,m})} < \frac{\sum_{i=1}^{k} \rho_{i,m}}{(1 + \delta) \sum_{i=1}^{k} \rho_{i,m}} + \frac{\sum_{i=k+1}^{j} \rho_{i,m}}{\rho_{0,m}}
\]

(if $k = j$, the last member is zero), which yields

\[
\lim_{m \to \infty} S_m \leq \frac{1}{1 + \delta}.
\]  

(3.37)

Now, consider the second member in (3.35) and put

\[
z_{i,m} = r_{i+1,m} + M_i(\rho_{i,m}), \ 0 \leq i \leq j, \ m \in \mathbb{N}.
\]  

(3.38)

Then conditions (3.33), (3.36) and (3.34) imply that

\[
\begin{cases}
\lim_{m \to \infty} r_{i,m} = \infty, \ 1 \leq i \leq k + 1, \\
\lim_{m \to \infty} z_{i,m} = \infty, \ 0 \leq i \leq k.
\end{cases}
\]  

(3.39)

It is immediate from (2.6) that for $0 \leq i \leq k$

\[
\lim_{m \to \infty} \frac{1}{z_{i,m}} \int_{t_i}^{t_{i+1}} \tilde{h}(t, z_{i,m}) \, dt = 0.
\]  

(3.40)

Further, for $1 \leq i \leq j$, by virtue of (3.34) and (3.38), we have

\[
\frac{z_{i,m}}{\sum_{l=0}^{j} M_l(\rho_{l,m})} < \frac{J_i(r_{i,m})}{\sum_{l=0}^{j} M_l(\rho_{l,m})} + 1 + \alpha \\
= \frac{J_i(r_{i,m})}{r_{i,m}} \cdot \frac{r_{i,m}}{\sum_{l=0}^{j} M_l(\rho_{l,m})} + 1 + \alpha \\
< \frac{J_i(r_{i,m})}{r_{i,m}} \left( \frac{J_{i-1}(r_{i-1,m})}{r_{i-1,m}} \cdot \frac{r_{i-1,m}}{\sum_{l=0}^{j} M_l(\rho_{l,m})} + \alpha \right) + 1 + \alpha.
\]
Continuing inductively we get for \(1 \leq i \leq j\)

\[
\sum_{l=0}^{j} \frac{z_{i,m}}{M_l(\rho_{l,m})} < \frac{J_i(r_{l,m})}{r_{l,m}} \\
\times \left( \frac{J_{i-1}(r_{i-1,m})}{r_{i-1,m}} \left( \frac{J_{i-2}(r_{i-2,m})}{r_{i-2,m}} \left( \ldots \frac{J_1(\alpha \rho_{0,m})}{\alpha \rho_{0,m}} \alpha + \alpha \ldots \right) + \alpha \right) + \alpha \right) + 1 + \alpha.
\]

Finally,

\[
\frac{z_{0,m}}{\sum_{l=0}^{j} M_l(\rho_{l,m})} = \frac{(1 + \alpha)\rho_{0,m}}{\rho_{0,m} + \sum_{l=1}^{j} M_l(\rho_{l,m})} < 1 + \alpha.
\]

Therefore, by virtue of (2.2), for \(0 \leq i \leq k\),

\[
\lim_{m \to \infty} \frac{z_{i,m}}{\sum_{l=0}^{j} M_l(\rho_{l,m})} \leq A_i(A_{i-1}(A_{i-2}(\ldots A_1 \alpha + \alpha \ldots) + \alpha) + \alpha) + 1 + \alpha, \quad (3.41)
\]

where

\[
A_i = \lim_{z \to \infty} \frac{J_i(z)}{z} < \infty, \quad 1 \leq i \leq k.
\]

Hence, using (3.38), (3.40) and (3.41), we get that for \(0 \leq i \leq k\)

\[
\lim_{m \to \infty} \frac{\int_{t_i}^{t_{i+1}} \tilde{h}(t, r_{i+1,m} + M_i(\rho_{i,m})) \, dt}{\sum_{l=0}^{j} M_l(\rho_{l,m})} = 0. \quad (3.42)
\]

Now, we are going to show that if \(k < j\), then (3.42) is valid for \(k + 1 \leq i \leq j\), as well. There are two cases to consider. These are \(\{r_{k+2,m}\}\) bounded and \(\{r_{k+2,m}\}\) unbounded. In the first case we see that \(\{r_{l,m}\}\) is bounded for \(k + 2 \leq i \leq j + 1\) by (3.34), and \(\{z_{i,m}\}\) is bounded for \(k + 1 \leq i \leq j\), by (3.38). Therefore \(\int_{t_i}^{t_{i+1}} \tilde{h}(t, z_{i,m}) \, dt\) is bounded which together with (3.33) yields (3.42) for \(k + 1 \leq i \leq j\). In the second case we can suppose that \(\lim_{m \to \infty} r_{k+2,m} = \infty\). This, due to (3.38), yields \(\lim_{m \to \infty} z_{k+1,m} = \infty\) and so, (3.40), (3.41) and consequently (3.42) are valid for \(i = k + 1\). Continuing inductively we conclude that (3.42) is true for \(k + 1 \leq i \leq j\) in the second case, as well. To summarize, we have proved that (3.42) is valid for \(0 \leq i \leq j\).

Let us go back to (3.35). Conditions (3.37) and (3.42) imply that

\[
1 \leq \lim_{m \to \infty} \frac{\sum_{i=1}^{j} \rho_{i,m}}{\sum_{i=0}^{j} M_l(\rho_{l,m})} + \lim_{m \to \infty} \frac{\sum_{i=0}^{j} \int_{t_i}^{t_{i+1}} \tilde{h}(t, r_{i+1,m} + M_i(\rho_{i,m})) \, dt + QT\kappa}{\sum_{i=0}^{j} M_l(\rho_{l,m})} \leq \frac{1}{1 + \delta},
\]
a contradiction. It means that there exists $B_j > 0$ such that

$$\sup\{|u'(t)| : t \in [0, t_{j+1}] \} < B_j,$$

(3.43)

for each function $u \in AC_l^1$ satisfying (1.4), (1.5), (3.9), (3.19), which has its critical point equal to $t_{j+1}$. This implies that there is $A_j > 0$ such that

$$\sup\{u(t) : t \in [0, t_{j+1}] \} < A_j.$$

(3.44)

**Part 2:** It remains to estimate $u$ and $|u'|$ on $(t_{j+1}, T]$. According to Lemma 3.1, $u$ is decreasing on $(t_i, t_{i+1})$, $j + 1 \leq i \leq p$, and $u(t_{p+1}) = u(T) = 0$, which together with (3.44) yields

$$\sup\{|u(t)| : t \in (t_{j+1}, t_{j+2}) \} = u(t_{j+1}+) \leq J_{j+1}(A_j) = c_{j+2} > 0,$$

$$\sup\{|u(t)| : t \in (t_i, t_{i+1}) \} = u(t_i+) \leq J_i(c_i) = c_{i+1} > 0, \quad j + 1 \leq i \leq p,$$

and we can find a constant $\tilde{A}_j > 0$ (independent on $u$) satisfying

$$\sup\{u(t) : t \in [t_{j+1}, T] \} < \tilde{A}_j, \quad j + 2 \leq i \leq p + 1.$$

(3.45)

Integrating (3.19) on $[t_{j+1}, T]$ we obtain by virtue of (3.21), (3.22)

$$\sum_{i=j+2}^{p} M_i(\rho_i) - \sum_{i=j+2}^{p+1} \rho_i \leq \int_{t_{j+1}}^{T} \left( h(t, u(t) + |u'(t)|) + q(t)\omega(u(t)) \right) dt,$$

wherefrom, due to (3.25), (3.45) and (3.26)

$$\sum_{i=j+2}^{p+1} |\rho_i| \leq \sum_{i=j+2}^{p} |M_i(\rho_i)| + \sum_{i=j+1}^{p} \int_{t_i}^{t_{i+1}} \tilde{h}(t, \tilde{A}_j + |\rho_{i+1}|) dt + Q \int_{t_{j+1}}^{T} \omega(u(t)) dt.$$

(3.46)

Applying statement (I) of Lemma 3.3, we get

$$\int_{t_{j+1}}^{T} \omega(u(t)) dt \leq \sum_{i=j+1}^{p} \int_{t_i}^{t_{i+1}} \omega \left( \frac{t_{i+1} - t}{t_{i+1} - t_i} \right) dt = \frac{1}{\gamma} \sum_{i=j+1}^{p} (t_{i+1} - t_i) \int_{0}^{\gamma} \omega(t) dt.$$

Hence

$$\int_{t_{j+1}}^{T} \omega(u(t)) dt \leq T\tilde{c}_0.$$

(3.47)

Employing (3.46) and (3.47), it follows that

$$1 \leq \frac{1}{\sum_{i=j+2}^{p+1} |\rho_i|} \left( \sum_{i=j+2}^{p} |M_i(\rho_i)| + \sum_{i=j+1}^{p} \int_{t_i}^{t_{i+1}} \tilde{h}(t, \tilde{A}_j + |\rho_{i+1}|) dt + QT\tilde{c}_0 \right).$$

(3.48)
Assume for the sake of contradiction, (a$_1$) as in Part 1 and, instead of (a$_2$), we now suppose
(a$_3$) if we put (according to (3.21))
\[ u'_m(t_i) = \rho_{i,m}, \quad j + 1 \leq i \leq p + 1, \quad m \in \mathbb{N}, \]  
then there is $k \in \{j + 2, \ldots, p + 1\}$ such that
\[ \lim_{m \to \infty} \rho_{k,m} = -\infty. \]  
Let $\{j + 2, \ldots, p + 1\} = \mathcal{J} \cup \mathcal{K}$, where
\[ \lim_{m \to \infty} \rho_{i,m} = -\infty \quad \text{for } i \in \mathcal{K} \]  
and
\[ \{\rho_{i,m}\} \text{ is bounded for } i \in \mathcal{J}. \]  
Further, let $\mathcal{K} = \mathcal{K}_1 \cup \mathcal{K}_2$, where
\[ \lim_{m \to \infty} M_i(\rho_{i,m}) = -\infty \quad \text{for } i \in \mathcal{K}_1 \]  
and
\[ \{M_i(\rho_{i,m})\} \text{ is bounded for } i \in \mathcal{K}_2. \]  
By virtue of (3.45), (3.48) and assumption (a$_1$), we have
\[ 1 \leq \frac{\sum_{i=j+2}^{p} |M_i(\rho_{i,m})|}{\sum_{i=j+2}^{p+1} |\rho_{i,m}|} \]
\[ + \frac{\sum_{i=j+1}^{p} \int_{t_i}^{t_{i+1}} \tilde{h}(t, \tilde{A} \rho_{i+1,m}) \, dt + QT \delta}{\sum_{i=j+2}^{p+1} |\rho_{i,m}|}, \quad m \in \mathbb{N}. \]
Consider the first member on the right-hand side of (3.52). Note that due to (2.4) and (3.51) we can find $\delta > 0$ and $m_0 \in \mathbb{N}$ such that for $m \geq m_0$
\[ \left\{ \begin{array}{ll}
|\rho_{p,m}| > \delta |M_p(\rho_{p,m})| & \text{if } p \in \mathcal{K}, \\
|\rho_{i,m}| > (1 + \delta) |M_i(\rho_{i,m})| & \text{if } i < p, \quad i \in \mathcal{K}.
\end{array} \right. \]  
Therefore, using also the inequality in (3.24) for $i = p$, we get
\[ R_m = \frac{\sum_{i=j+2}^{p} |M_i(\rho_{i,m})|}{\sum_{i=j+2}^{p+1} |\rho_{i,m}|} \leq \frac{\sum_{i \in \mathcal{J} \cup \mathcal{K}_2} |M_i(\rho_{i,m})|}{\sum_{i \in \mathcal{K}} |\rho_{i,m}|} + \frac{\sum_{i \in \mathcal{K}_1} |M_i(\rho_{i,m})|}{(1 + \delta) \sum_{i \in \mathcal{K}_1} |M_i(\rho_{i,m})|}. \]
which yields

$$\lim_{m \to \infty} R_m \leq \frac{1}{1 + \delta}. \quad (3.54)$$

Now, consider the second member in (3.52) and put

$$d_{i+1,m} = \tilde{A}_j + |\rho_{i+1,m}|, \quad j + 1 \leq i \leq p, \ m \in \mathbb{N}. \quad (3.55)$$

Then, for $k \in \mathbb{N}$

$$\lim_{m \to \infty} d_{k,m} = \infty, \quad \lim_{m \to \infty} \frac{d_{k,m}}{\sum_{i=j+2}^{p+1} |\rho_{i,m}|} \leq 1. \quad (3.56)$$

Further, it is immediate from (2.6) that for $k \in \mathbb{N}$

$$\lim_{m \to \infty} \frac{1}{d_{k,m}} \int_{t_{k-1}}^{t_k} \tilde{h}(t, d_{k,m}) \, dt = 0. \quad (3.57)$$

Therefore, according to (3.56) and (3.57),

$$\lim_{m \to \infty} \frac{\sum_{k \in \mathbb{N}} \int_{t_{k-1}}^{t_k} \tilde{h}(t, d_{k,m}) \, dt}{\sum_{i=j+2}^{p+1} |\rho_{i,m}|} = 0. \quad (3.58)$$

Finally, for $k \in \mathbb{N}$ the sequences $\{d_{k,m}\}$ and $\{\int_{t_{k-1}}^{t_k} \tilde{h}(t, d_{k,m}) \, dt\}$ are bounded which yields

$$\lim_{m \to \infty} \frac{\sum_{k \in \mathbb{N}} \int_{t_{k-1}}^{t_k} \tilde{h}(t, d_{k,m}) \, dt}{\sum_{i=j+2}^{p+1} |\rho_{i,m}|} = 0. \quad (3.59)$$

Let us go back to (3.52). Conditions (3.58), (3.59) and (3.54) imply that

$$1 \leq \lim_{m \to \infty} \frac{\sum_{i=j+2}^{p+1} |M_i(\rho_{i,m})|}{\sum_{i=j+2}^{p+1} |\rho_{i,m}|} + \lim_{m \to \infty} \frac{\sum_{i=j+1}^{p+1} \int_{t_i}^{t_{i+1}} \tilde{h}(t, \tilde{A}_j + |\rho_{i+1,m}|) \, dt + QT \tilde{\omega}}{\sum_{i=j+2}^{p+1} |\rho_{i,m}|} \leq \frac{1}{1 + \delta},$$

a contradiction. It means that there exists $\tilde{B}_j > 0$ such that

$$\sup\{|u'(t)|: t \in [t_{j+1}, T]\} < \tilde{B}_j, \quad (3.60)$$

for each function $u \in AC_{12}^1$ satisfying (1.4), (1.5), (3.9), (3.19) which has its critical point equal to $t_{j+1}$.

If we find $A_j, \tilde{A}_j$ satisfying (3.44), (3.45) and $B_j, \tilde{B}_j$ satisfying (3.43), (3.60) for each $j \in \{0, \ldots, p - 1\}$ and put

$$A^* = \max\{A_j, \tilde{A}_j, 0 \leq j \leq p - 1\}, \quad B^* = \max\{B_j, \tilde{B}_j, 0 \leq j \leq p - 1\},$$

we get (3.20) for each function $u \in AC_{12}^1$ satisfying (1.4), (1.5), (3.9) and (3.19) and having its critical point in $\mathcal{D}$. 
Case (ii). Suppose that \( u \in AC^1_D \) fulfills (1.4), (1.5), (3.9) and (3.19) and has its critical point \( \xi \in (0, T) \setminus D \). It means that there is \( j \in \{0, \ldots, p \} \) such that \( \xi \in (t_j, t_{j+1}) \). Then we argue as in Case (i). Particularly, in Part 1 we take the interval \((t_j, \xi]\) instead of \((t_j, t_{j+1}]\) and use assertion (II) of Lemma 3.3 instead of assertion (I). In Part 2 we have in addition the interval \((\xi, t_{j+1}]\), where \( u \) has the same properties as on \((t_{j+1}, t_{j+2}]\) in Case (i). We also use assertion (II) of Lemma 3.3 and then argue as in Case (i).

4. Uniform absolute continuity

Let us denote by \( B \) the set of all functions \( x \in AC^1_D \) having a unique critical point \( \xi = \xi(x) \) and fulfilling (I), (II) of Lemma 3.3 and let \( x(i) \in C^1[t_i, t_{i+1}], 0 \leq i \leq p, \) fulfil (1.1).

**Lemma 4.1.** Let \( \omega \) satisfy \((H_4)\) and \( i \in \{0, \ldots, p \} \). Then the set

\[ \mathcal{A}_i = \{ \omega(x(i)): x \in B \} \]

is uniformly absolutely continuous on \([t_i, t_{i+1}]\), i.e. for each \( \varepsilon > 0 \) there exists \( \delta > 0 \) such that

\[ \int_{\mathcal{A}_i} \omega(x(i)(t)) \, dt < \varepsilon \]

for each function \( x \in B \) and each set \( \mathcal{M} \subset [t_i, t_{i+1}] \) such that \( \mu(\mathcal{M}) < \delta \).

**Proof.** It is sufficient to prove that for any \( i \in \{0, \ldots, p \} \) and each \( \varepsilon > 0 \) there exists \( \delta > 0 \) such that for each system \( \{(\alpha_k, \beta_k)\}_{k=1}^{\infty} \) of mutually disjoint intervals \( (\alpha_k, \beta_k) \subset [t_i, t_{i+1}] \) the implication

\[ \sum_{k=1}^{\infty} (\beta_k - \alpha_k) < \delta \Rightarrow \sum_{k=1}^{\infty} \int_{t_k}^{t_{2k}} \omega(x(i)(t)) \, dt < \varepsilon \quad (4.1) \]

is valid for each function \( x \in B \).

Let us choose \( x \in B \) and \( i \in \{0, \ldots, p \} \). Then \( x \) has a critical point \( \xi = \xi(x) \in (0, T) \). We are going to estimate the integral

\[ I_k = \int_{t_k}^{t_{2k}} \omega(x(i)(t)) \, dt. \]

Denote

\[ \Omega(z) = \int_0^z \omega(s) \, ds. \]
We distinguish 3 types of locations of $\xi, x_k, \beta_k$.

**Location 1:** Let $\xi > \beta_k$. Then

$$I_k \leq \frac{T}{\gamma} \left( \Omega \left( \frac{\gamma}{T}(\beta_k - t_i) \right) - \Omega \left( \frac{\gamma}{T}(x_k - t_i) \right) \right).$$

(4.2)

**Location 2:** Let $\xi < x_k$. Then

$$I_k \leq \frac{T}{\gamma} \left( \Omega \left( \frac{\gamma}{T}(t_{i+1} - x_k) \right) - \Omega \left( \frac{\gamma}{T}(t_{i+1} - \beta_k) \right) \right).$$

(4.3)

**Location 3:** Let $x_k < \xi < \beta_k$. Then

$$I_k \leq \frac{T}{\gamma} \left( \Omega \left( \frac{\gamma}{T}(\xi - t_i) \right) - \Omega \left( \frac{\gamma}{T}(x_k - t_i) \right) \right)
+ \frac{T}{\gamma} \left( \Omega \left( \frac{\gamma}{T}(t_{i+1} - \xi) \right) - \Omega \left( \frac{\gamma}{T}(t_{i+1} - \beta_k) \right) \right).$$

(4.4)

Choose an $\varepsilon > 0$ and put $\varepsilon_1 = \varepsilon \frac{2T}{\gamma}$. Since $\Omega$ is absolutely continuous on $[0, \gamma]$, we can find $\delta > 0$ such that for any system $\{ (a_k, b_k) \}_{k=1}^{\infty}$ of mutually disjoint intervals in $[0, \gamma]$

$$\sum_{k=1}^{\infty} (b_k - a_k) < \delta \Rightarrow \sum_{k=1}^{\infty} (\Omega(b_k) - \Omega(a_k)) < \varepsilon_1 \quad (5.5)$$

is valid. Put $\delta = \delta_1 \frac{T}{\gamma}$ and take a system $\{ (x_k, \beta_k) \}_{k=1}^{\infty} \subset [t_i, t_{i+1}]$ such that $\sum_{k=1}^{\infty} (\beta_k - x_k) < \delta$. Then, using (4.2)–(4.5) and the inequality $||\beta_k - t_i| - |x_k - t_i|| \leq \beta_k - x_k$, we get

$$\sum_{k=1}^{\infty} I_k \leq \frac{2T}{\gamma} \varepsilon_1 = \varepsilon,$$

and hence (4.1) is proved. \(\square\)

5. Existence principle for regular impulsive BVPs

**Lemma 5.1.** Let $h \in L_1[0, T]$ and $c_i, d_i \in \mathbb{R}, 1 \leq i \leq p$. Then there is a unique solution $u$ of problem (1.5),

$$-u''(t) = h(t),$$

(5.1)

$$u(t_{i+}) = c_i + u(t_i), \quad u'(t_{i+}) = d_i + u'(t_i), \quad 1 \leq i \leq p.$$

(5.2)
This solution is given by

$$u(t) = \sum_{i=1}^{p} \tilde{G}(t, t_i)c_i + G(t, t_i)d_i - \int_{0}^{T} G(t, s)h(s) \, ds,$$

(5.3)

for $t \in [0, T]$, where

$$\tilde{G}(t, s) = \begin{cases} \frac{T-t}{T} & \text{if } 0 \leq s < t \leq T, \\ \frac{t}{T} & \text{if } 0 \leq t < s \leq T, \end{cases}$$

(5.4)

$$G(t, s) = \begin{cases} \frac{s(t-T)}{T} & \text{if } 0 \leq s \leq t \leq T, \\ \frac{t(s-T)}{T} & \text{if } 0 \leq t < s \leq T. \end{cases}$$

(5.5)

**Proof.** We can argue as in the proof of Lemma 2.1 in [16].

Now, suppose that $C^1_{\mathcal{D}}$ is equipped with the norm

$$||x||_{\mathcal{D}} = \sup\{ |x(t)| + |x'(t)| : t \in [0, T] \}.$$  

Then $C^1_{\mathcal{D}}$ becomes a Banach space (see e.g. [7]). For $R > 0$ define a set

$$K(R) = \{ x \in C^1_{\mathcal{D}} : ||x||_{\mathcal{D}} < R \}$$

and denote its closure by $\text{cl}(K(R))$.

**Lemma 5.2.** Let us suppose that $g \in L^1[0, T]$ and $(H_1)$ holds. Then there exists a constant $R^* > 0$ such that each function $u \in AC^1_{\mathcal{D}}$ fulfilling (1.4), (1.5) and

$$0 < -u''(t) \leq g(t) \text{ for a.e. } t \in [0, T]$$

(5.6)

belongs to $K(R^*)$.

**Proof.** By Lemma 3.1 $u$ has a critical point $\xi \in \mathcal{D}$. First, assume that $\xi \in \mathcal{D}$, i.e. $\xi = t_j$ for some $j \in \{1, \ldots, p\}$. Integrate (5.6) from $\xi$ to $t \in [\xi, t_j+1]$. We get

$$0 \leq -u'(t) \leq ||g||_{L_1} \text{ for } t \in [\xi, t_j+1].$$

If $j < p$ we integrate (5.6) from $t_{j+1}$ to $t \in (t_{j+1}, t_{j+2}]$ and get

$$0 \leq -u'(t) \leq M_{j+1}(||g||_{L_1}) + ||g||_{L_1} \text{ for } t \in [t_{j+1}, t_{j+2}].$$
If \( j < p - 1 \) we integrate again and continue inductively to find a constant \( m_1 > 0 \) such that
\[
0 \leq -u'(t) \leq m_1 \quad \text{for} \quad t \in [\xi, T],
\]
(5.7)
for any \( u \in AC^1_{\mathcal{D}} \) satisfying (1.4), (1.5) and (5.6). Similarly we find \( m_2 > 0 \) such that
\[
0 \leq u'(t) \leq m_2 \quad \text{for} \quad t \in [0, \xi].
\]
(5.8)
If \( \xi \in (0, T) \setminus \mathcal{D} \) we can use a similar integral procedure and get (5.7), (5.8), as well. Now, integrate (5.8) from 0 to \( t \in (0, t_1] \). Then
\[
0 \leq u(t) \leq t_1 m_2 \quad \text{for} \quad t \in [0, t_1].
\]
Integrate (5.8) from \( t_1 \) to \( t \in (t_1, t_2] \). Then
\[
0 < u(t) \leq (t_2 - t_1) m_2 + J_1(t_1 m_2) \quad \text{for} \quad t \in (t_1, t_2].
\]
Continuing inductively we deduce that there exists a constant \( m_3 \) (independent on \( u \)) such that
\[
0 < \sup \{ u(t): \ t \in [0, T] \} \leq m_3.
\]
Hence, it suffices to put \( R' = m_1 + m_2 + m_3 \) and lemma is proved. \( \square \)

**Theorem 5.3.** Let us suppose that \( \tilde{f} \) satisfies the Carathéodory conditions on \( [0, T] \times \mathbb{R}^2 \), (H1) holds and that there exists a function \( g \in L_1[0, T] \) such that
\[
0 < f(t, x, y) \leq g(t) \quad \text{for a.e.} \ t \in [0, T] \text{ and for all } x, y \in \mathbb{R}.
\]
(5.9)
Then problem (1.4), (1.5),
\[
-u''(t) = \tilde{f}(t, u(t), u'(t))
\]
(5.10)
has a positive solution.

**Proof.** Step 1: Choose an arbitrary \( y \in C^1_{\mathcal{D}} \) and consider the auxiliary linear problem (1.5)
\[
-x''(t) = \tilde{f}(t, y(t), y'(t)),
\]
(5.11)
\[
\begin{align*}
  x(t_{i+}) - x(t_i) &= J_i(y(t_i)) - y(t_i), \\
  x'(t_{i+}) - x'(t_i) &= M_i(y'(t_i)) - y'(t_i), \quad 1 \leq i \leq p.
\end{align*}
\]
(5.12)
Clearly \( \tilde{f}(t, y(t), y'(t)) \in L_1[0, T], \ J_i(y(t_i)) - y(t_i) = c_i \in \mathbb{R}, \ M_i(y'(t_i)) - y'(t_i) = d_i \in \mathbb{R}, \ 1 \leq i \leq p, \) and hence, by Lemma 5.1, problem (1.5), (5.11), (5.12) has a unique
By virtue of (5.3) this solution is of the form
\[ x(t) = (F y)(t) \quad \text{for} \quad t \in [0, T], \]
where \( F : C^1_{\omega} \to C^1_{\omega} \) is given by
\[
(F y)(t) = \sum_{i=1}^{p} \tilde{G}(t, t_i)(J_i(y(t_i)) - y(t_i)) + \sum_{i=1}^{p} G(t, t_i)(M_i(y'(t_i)) - y'(t_i)) - \int_{0}^{T} G(t, s)\tilde{f}(s, y(s), y'(s)) \, ds.
\]
Therefore, \( u \) is a solution of (1.4), (1.5), (5.10) if and only if \( u \) is a fixed point of the operator \( F \). Let \( F_1 : C^1_{\omega} \to C^1_{\omega} \) be defined by the formula
\[
(F_1 y)(t) = \int_{0}^{T} G(t, s)\tilde{f}(s, y(s), y'(s)) \, ds.
\]
Due to (5.9) we can use the Lebesgue dominated convergence theorem and the Arzelà–Ascoli theorem and get that \( F_1 \) is absolutely continuous. Further, since \( J_i \) and \( M_i, 1 \leq i \leq p \), are continuous, the operator \( F_2 = F + F_1 \) is continuous, as well. Since \( F_2 \) maps \( C^1_{\omega} \) in a \( 2p \)-dimensional subspace of \( C^1_{\omega} \), we deduce that \( F_2 \) and consequently \( F \) are absolutely continuous operators.

**Step 2:** We are going to prove the existence of a fixed point of \( F \) by means of the topological degree arguments. To this aim we consider the operator equation
\[
u = Fu
\]
and the parameter system of equations
\[
u = F^*(\lambda, u),
\]
with \( F^* : [0, 1] \times C^1_{\omega} \to C^1_{\omega} \),
\[
F^*(\lambda, u) = \sum_{i=1}^{p} \tilde{G}(t, t_i)(J_i(u(t_i)) - u(t_i)) + \sum_{i=1}^{p} G(t, t_i)(M_i(u'(t_i)) - u'(t_i)) - \lambda \int_{0}^{T} G(t, s)\tilde{f}(s, u(s), u'(s)) \, ds.
\]
Clearly \( F^*(1, u) = Fu \) and \( F^* \) is absolutely continuous. Let us choose \( \lambda \in (0, 1] \) and let \( u \in C^1_{\omega} \) be a corresponding solution of (5.14), i.e. \( u = F^*(\lambda, u) \). It means that the function \( u \) satisfies
\[
-u''(t) = \lambda \tilde{f}(t, u(t), u'(t)) \quad \text{for a.e.} \quad t \in [0, T],
\]
and \( u \in AC_{\mathcal{L}}^1 \) fulfils (1.4) and (1.5). Hence \( u \) is a solution of problem (5.15), (1.4), (1.5). By virtue of (5.9) \( u \) satisfies

\[
0 < -u''(t) \leq \lambda g(t) \leq g(t) \quad \text{for a.e. } t \in [0, T],
\]

and, hence by Lemma 5.2, there exists \( R^* > 0 \) (independent on \( u \) and \( \lambda \)) such that

\[
u \in K(R^*). \quad (5.16)
\]

Let \( u \in C_{\mathcal{L}}^1 \) be a solution of (5.14) for \( \lambda = 0 \), i.e. \( u = F^*(0, u) \). Then \( u \in AC_{\mathcal{L}}^1 \) satisfies (1.4), (1.5) and \(-u''(t) = 0\) for a.e. \( t \in [0, T] \). Therefore \( u(t) = a + bt, \ a, b \in \mathbb{R} \). Since \( u(0) = 0 \), we get \( a = 0 \) and the condition \( u(T) = 0 \) implies \( b = 0 \). Hence \( u(t) = 0 \) for \( t \in [0, T] \) and consequently \( u \) fulfils (5.16). To summarize, we have proved that there exists a constant \( R^* > 0 \) such that for any \( \lambda \in [0, 1] \) each solution of (5.14) belongs to \( K(R^*) \). This means that \( Iu - F^*(\lambda, u) \) is a homotopy on \([0, 1] \times cl(K(R^*))\) and thus

\[
1 = \deg(I, K(R^*)) = \deg(I - F, K(R^*)). \quad (5.17)
\]

Here, \( \deg \) is the Leray–Schauder topological degree and \( I : C_{\mathcal{L}}^1 \to C_{\mathcal{L}}^1 \) is the identity operator \( Ix = x \). Condition (5.17) implies that \( F \) has a fixed point \( u \in K(R^*) \). Since fixed points of \( F \) are solutions of (1.4), (1.5), (5.10), and due to Lemma 3.1 these solutions are positive on \((0, T)\), Theorem 5.3 is proved. \( \Box \)

6. Main results

In this section we construct a sequence of auxiliary regular BVPs and, by Theorem 5.3, we get a sequence of their solutions. Then, using the limiting process we prove the existence of a positive solution to our original singular Dirichlet BVP (1.3)–(1.5).

**Theorem 6.1.** Let assumptions \((H_1) - (H_5)\) be satisfied. Then there exists a positive solution of BVP (1.3)–(1.5).

**Proof.** For a.e. \( t \in [0, T] \) and all \( z \in [0, \infty) \) put

\[
\tilde{h}(t, z) = h(t, 1 + z) + q(t)\omega(1). \quad (6.1)
\]

Then, due to \((H_4)\), \( \tilde{h} \) satisfies the Carathéodory conditions on \([0, T] \times [0, \infty)\), \( \tilde{h} \) is nonnegative and nondecreasing in its second argument and, by virtue of (2.6),

\[
\lim_{z \to \infty} \frac{1}{z} \int_0^T \tilde{h}(t, z) \, dt = 0.
\]
Therefore, we can find positive constants $A^*, B^*$ satisfying Lemma 3.4.

Now, choose an arbitrary $m \in \mathbb{N}$ and $x \in [0, \infty), y \in \mathbb{R}$ define

$$
\sigma_1 \left( \frac{1}{m} x \right) = \begin{cases} 
\frac{1}{m} & \text{if } 0 \leq x \leq \frac{1}{m}, \\
x & \text{if } \frac{1}{m} \leq x \leq 1 + A^*, \\
1 + A^* & \text{if } x > 1 + A^*,
\end{cases}
$$

Further, for a.e. $t \in [0, T]$ and all $x, y \in \mathbb{R}$ define

$$
f_m(t, x, y) = f \left( t, \sigma_1 \left( \frac{1}{m} |x| \right), \sigma_2(y) \right),
$$

and consider the auxiliary equation

$$
-u''(t) = f_m(t, u(t), u'(t)). \quad (6.2)
$$

Then, by (H₃), $f_m$ satisfies the Carathéodory conditions on $[0, T] \times \mathbb{R}^2$ and for a.e. $t \in [0, T]$ and all $x, y \in \mathbb{R}$

$$
0 < f_m(t, x, y) \leq g_m(t), \quad (6.3)
$$

where

$$
g_m(t) = \sup \left\{ f(t, x, y) : x \in \left[ \frac{1}{m}, 1 + A^* \right], y \in [-B^*, B^*] \right\} \in L_1[0, T].
$$

Therefore, according to Theorem 5.3, for each $m \in \mathbb{N}$ problem (6.2), (1.4), (1.5) has a positive solution $u_m$. Thus, we get a sequence $\{u_m\}$ of solutions. By Lemma 3.1 and (6.2), (6.3), each $u_m$ has a unique critical point $\xi_m = \xi_m(u_m) \in (0, T), m \in \mathbb{N}$.

Further, by virtue of (H₃)–(H₅), we see that for a.e. $t \in [0, T]$ and all $x \in (0, \infty), y \in \mathbb{R}, m \in \mathbb{N}$, the inequalities

$$
0 < \psi(t) \leq f_m(t, x, y) \quad (6.4)
$$

and

$$
f_m(t, x, y) \leq \hat{h}(t, x + |y|) + q(t)\omega(x) \quad (6.5)
$$

are valid, where $\psi$ is from (H₃) and $\hat{h}$ (on the place of $h$), $q, \omega$ satisfy (H₄). Note, that (6.5) follows from (2.8), (6.1) and relations

$$
\sigma_1 \left( \frac{1}{m} x \right) \leq 1 + x, \quad |\sigma_2(y)| \leq |y|
$$
and
\[
\omega \left( \sigma_1 \left( \frac{1}{m}, x \right) \right) \leq \omega(1 + A^*) + \omega(x) \leq \omega(1) + \omega(x).
\]

In view of (6.4) we can use Lemma 3.3 and find \( \gamma > 0 \) (independent on \( u_m \)) satisfying (3.10), (3.11), where \( u \) is replaced with \( u_m, m \in \mathbb{N} \). It means that
\[
\{u_m\} \subset \mathcal{B}.
\]
Moreover, Lemma 3.4 yields
\[
\begin{cases}
\sup \{u_m(t): t \in [0, T]\} < A^*, \\
\sup \{|u_m'(t)|: t \in [0, T]\} < B^*.
\end{cases}
\]

Now, choose an arbitrary \( i \in \{0, \ldots, p\} \) and denote by \( u_{m(i)} \) functions from \( C^1[t_i, t_{i+1}] \) which correspond to \( u_m \) in the sense of formula (1.1). Put as before
\[
Q = \sup \{q(t): t \in [0, T]\}.
\]
By (6.5), we have for \( t, \tau \in [t_i, t_{i+1}], \ \tau < t, \)
\[
|u_{m(i)}'(t) - u_{m(i)}'(\tau)| \leq \int_\tau^t \tilde{h}(s, A^* + B^*) \, ds + Q \int_\tau^t \omega(u_{m(i)}(s)) \, ds.
\]
Due to (6.6) we can use Lemma 4.1 and obtain that the sequence \( \{\omega(u_{m(i)})\} \) is uniformly absolutely continuous on \( [t_i, t_{i+1}] \). This, by (6.8), implies that the sequence \( \{u_{m(i)}'\} \) is equicontinuous on \([t_i, t_{i+1}]\). Further, by (6.7), we see that the sequence \( \{u_{m(i)}\} \) is bounded in \( C^1[t_i, t_{i+1}] \). Thus by the Arzelà–Ascoli theorem, we can choose a subsequence \( \{u_{k(i)}\} \) which converges in \( C^1[t_i, t_{i+1}] \) to a function \( u(\cdot) \in C^1[t_i, t_{i+1}] \). Consider the sequence of equalities
\[
u_{k(i)}'(t) = u_{k(i)}'(t_i) - \int_{t_i}^t f_k(s, u_{k(i)}(s), u_{k(i)}'(s)) \, ds \quad \text{for } t \in [t_i, t_{i+1}].
\]
Denote (by \( \mathcal{U} \)) the set of all \( t \in [0, T] \) such that \( f(t, \cdot, \cdot) : (0, \infty) \times \mathbb{R} \to \mathbb{R} \) is continuous. Then \( \mu([0, T] \setminus \mathcal{U}) = 0 \) and
\[
\lim_{k \to \infty} f_k(t, u_{k(i)}(t), u_{k(i)}'(t)) = f(t, u(\cdot)(t), u'(\cdot)(t)) \quad \text{for all } t \in (t_i, t_{i+1}) \cap \mathcal{U},
\]
because \( u(\cdot) \) is positive on \( (t_i, t_{i+1}) \) by (6.6). Using (6.5) and the uniform absolute continuity of \( \{\omega(u_{k(i)})\} \) on \([t_i, t_{i+1}]\), we deduce that \( \{f_k(t, u_{k(i)}(t), u_{k(i)}'(t))\} \) is also uniformly absolutely continuous on \([t_i, t_{i+1}]\). Therefore, we can use the Vitali convergence theorem by which \( f(t, u(\cdot)(t), u'(\cdot)(t)) \in L_1[t_i, t_{i+1}] \) and letting \( k \to \infty \)
in (6.9) we have that
\[ u'(i)(t) = u'(i)(t_i) - \int_{t_i}^{t} f(s, u(i)(s), u'(i)(s)) \, ds \quad \text{for } t \in [t_i, t_{i+1}]. \]

It means that \( u(i) \in AC^1[t_i, t_{i+1}] \) and \( u(i) \) satisfies (1.3) a.e. on \([t_i, t_{i+1}]\). Since \( i \in \{0, \ldots, p\} \) has been chosen arbitrarily, we can put
\[
\begin{aligned}
    u(t) &= \begin{cases} 
        u(0)(t) & \text{for } t \in [0, t_1], \\
        u(1)(t) & \text{for } t \in (t_1, t_2), \\
        \vdots & \vdots \\
        u(p)(t) & \text{for } t \in (t_p, T) 
    \end{cases}
\end{aligned}
\]

and get \( u \in AC^1_2, u \) satisfies (1.3) a.e. on \([0, T]\) and fulfills (1.5). Having in mind that \( J_i, M_i, 1 \leq i \leq p \), are continuous we deduce that \( u \) fulfills (1.4). Really, we have
\[
\begin{aligned}
u(t_i+) &= u(i)(t_i) = \lim_{k \to \infty} u_k(i)(t_i) = \lim_{k \to \infty} J_i(u_{k(i-1)})(t_i)) \\
&= J_i \left( \lim_{k \to \infty} u_k(i-1)(t_i) \right) = J_i(u(i-1)(t_i)) = J_i(u(t_i)).
\end{aligned}
\]

Similarly for \( u'(t_i+) \). Finally, due to Lemma 3.1 and \((H_3)\), \( u \) is positive on \([0, T]\). Theorem 6.1 is proved. \( \square \)

References


